

Generic Planning and Control of Automated Material Handling Systems: Practical Requirements Versus Existing Theory

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GENERIC PLANNING AND CONTROL OF AUTOMATED MATERIAL HANDLING SYSTEMS: PRACTICAL REQUIREMENTS VERSUS EXISTING THEORY

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Abstract

This paper discusses the problem of generic planning and control of Automated Material Handling Systems (AMHSs). The paper illustrates the relevance of this research direction, and then addresses three different market sectors where AMHSs are used. These market sectors are: baggage handling, distribution, and parcel & postal. Research in these sectors is heavily motivated by a collaboration between the authors and a major global company supplying AMHSs. The paper analyzes requirements from practice for a generic control architecture, and then reviews literature to investigate whether answers can be found for practical requirements. Next, the paper confronts theory with practice, and concludes that there is still much work to be done in this area. The paper takes the initiative to define a research direction in concrete terms, pinpoints problems to work on, and proposes an agenda for future research.

Keywords: Automated material handling systems, Real-time scheduling, Generic control architecture.

1. Introduction

This paper focuses on planning and control methods for complex Automated Material Handling Systems (AMHSs). We pay attention to three different market sectors i.e. Baggage Handling (BH), Distribution (D), and Parcel & Postal (P&P). Planning and control of these systems need to be robust and yield close-to-optimal systems' performance. Typical performance indicators concern throughput, lead time, and reliability. AMHSs are in general complex installations that comprise various processes, such as inbound, storage, batching, sorting, picking, and outbound processes. Currently, planning and control of AMHSs is highly customized and project specific. This has important drawbacks for at least two practical reasons. From a customer point of view, the environment and user requirements of systems may vary over time, yielding the need for adaptation of the planning and control procedures. From a systems' deliverer point of view, an overall planning and control architecture that optimally exploits synergy between the different market sectors, and at the same time is flexible with respect to changing business parameters and objectives, may reduce design time and costs considerably. Moreover, from a scientific point of view, we address the challenge of finding a common ground to model AMHSs in totally different market sectors and developing a generic control architecture that can be applied to AMHSs in these different sectors.

This research direction aims at an integral planning and control architecture, which clearly describes the hierarchical framework of decisions to be taken at various levels, as well as the required information for decisions at each level (e.g., from overall workload planning to local traffic control). The planning and control architecture should be flexible, allowing for easy adaptation to configuration changes, changes in performance criteria, different operational modes, and adjustment of the control strategies.

Our main task is to pave the road for a generic control architecture that can satisfy the requirements of AMHSs designed for distinct market sectors. However, before presenting the structure of this paper, we draw our scope boundaries. Figure 1 shows three possible scopes of analysis, along with the party mainly responsible for decision making within each scope, i.e., customer/supplier. The research direction we introduce, excludes Scope 3, because the focus there shifts more towards network optimization. A shift towards network optimization results in limiting the attention paid to the internal system within a single facility in the network, i.e., the AMHS, which is our main area of interest. The focus is on the control of complex AMHSs, which is the analysis within Scope 1. However, it is

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worth to mention that Scope 2 may also entail interesting problems to work on, which may be closely related to the operation of the AMHS. An example is how to sequence the unloading of incoming containers at a parcel sorting hub in order to make the operation of the AMHS more efficient. Solving such a problem needs real-time information from the AMHS, e.g. on the nature of the load in transport within the AMHS.

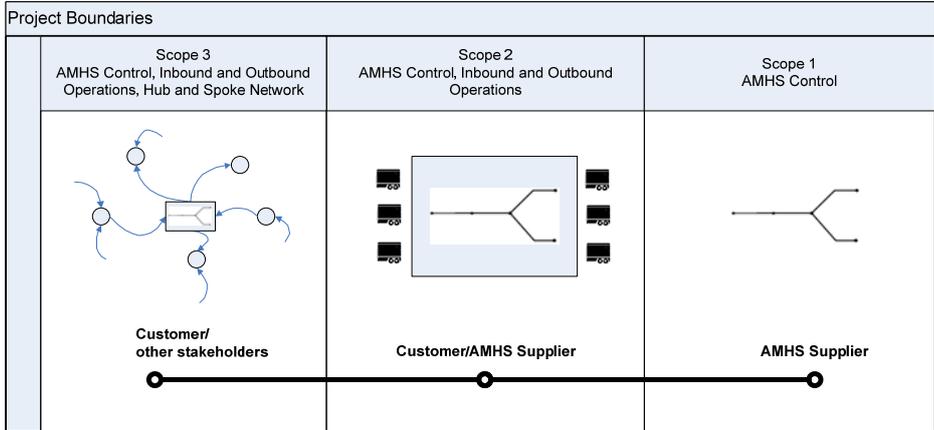


Figure 1. Scope boundaries.

This paper proceeds as follows: we first get close to practice by analyzing the functionality and requirements of AMHSs installed in different market sectors (Section 2). Here, we stress that our research is heavily motivated by our collaboration with a major global company supplying material handling systems in all market sectors discussed in the paper. Next, as we gain insight from practice, Section 3 addresses theory by conducting a literature review in a search for answers from existing theory to the requirements from practice. Section 4 weighs the practical requirements against the theoretical knowledge, and clarifies the appropriate research directions. Finally, Section 5 ends with concluding remarks.

2. Practice: Market Sectors

This section addresses three different sectors using AMHSs. The aim is to gain insight into the requirements and functionalities of AMHSs in these sectors. Our scope of analysis is restricted to the built-in control of the AMHS that is within the responsibility of the AMHS supplier, not the AMHS user.

2.1 Market Sectors

Parcel & Postal In the parcel & postal sector, the systems are typically used by Logistic Service Providers (LSPs) such as DHL, UPS, and TNT to receive items coming to a hub from various sources, and then sort them according to destination, in preparation for further transport. In this business, as the quantities to be handled grow, manual operations fall short. Thus, the need for automated sorting systems is evident. Such systems can be seen in different forms and different capabilities to meet the specific demands of customers. The term parcel is used throughout this paper as the main item handled within these systems. However, other items, such as totes, can be handled by the same sorting systems as clarified later on. Figure 2 shows the generic scheme of a simple sorting system.

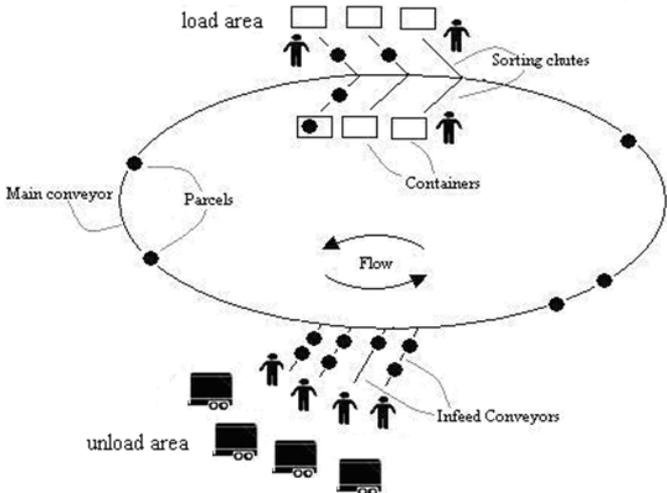


Figure 2. Generic scheme of a closed-loop parcels sorting system.

The process starts at the unload area, where containers carrying parcels arrive at the system via airplanes or trucks. Operators unload the containers and place the parcels on the *infeed* conveyors (or simply infeeds). These infeeds transport the parcels to the main conveyor represented by the big loop in Figure 2. The merge operation takes place when the parcels transported on the infeeds reach the main conveyor. When the parcels are on the main conveyor, they circulate on it to reach the load area. In this area, parcels are automatically directed to their destinations, based on parcel identification labels. Parcels are released into special conveyors called sorting chutes (see Figure 2). At the end of these chutes, operators gather the parcels in containers. In the layout given in Figure 2, some parcels may flow back into the unload area, which means that they have passed the load area without being sorted. This is possible when the chutes are full or when there is some disruption in the system. Such a system is therefore referred to as a *closed-loop* sorting system, or *loop* sorter. However, the system depicted in Figure 2 is a simple one, larger and more complex systems can entail several load and unload areas, multiple loops, more complex layouts, etc. Such complex systems may provide alternative routes to reach a certain destination (chute).

A parcel sorting hub operates at full power in specific time intervals, mostly during night-time. Normally, tons of parcels (and documents) are delivered, sorted, and transported within few hours. In these rush-hour conditions, the main objective is to maximize throughput of the systems, in order to minimize the time period between the arrival and departure times of planes or trucks. This may result in some other functional requirements that may bring more efficiency to the process, e.g., balancing material flows within the system.

Baggage Handling We focus on Baggage handling systems (BHSs) in airports. Baggage handling is a sector that differs from all other sectors in AMHSs. The main difference is that there are multiple stakeholders involved, and have a say in a baggage handling system. These stakeholders are: the airport (main customer), airlines and handlers (parties using the BHS), security, and customs. The latter two are external parties that impose restrictions on the operation of the BHS.

In a BHS, the bag as the main item treated belongs to one of three possible categories (see Figure 3). On a very generic level, first a bag may belong to a passenger who arrives at the airport and has a departing flight to catch. Second, it may belong to a transit passenger who lands on the airport and has a connecting flight to catch. Finally, a bag may belong to a passenger for whom the airport is his final destination. In a BHS, there is an Early Bag Storage (EBS), where bags that arrive early to the system are temporarily stored.

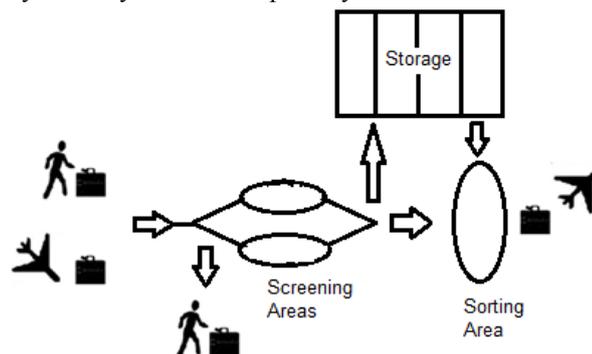


Figure 3. Generic scheme of a baggage handling system.

The purpose of a BHS is to deliver each bag from some source point A to some destination point B, within a specific time limit. However, the airport environment is very dynamic and stochastic, which complicates the delivery job, and raises many additional considerations. Moreover, every stakeholder has his own desires, which affect his criteria for assessing the BHS. A main performance measure for BHS is the *irregularity rate*. The irregularity rate is the number of bags (per 1000) that are supposed to be on a certain plane but are not on it (luggage that missed the correct plane, and lost luggage). From a practical point of view, minimizing the irregularity rate is most challenging when dealing with the connecting flights. This is because several things can go wrong when trying to correctly deliver an arriving bag to the next connecting plane within a given time window. Problems may arise from: wrong or corrupted bag tags, plane arriving late, disruptions in the BHS causing bags to miss their connecting flight, etc. As a result, the main objective for a BHS is to minimize the irregularity rate. An important system design parameter is the *in-system time*. This is the time a bag needs to travel along the longest path between the input and output points that are farthest apart in the BHS. This measure does not account for manual operations such as manual coding of bags when bag tags are found corrupted.

Within the BHS, an important attribute of each bag is the urgency measure in terms of the time left for the departure of its corresponding flight. Urgent bags have the highest priority to move to the intended destination as the time window available for them is the shortest. As time goes by, non-urgent bags become urgent. Business class bags have a priority when loading and unloading the plane, but they do not affect the urgency classification.

A BHS is a complex system consisting of several routes of transportation by different possible means such as conveyors and Destination Coded Vehicles (DCVs). The system includes different resources, e.g., screening machines, and redundant transport systems to ensure high availability. Therefore, there are different possible routings to realize the transport operation. The logistic control of this system must use the resources in a way that

optimizes the bag's flow time in the system (Section 2.3 discusses other relevant requirements). To sum up, the general high level objective for the control architecture of BHSs is to minimize the irregularity rate. This is done by achieving the overall transportation operation within the time limits, which requires a smooth process that is able to avoid disruptions or bag congestion that may result in bags missing their corresponding flights.

Distribution The Distribution sector concerns the AMHSs used in warehouses and distribution centers to handle various types of products for various customers. In distribution, projects vary considerably in terms of customer requirements and the variety of system designs and operational approaches that can be implemented. However, for all systems the generic set of ordered activities in a distribution center (DC) are as follows: Receiving, Storage, Order Picking, Consolidation, and Shipping. Moreover, Cross Docking is an operation in which the DC acts merely as a material handler without intermediate storage. Figure 4 shows a schematic view of a warehouse with a goods receiving area, storage area where an automated storage and retrieval system (ASRS) is installed, order picking area (with three pick stations), and consolidation area.

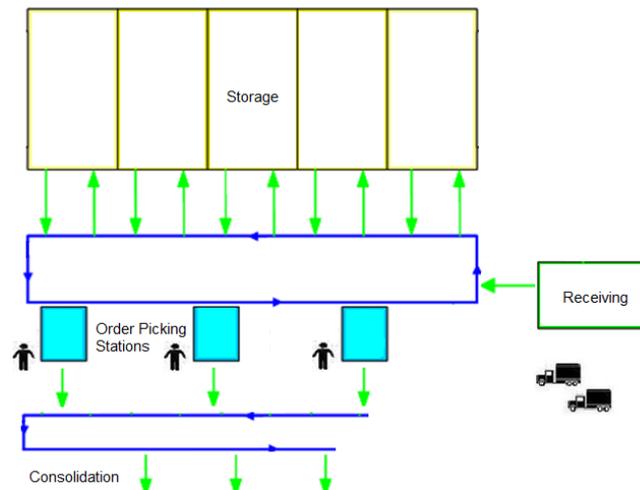


Figure 4. Generic scheme of a distribution center/warehouse.

In this sector, the general purpose is to satisfy the orders in time and with good quality, given time, cost, and other operational constraints. In order to satisfy orders properly within a certain time frame, a high throughput of the AMHSs is a main objective. In these systems, at each process stage, there is normally a set of parallel stations performing the same tasks, for example, parallel order pick stations, parallel aisle cranes, etc. Therefore, it is crucial to have proper workload balancing within the system. There should be a generic control approach that entails generic algorithms, allowing for applications in different types of systems. However, current control of distribution centers is highly customized and includes a lot of relatively complicated rules to realize as much throughput as possible of the AMHS. According to observations from practice, there is an increasing interest, from system control architects, towards more robust and generic control solutions, and less emphasis on achieving maximum throughput from the system. This is due to certain design and operational requirements that are explained in Section 2.3.

2.2 AMHSs in three market sectors: similarities and differences

Different market sectors imply different customer environments and requirements. However, the aim is to model the AMHSs in different sectors in a generic way in order to maximally exploit synergies. A first impression from the general study of these different sectors, leads to a belief that there is a certain level of synergy among them. BHSs and parcel & postal systems in particular seem to have more similarity. In the following, we list the main similarities of these two sectors, and for some points we indicate how the distribution sector differs:

- Routing within the system can be complex, and with more than one route to go from one point to another.
- Compared to distribution, the time pressure is higher in AMHSs in these two sectors, as is reflected in the necessity to deliver the items to their intended destinations in time to meet strict deadlines.
- Unpredictable arrivals: in baggage handling, there is no information ahead about the type, number, or weight of bags from check-in passengers. For parcel & postal and transit bags, information is in the network but not used to plan the operations. In distribution, there are planned goods to receive with known quantities and arrival times, so the distribution center can plan operations ahead.
- Item integrity: the bag or parcel enters and leaves the system in the same form, and with the same characteristics or attributes. On the other hand, in distribution, pallets are broken into product totes, and these product totes are handled within the material handling system. The unit transported by the AMHS may be the same, i.e., totes, but the characteristic of the tote changes. A product tote changes, e.g., when some items are picked from it.
- Items uniqueness: a parcel or a bag is a unique item in the system, and is required for a certain plane or truck. However, in distribution there are multiple alternatives for a certain item. If an order requires one unit from item x, there may be several totes containing item x. There is a choice from which tote to pick.

- Unit handled: in baggage handling and parcel & postal, the bag or parcel is normally picked, stored, and transported throughout the AMHS. In this sense, bags or parcels are single unit loads. However, in distribution, there may be a different definition of the unit load, which implies a number of items to be handled together and usually supported by a handling device such as a pallet, case, tote, etc.
- Heterogeneous items: bags and parcels may be of different shapes, weights, dimensions, which affect the convey-ability on an AMHS. However, in a distribution center there are normally standardized unit loads.

In the distribution sector, the synergy on a higher level may be less apparent, especially due to the high variation in implemented systems. However, taking some distribution centers from practice, there is synergy on a subsystem level in terms of physical components. Direct examples are:

- The storage in the ASRS system is analogous to the early bag storage in baggage handling. The physical system is very similar in these two sectors, but there are storage rules in distribution centers that determine where an item is stored, based on criteria like item availability in lanes. On the other hand, for baggage handling during peak times, the main concern is to store all bags that need storage as fast as possible without considering storage rules and anticipating the balance of picking from different storage aisles. These functional issues raise challenges for developing a generic storage and retrieval strategy that can be used by both sectors. Finally, the unit of storage in baggage handling is always a bag, whereas in distribution there are storage concepts for totes, pallets, cartons, etc. and the picking operation differs accordingly.
- Sorting systems: the backbone of the AMHS in the parcel & postal sector is the sorting system, but such sorting systems may be a sub-system in the other two sectors. In distribution, products arriving to be stored are normally merged on a conveyor loop that leads totes to storage aisles. In this context, guiding a tote to its destined storage aisle is a sorting operation like guiding the parcel to its destined sorting chute. Broken totes, which are totes that are picked from but that still contain items, return from order pick stations and subsequently merge on the conveyor loop that leads totes back to storage, which is again similar to the merge operation in parcel & postal. In the other direction, totes leave the storage aisles to go to the pick stations, this transport operation sorts totes to destined pick stations as well. In baggage handling, sorting systems are also used for sorting bags to, e.g., parallel screening machines, or to *laterals*. Laterals are areas where bags for a certain flight are consolidated for loading.

We find it sensible to provide a generic material flow model to explain the processes in the different sectors. The model entails generic process stages, which should cover all possible operations of AMHSs in practice. Therefore, we propose the material flow terminology of the most complex sector in terms of operations or process stages, which is distribution. AMHSs in distribution entail some complex and more detailed operations than the other two sectors, e.g., the order picking operation that changes the characteristics of handled items. Our claim is that any operation in the other two sectors can be mapped to one of the operations in the distribution sector. Transportation channels may be more complex in BHSs, but this is a matter of transportation complexity, not operational variety. Figure 5 presents a generic material flow model, together with a tabulated description of process stages, based on the analysis of selected reference sites from the different market sectors in practice. The model divides the physical flow into six process stages. In each stage, there is a set of resources modeled in abstract terms as workstations. This model lists resources and indicates transportation possibilities between them, but no explicit transportation routes.

2.3 Common Requirements of AMHSs/Control Architecture

The objective of the research direction in which we are interested, is to have a generic control architecture that can be applied to various types of AMHSs. The challenge for a generic control architecture lies in its ability to satisfy the objectives of different sectors. Therefore, we first look at the objectives of AMHSs in different sectors to decide whether a generic control architecture can be achieved.

From our close collaboration with a major global company supplying material handling systems in all the sectors discussed in the paper, we define a set of generic requirements for an appropriate control architecture. We distinguish *functional* and *design* requirements. Functional requirements are the key performance indicators (*KPIs*) for AMHSs. Design requirements are the basic characteristics of a control architecture from development, implementation, and maintenance perspectives. This section presents functional then design requirements. At a system level, there are two important functional objectives that serve as KPIs for AMHSs in all sectors:

- *Throughput*: this is a measure concerned with the capacity of systems. In general terms, it measures the number of items handled per unit time. Throughput has to conform to the *functional capacity*, which is the capacity that the AMHS is able to provide while operating, according to design specifications. This presents a constraint to achieve by the AMHS. Moreover, throughput may be directly related to the overall operation time. For example, a transfer operation in an express parcel sorting system refers to the operation of unloading all arriving containers, sorting all parcels, and finally loading all sorted parcels. When this operation is performed in less time, the throughput is higher since throughput is measured in terms of parcels sorted per hour.
- *Response time*: this is a measure of the promptness in coping with dynamic operational requirements such as an urgent order in a distribution center, or a batch of urgent bags arriving at an airport.

The time dimension may suggest an overlap in the definition of these two main KPIs. However, a crucial difference is that throughput is measured at some point and as an average value, e.g., number of parcels passing the output chute per hour. On the other hand, response time covers the variation in the operational requirements by providing a time frame within which to respond, measured at a system level.

Stage	Sector	Description
Receiving	P&P	Containers are broken into parcels. In our scope of analysis, arrival of parcels to the system is uncontrollable. Workstations can be merge areas or even infed conveyors on which parcels are.
	BH	Containers/ULDs coming from arriving planes are broken into bags. Again arrival of bags to the system is uncontrollable within our scope of analysis. Workstations are: (a) check-in desks where bags are brought by departing passengers, (b) loading belts for bags coming from arriving planes.
	D	Containers are broken into totes or items. Workstation is the (pallets) unloading point of incoming trucks, unloading can be done by an operator, but can also be automated (e.g., robots).
Quality Control	P&P	In some air-hub systems, each parcel has to pass through one of a set of parallel screening machines. Thereafter, parcels are merged back on the sorter. Workstations are screening machines.
	BH	Each bag has to pass through one of a set of parallel screening machines, which are the workstations.
	D	Quality control occurs in distribution centers to check incoming materials in terms of conformance to requirements and specifications. Workstations are operators checking the quality of incoming materials.
Storage	P&P	Normally there is no storage operation in express parcel sorting systems.
	BH	Early bags are stored in the ASRS. Workstations here can be mini-load cranes/aisles in which a bag is stored.
	D	ASRS represents the forward storage area/Pick face. Workstations here can be mini-load cranes/aisles in which a SKU/tote is stored.
Order Picking	P&P	Parcels to be sorted to different destinations are picked at the chutes, so (depending on the level of aggregation) we model sort areas or the chutes as order picking stations. Parcels for different destinations are routed simultaneously. Parcels are then sorted to chutes.
	BH	Bags of departing flights are picked at the laterals, so we model the laterals as order picking stations.
	D	(Manned) pick stations represent the workstations here, mainly in goods-to-man systems. Picked items are placed in customer totes. Totes/items for different orders are also retrieved simultaneously and then sorted to pick stations, where items are placed in corresponding customer totes. If the item picked is not the last one in the tote, then the tote is routed back to the ASRS.
Consolidation	P&P	Several chutes can be assigned to a certain destination. Parcels with same destination are consolidated, they are assigned to different containers. Thereafter, containers going to the same destination by a truck/plane are consolidated. Workstations are operators working on manual loading of parcels to containers/ULDs.
	BH	ULDs for the same flight and coming from different laterals are consolidated. Workstations can be operators working on manual loading of bags.
	D	Totes/SKUs for the same order and coming from different pick stations or zones, are consolidated and prepared in (pallets) for shipment.
Shipping	P&P BH D	Consolidated pallets/ULDs/containers for a certain truck/plane are loaded for shipping.

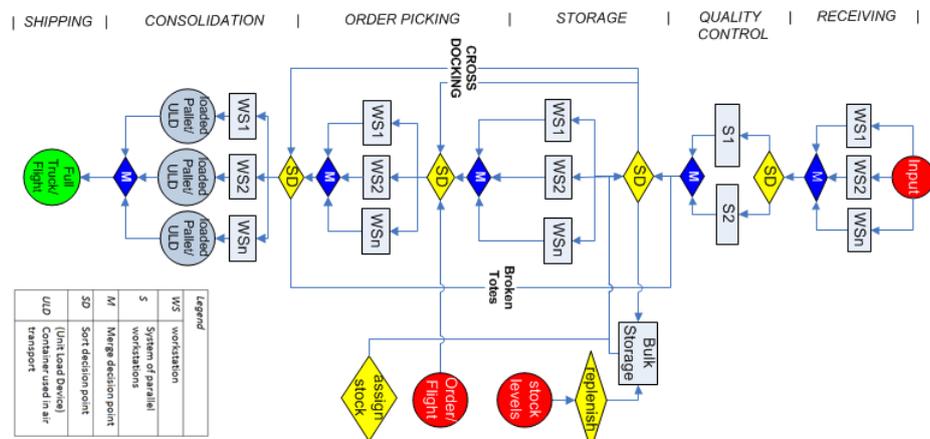


Figure 5. Generic material flow model with the description of process stages per sector.

Response time and throughput are the main KPIs for the AMHS. However, we also point out a KPI that depends on the AMHS itself, but has to do with operators working at the AMHS. This KPI is *labor efficiency*, from the following perspective: wherever an interaction between the AMHS and operators occurs, the AMHS should function in a way that ensures efficient task allocation to operators even if inefficient allocation does not hamper throughput

or response time. An example is when several operators load parcels onto parallel infeed conveyors in a sorting system (see Section 2.1). In this case, the speeds of the infeeds should be synchronized in a way that results in an even demand for parcels to be loaded by operators. In other words, having an infeed moving at a slow pace (e.g., due to blocked output point), and another infeed moving at a fast pace, would require the operator on the fast infeed to load parcels at a higher rate than his peer on the slow infeed. This results in unfair workload distribution among operators. We summarize the aforementioned requirements in the following model:

Minimize Response time

Subject to

Throughput \geq *prescribed target (functional capacity)*

Labor Efficiency \geq *prescribed target*

As a matter of fact, our contact with experts from practice resulted in a long list of functional requirements for AMHSs. However, we claim that the model above presents a compact set of functional requirements, in which all other functional requirements are implicitly involved. In the following, we present a list of the other functional requirements for the AMHS, which are implicit in the model above:

- *Starvation avoidance*: starvation to material in an active resource/workstation is caused by delays in delivery from other resources or improper workload balancing. This phenomenon is implicitly handled as a means to reduce response time, or to strive for higher throughput.
- *Blocking avoidance*: blocking occurs when an item is unable to get service from a workstation/resource, because it is still occupied or its buffer is full. Blocking is an obstacle to throughput, and may cause response times to be unnecessarily long. Therefore, blocking avoidance plays a role in the model.
- *Deadlock avoidance*: A deadlock is a condition in which material does not move on a certain transportation resource or is blocked at a certain workstation as a result of overloading the system resources.
- *Saturation management*: it is known in practice, especially in BHSs, that the capacity of the system decreases dramatically if the load on the system exceeds a certain threshold value. This state is called *saturation*. Undesired resource allocation may lead to saturation, which in turn leads to longer response times, and eventually may lead to a deadlock situation.
- *Prevention of imbalanced queues and recirculation* as they cause a decline in throughput.
- *Management of buffers*: in all systems there can be buffers. It is critical to deal with buffers properly; where, when, and how much to buffer in order to minimize response time and to satisfy throughput requirements.
- *Dealing with urgent items* (e.g., critical bags). This is directly related to optimizing response times.
- *Dealing with disruptions*: the control architecture should be able to respond to disruptions. E.g., divert bags in a BHS to a less occupied cluster of screening machines when another cluster suffers from an accumulation of workload. Moreover, the control architecture should respond to failures of physical equipment by proceeding the operation on the active equipment. E.g., when a crane fails in a distribution system then the retrieval tasks of the crane should be reassigned to the (active) cranes. These issues are related to the overall objective of response time minimization.
- *Operational flexibility*: this perspective of flexibility refers to the ability to cope with a changing operational environment. This requirement may be involved in response time minimization and throughput maximization simultaneously. For example, bags coming towards the early bags storage have to be distributed evenly among parallel storage aisles. In this way, we gain higher throughput in the storage operation, and later in the retrieval operation as cranes can retrieve bags from all aisles simultaneously. Moreover, response time to retrieve all bags for a certain flight is minimized when bags of this flight are distributed over different aisles, allowing several cranes to work on retrievals for the same flight. When the load in the system is high, incoming bags can be allocated to the first available aisle, i.e., *water fall principle*. This strategy would result in even quantities over all aisles when the load is high enough to fill all aisles. However, when the load in the system is low, the water fall principle results in the first aisle to have a high load, whereas the load in aisles decreases as we go downstream. This happens as the load in the system is not high enough to fill all aisles evenly using the water fall principle. Therefore, we have to implement a smarter balancing strategy that reacts to changes in the operational environment (in this case low load in transport). In this context, operational flexibility is a functional requirement to be handled.

So far we discussed the functional requirements. At this point, we present the design requirements for a generic control architecture. Obviously, the main objective we seek is the design of a generic control architecture that may apply to AMHSs in different market sectors. Moreover, we find that, in practice, other design requirements are necessary for a generic control architecture. In the following we list these design requirements, and make use of some descriptions presented by Zimran (1990), to define these requirements formally:

- ***Flexibility***: the flexibility of a control architecture from the design perspective is the ability to introduce changes in the system layout with minor modifications in the control architecture.
- ***Modularity***: this allows to build the architecture gradually through the use of a decomposed structure, and to have the architecture capable of introducing or removing some applications based on case-specific details.
- ***Scalability***: the scalable design allows the control architecture to control a wide range of system sizes.

- **Robustness:** a robust design entails: first, *graceful degradation*, which is a term used often in practice and refers to the ability of the control architecture to keep functioning, and keep the AMHS up and running when some units of the physical system fail. Second, the ability to take action when disruptions occur.

Section 3 presents summarized results of a systematic literature review carried out to look for answers, or useful studies, which help in synthesizing a control architecture that is in line with the requirements presented in Section 2.

3. Theory: Literature Review

This section presents the results of a systematic literature review carried out to identify what type of control architectures are available in literature, and what theories and studies are available on this subject. We perform the review first for control architectures of AMHSs in general, and thereafter we conduct a review to identify available control architectures and approaches for each market sector separately.

General There are not many studies in the literature discussing control architectures or approaches that can represent a generic framework to be applied on different AMHSs. However, there are four basic forms of control that have been suggested in the literature. We provide a description based on Dilts et al. (1991), who review the evolution of control architectures grouped in the major four forms of control (see Figure 6, where control units are represented by squares and resources by circles). In the following, we briefly discuss the main characteristics of these forms:

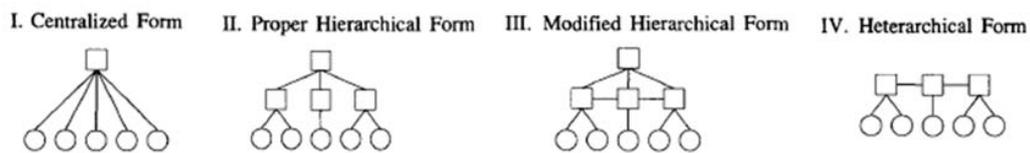


Figure 6. Evolution of control architectures (Dilts et al., 1991).

1. **Centralized form:** here a central control unit performs all planning and control functions for all resources in the system. Moreover, it uses a global database that contains all types of detailed information about the system. Advantages of centralized control are: access to global information, possibility of global optimization, and a single source for system-status information. Disadvantages include: single point of failure, where any problem with the central unit causes the whole system to stop functioning, slow and inconsistent speed of response, high dependency in the structure, i.e., single control unit, and complex software that is difficult to modify. Authors state that such control mechanisms are no longer common as they cannot deal with the requirements of today's complex systems.
2. **Proper Hierarchical Form:** in this form there are multiple control units, and a rigid master-slave relation between decision-making levels. The control unit in an upper hierarchy acts as a supervisor for resources in the subordinate level. Decisions taken by the supervisor have an aggregate view on the system, and are of low detail. Subordinate control units have to comply with tasks imposed by controls in the upper level of hierarchy, but as tasks are delegated, subordinates make more detailed decisions. We notice that control decisions are executed top-down, while status reporting goes bottom-up. Main advantages of this form are: adequacy for gradual implementation of software, with less room for problems compared to the central control, fast response times, and surely delegation of lower level decisions to lower levels in the hierarchy so that not all details are at the highest level. Disadvantages include: making future modifications in the design is difficult, because the structure tends to be rigid and fixed in the early design stages (Dilts et al., 1991), an increased number of inter-level communication links, and computational limitations of local controllers.
3. **Modified Hierarchical Form:** this form evolved in order to deal with some shortcomings in the proper hierarchical form, mainly the rigid master-slave relationship. The degree of autonomy of subordinates is the main distinction from the proper hierarchical form. In this form there is some degree of coordination among subordinates on the same hierarchical level. This loosening of the master-slave relation brings additional advantages: more robustness to disturbances if the supervisor unit fails, because there is less need for continuous supervision, and subordinates have the ability to coordinate tasks among them. Disadvantages are: connectivity problems among subordinates and with supervisors, capacity limitation of low-level controllers, and increased difficulty of the control system design.
4. **Heterarchical Form:** this form is the extreme of decentralized control, which became popular recently. An example is a multi-agent system. In this form, control structures have distributed locally autonomous entities. These entities communicate with each other to make decisions in cooperation. The master-slave relationship is totally abandoned and not just loosened as in the modified hierarchical form. In this control form, decision making is distributed in some manner within the system, distribution can be based on functions, geographical areas, task sequence, etc. Each control unit has its own rules and objectives, and communicates with other units to fulfill its own requirements. This notion is the general form of the agent-based systems that are going to be addressed further in this paper. Main advantages of the heterarchical form are: full local autonomy, reduced software complexity, implicit fault-tolerance, high modularity, and faster diffusion of information as subordinates have smarter controllers. Disadvantages are primarily due to

technical limits of controllers, no standards for communication protocols, and likelihood of local optimization.

(Babiceanu et al., 2004) present a framework for the control of AMHSs as part of the holonic manufacturing approach. Holons are units that act as parts and as wholes at the same time, meaning that they have a high degree of autonomy but operate as part of a more general system. Therefore, holons have two main properties: autonomy in making decisions, and cooperation with other holons for mutually acceptable plans. The authors claim that there is a significant amount of papers in the area of agent-based and holonic manufacturing, but very few papers considering the material handling problem. The authors present a case study focusing on a material handling system.

The holonic paradigm is similar to the agent paradigm in many aspects, but there are some differences. (Giret and Botti, 2004) conduct a thorough study to provide a comprehensive comparison of holons and agents. Their main conclusion is that a holon is a special case of an agent. A holonic system is a manufacturing-specific approach for distributed intelligent control. On the other hand, a multi-agent system is a broad software approach, where one of its uses is distributed intelligent control. For more details we refer to (Giret and Botti, 2004).

(Lau and Woo, 2008) develop an agent-based dynamic routing strategy for AMHSs. They emphasize that existing routing strategies in theory often use static routing information based on shortest path, least utilization, round-robin assignments, etc. In their study, they map the AMHS to a network with node agents connected by unidirectional links; where control points of a network of AMHS components are modeled as cooperating node agents. To make routing decisions, they define the best route in terms of: cycle time of material, workload balancing, and degree of tolerance to unexpected events. In their architecture, each agent is responsible for its zone of coverage. They implement their architecture in a simulation environment of a DC. The authors outline a generic classification of routing strategies and position their approach as *distributed real-time state-dependent*.

(Mo et al., 2009) study flow diversion over multiple paths in integrated automatic shipment handling systems. The authors take a network optimization perspective and formulate a nonlinear multi-commodity flow problem. They develop a mathematical programming model to propose routing strategies with the objective of minimizing the total shipment travel time in the system. However, they make assumptions that may not hold in practical settings, and do not apply their theoretical framework to a business case in their study.

(Zimran, 1990) presents a commercial generic controller for material handling systems. His design is mostly based on hardware and software linkages and communication. The routing decision making is supported by tree graph algorithms. Tree graphs have only one path between every pair of origin and destination. These tree graphs change while the system is running (based on system state), by adding or removing arcs. Since the algorithm is computationally expensive, simpler algorithms are used for low level controllers.

We conclude the general review by mentioning some simulation-based studies in the area of AMHSs. Timothy et al. (1999) present a modular simulation approach for the evaluation of AMHSs. (Babiceanu and Chen, 2005) use simulation to justify the use of a decentralized agent-based approach and assess its performance compared to conventional scheduling systems. (Jahangirian et al., 2010) conduct a broad review of simulation studies in manufacturing. A trend they notice concerns the increasing interest in hybrid modeling as an approach to cope with complex enterprise-wide systems. (Babiceanu and Chen, 2005) use simulation to conduct a performance analysis of agent-based material handling systems. Finally, (Hunter, 1994) presents a model evolution analysis for simulating AMHSs.

Baggage Handling Systems (Tařau et al., 2009a) study route control in BHSs. They compare centralized and decentralized route choice in BHSs, particularly in systems using Destination Coded Vehicles (DCVs) as a transport mechanism. They implement centralized control approaches, but find them computationally expensive and not robust. Furthermore, they develop decentralized control rules for *Merge* and *Divert* switches, where each switch has its own controller. In another study (Tařau et al., 2009b), they pay attention to hierarchical control for route choice. To this end, they design a control architecture with three levels of hierarchy: network controller, switch controller, and DCV controller. In the same study, they examine multi-agent systems, but find them difficult due to the extensive communication required between the agents. In general, Tařau et al. focus on BHSs, and only on routing by controlling switches within BHSs, but they do not consider the early bag storage operation.

(Johnstone et al., 2010) study status-based routing. In their approach, the status of the bag determines its processing requirements, and triggers computation of the route to be followed depending on the states of required resources ahead. They study two main algorithms, the first one is based on learning agents, while the second uses a graph representation of the network to find all possible routes at switches via Dijkstra's algorithm. They find learning agents more efficient in larger systems, its main advantage being the use of information from operations performed on the bag upstream. With this information they limit the possible routing options downstream.

(Hallenborg & Demazeau, 2006) use multi-agent technology as generic software components to replace traditional system-specific centralized control software. In their approach, when the bag enters the system, the first Agent on the route can make an agreement with all agents on the route to destination. However, it is also possible to make an agreement only with the next agent on the route. This raises the distinction between routing by static shortest path, or routing on the way. Moreover, (Hallenborg, 2007) presents an interesting case study of a large airport hub in Asia, in which a centralized control architecture is replaced by an agent-based solution.

Distribution and Warehousing Systems (Amato et al., 2005) state that control systems of warehouses have three main hierarchical levels: Planning System, Management System, and Handling System. The authors introduce the *Optimizer System* as a new level to bridge the gap between planning/management and the shop floor control systems by improving the realization of decisions by handling devices such as the cranes and a shuttle handling device.

(Kim et al., 2003) propose a hybrid scheduling and control architecture for warehouse management based on a multi-agent system. They develop the architecture mainly for order picking. In their architecture, they have three hierarchical levels of control: high level optimizer agent, medium level guide agent, and low level agents, which have some degree of autonomy. Finally, we mention (Van den Berg, 1999), (Rouwenhorst et al., 2000), and (Gu et al., 2010) as useful literature reviews.

Express Parcel Systems (McWilliams et al., 2005) introduce the Parcel Hub Scheduling Problem (PHSP); this problem concerns scheduling a set of inbound trailers to a fixed number of unload docks at an express parcel sorting hub. The objective is to minimize the make-span of the transfer operation, i.e., sorting all unloaded parcels to the required destinations. In his studies, McWilliams deals with the AMHS as a black box and does not interfere with the inner control. His studies include simulation-based genetic algorithms, and dynamic load balancing heuristics. From his work on the PHSP, we mention the development of a dynamic load-balancing scheme for the parcel hub-scheduling problem, (McWilliams, 2009). A very useful result from his studies is that having a balanced flow within the system results in minimizing the time required to accomplish the transfer operation.

Conclusion As a general remark, there are few studies that attempt to build a generic control architecture for different market sectors. From the studies we reviewed, we observe that a control architecture normally targets a specific sector, or deals with material handling as part of a manufacturing environment. From our point of view, the most relevant study is the holonic architecture proposed by (Babiceanu et al., 2004). Although this architecture is based on a manufacturing system, it does suggest a framework for material handling. However, the AMHSs in the sectors we address are much more complex and diverse than the AMHS modeled by the authors. We conclude that their study misses an in-depth treatment of practical requirements of complex AMHSs. Moreover, the authors focus on the design aspect, but do not show how decision-making processes can be employed to achieve the functional requirements as presented in Section 2.3. In general, many authors favor distributed control to dealing with complex systems. Here we stress that distributed control means “having decisions made at the right level”, and thus that it is not restricted to the heterarchical form.

Multi agent-based architectures seem to be the trend for modern control. Some authors doubt their applicability within sectors like baggage handling due to the extensive communication required (Tařau et al., 2009). However the nature of the agents has an impact on this observation; negotiating agents may require more time than reactive agents. In general, distributed control seems beneficial when dealing with complex systems. Here it should be stressed that distributed control means having *decisions made at the right level*, and thus that it can be realized with other forms of control, e.g., hierarchical form, and not only the heterarchical form.

From the studies we reviewed, we observe that a control architecture is initially designed and then applied to some sector, often to a distribution center. For baggage handling, there are few studies on control architectures. Most of the studies focus on route planning through divert and merge switches, and do not take the storage operation into account. On the other hand, the relatively abundant studies on warehousing systems emphasize either on the design aspects, or on gaining more throughput of the system through the use of advanced algorithms for warehousing activities such as: storage and retrieval sequencing, and order pick concepts. However, we learned from our collaboration with practice that other requirements are necessary to make the control architecture applicable in a practical setting. For example, experts from practice value a robust control architecture that provides satisfactory solutions higher than a less robust architecture that provides near optimal solutions.

Finally, parcel & postal studies deal with inbound and outbound operations, but not the inner control of the AMHS itself. The most relevant in this context, is the parcel hub scheduling problem introduced by McWilliams et al. (2005).

4. Planning and Control of AMHSs: Practice versus Theory

Confronting theoretical frameworks with practical requirements As mentioned briefly in Section 3, there is a lack of in-depth studies dedicated to the generic control of complex AMHSs. There are studies addressing AMHSs from different perspectives. A few studies claim that they propose a generic control architecture or framework. However, we find them lacking due to one or more of the following reasons:

Being applicable to a specific sector: apart from studies that are intended for specific market sectors, some studies claim to be generic but we find them based on one sector, typically distribution. When an architecture is based on one sector, it becomes impractical for other sectors as it normally misses relevant problems, constraints, and objectives in a different operational environment.

Lacking an in-depth treatment of practical requirements: the functional requirements listed in Section 2.3, present necessary considerations for a comprehensive control architecture. Moreover, the architecture has to control all possible subsystems of a complex AMHS, e.g., ASRS and divert switches. We conclude that literature lacks a

comprehensive coverage of these requirements because current studies are limited in several ways. First, they model simple material handling systems where no complex decision making is required. Second, they focus on certain problems/subsystems, e.g., dealing with urgent items/routing at divers and not addressing other problems, e.g. management of buffers/ASRS control, in the same architecture.

Treating AMHSs as a support to a manufacturing environment: There is limited focus on complex AMHSs that are functioning for the sake of material handling, and not merely as part of a manufacturing environment. The latter trend generally results in simplified AMHS problems.

Missing the combination of design requirements and functional requirements in a unified architecture: there is a need for a comprehensive control architecture that is designed according to the design requirements, but that also entails control rules and algorithms implemented to satisfy the functional requirements. Studies on control architectures normally address design requirements (modularity, robustness, scalability, and flexibility). Yet, we could hardly find any study with proven implementation potential on AMHSs in different market sectors.

At a lower level of analysis, we find studies addressing specific problems, or sub-systems within AMHSs. Moreover, we can find sector-specific studies (e.g., control of BHSs). Therefore, results of specific problems can be used as building blocks in a new generic control architecture. However, having subsystems functioning properly on their own does not mean that the combination of sub-systems functions properly. Therefore, a top-down design approach is sensible, because it allows for dealing with the system dynamics at an early stage. Moreover, there may be a need to adapt solutions for subsystems in certain sectors to be generic for similar subsystems in all sectors.

Agenda for future research In this paper, we promote a research direction that aims at developing a comprehensive generic control architecture that satisfies design requirements, and controls the operation of the AMHSs in a way that satisfies the functional requirements. Both sets of requirements are defined based upon the research we performed at a major global company supplying material handling systems in all sectors discussed in the paper. We believe that current literature is not very promising in answering questions in practice. The missing points in current studies provide starting points to propose an agenda for future research. In addition, we aim for a research direction that differs from other studies in addressing three different sectors from practice, and using their requirements simultaneously to develop a generic control architecture. Current studies either develop control approaches and then apply them to a certain sector, or use cases from one specific sector as a starting point. Future research should deal with the following:

Proposing a concept for a control architecture: the concept may use the basic forms of control (see Section 3) to decide upon the most appropriate form, or propose a hybrid of several basic forms.

Detailing the concept in terms of control levels (hierarchies) and control units: detailing the concept has to address the relations between these different decision making bodies, and the spans of control for each. This point has to satisfy the design requirements (see Section 2.3).

Develop the concept into a concrete control architecture: this requires proposing control rules and algorithms in the control levels and units, the links between control levels or control units have to be defined in terms of information transmitted and the way information is reacted upon and communicated. This point has to satisfy the functional requirements (see Section 2.3).

Validating the generic control architecture: this requires modeling and testing operational scenarios of AMHSs in different market sectors.

Proving the adequacy of the control architecture: this requires implementation on business cases from different market sectors to prove its adequacy to serve as a generic control architecture.

In our future research, we will work on a concept control architecture, and detail the concept in an attempt to design a generic control architecture. To this end, we focus on the requirements we defined in Section 2.3. However, there are other perspectives to the problem that may open other issues for future research.

By enlarging the view to the second scope of analysis (see Section 1), we find potential work to be done in planning and scheduling inbound and outbound operations at AMHSs in a parcel sorting facility, or an airport. Again, it becomes more interesting if generic approaches can be developed for both sectors. These problems occur at the interface between the AMHS and the surrounding environment, resulting in interesting problems where the process of the AMHS-user interferes with the process of the AMHS-supplier.

Finally, in our logistic control perspective, we do not get involved in the design phase of AMHSs. E.g., before settling on a warehouse design it is important to examine numerous alternative warehouse configurations, and material handling technologies (e.g., conventional AS/RS vs. autonomous vehicle storage and retrieval system AVS/RS). A direct example to this domain of research is the work by Heragu et al. (2011), which presents an analytical approach for a comprehensive analysis of AVS/RS and AS/RS, and design conception, based on an open queuing network model. The study is comprehensive in the sense that it allows for examining many different design configurations in short time, where, traditionally, all manufacturers and system providers, work with few configurations that they are familiar with and choose the best design from this limited subset of possible designs using time-consuming simulation studies (Heragu et al., 2011).

To analyze their open queuing network model, Heragu et al. build upon the QNA (Queuing Network Analyzer), which is a software package implementing the parametric decomposition method for analyzing queuing networks. Heragu et al. use the MPA (Manufacturing Performance Analyzer), as an extension of the QNA that is specifically

designed to evaluate the performance of a manufacturing system. MPA is used to quickly analyze a large number of alternative configurations or layouts, exclusively in the area of warehousing and distribution. This includes distribution centers, but also raw materials warehouses prior to manufacturing. In this context, we find two interesting questions relevant for future research:

1. Can the analysis technique(s) presented by Heragu et al. be broadened to cover all three areas we are studying, i.e., be extended to baggage handling, and parcel & postal?
2. Does the QNA or MPA technique also allow for analyzing the impact different control architectures and rules will have on performance measures, i.e., throughout and response time, preferably again in all three areas?

5. Conclusion

This paper discussed the application of AMHSs in different market sectors. Our aim was to investigate the possibility of developing generic planning and control approaches. Section 2 analyzed the synergy among the different sectors. Furthermore, it modeled the process flow in the different sectors in an analogous way given a certain level of abstraction. This analysis, aided by close contact with practice, led to a list of general requirements for a generic control architecture. These requirements are both in terms of design and functionality of the control architecture, and are valuable for all market sectors. Afterwards, Section 3 reviewed the literature to investigate the availability of answers to the requirements from practice. Consequently, Section 4 weighed the requirements from practice against existing literature and highlighted the missing links to propose an agenda for future research in the field of planning and control of AMHSs.

Our main conclusion is that current literature does not seem to be very promising in answering the problems we address. We emphasize the need for a generic control architecture for AMHSs, which considers the objectives and functionalities of different market sectors in the early design stages. The aim is to develop a generic architectural design that is flexible, modular, robust, and scalable. In addition, the architecture should entail control approaches to achieve functional requirements of different market sectors. The control approaches have to remain generic unless it is inevitable to deviate in order to adapt to sector-specific limitations. We stress again that this research direction is relevant from at least two practical perspectives. First, from a customer point of view, the environment and user requirements of systems may vary over time, yielding the need for adaptation of the planning and control procedures. Second, from a systems' deliverer point of view, an overall planning and control architecture that exploits synergy between the different market sectors, and at the same time is flexible with respect to changing business parameters and objectives, may reduce design time and costs considerably. Moreover, from a scientific point of view, this research addresses the challenge of finding a common ground to model AMHSs in totally different market sectors, and developing a generic control architecture that can be applied to these AMHSs.

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7. Glossary

AMHS	Automated Material Handling System
BH	Baggage Handling (market sector)
BHS	Baggage Handling System
Broken Tote	a tote that is picked from at a pick station, but still contain items and returns to the storage area.
Chute	a specially designed exit resource for parcel in a parcel sorting system.
D	Distribution (market sector)
DC	Distribution Center
DCV	Destination Coded Vehicle
Deadlock	a situation where materials cannot be moved anymore on a resource such as a conveyor due to overloading downstream that propagates upstream.
DHL	acronym that stands for the surnames of the founders of this LSP; A. Dalsey, L. Hillblom and R. Lynn
Divert Switch	a switch that can divert items to one of two possible routes.
EBS	Early Bag Storage
Functional Capacity	The capacity that the AMHS is to provide while operating, according to design specifications.
Infeed	a conveyor responsible for transporting items, e.g., parcels, toward the main conveyor in a merge area.
In-System Time	maximum time a bag needs to travel between the input and output points that are farthest apart in a BHS.
Irregularity Rate	Number of bags (per 1000) that are supposed to be on a certain flight but are not on it.
KPI	Key Performance Indicator.
Lateral	An outfeed of bags in a BHS, where flights are built.
Load Area	An area where material is loaded for transport after being handled by an AMHS, it can be sorted parcels, bags to be loaded on planes, or products read for transport to customers at a DC.
Loop Sorter	A sorting system with the possibility for items to recirculate if they are not sorted in the first circulation.
LSP	Logistic Services Provider.
MAS	Multi-Agent System.
Main Conveyor	The conveyor on which items are merged in a sorting system.
Merge Switch	A switch combining two incoming flows into one flow.
Merge Area	The area where several inputs or infeeds transport items to be merged onto one main conveyor.
MPA	Manufacturing Performance Analyzer
Negotiating Agent	An agent that makes decision based on negotiation with other agents, negotiations can be iterative.
P&P	Parcel and Postal (market sector).
Pick Station	a work station in the order picking operation. At such stations, items are picked to fulfill orders.
QNA	Queuing Network Analyzer
Reactive Agent	An agent that makes decisions by reacting to certain environmental occurrences. The reactive decisions can be predictable based on the decision making strategies of the agent.

Saturation	A situation where the capacity of the system goes dramatically down, because the load exceeded a certain threshold value.
Sorting System	A system that has multiple inputs for items and works on sorting incoming items to predefined destinations via different possible types of output means.
TNT	acronym that stands for Thomas Nationwide Transport, which is an LSP.
Tote	A box that carries items, which is normally used in DCs.
Unit Load	refers to a standardized mean by which a number of items are handled together and usually supported by a handling resource such as a pallet, case, tote, etc. This concept applies normally in DCs.
Unload Area	An area where materials arriving to the AMHS is unloaded. Normally, in preparation for being loaded onto the AMHS.
UPS	acronym that stands for United Parcel Service, which is an LSP.

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