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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 to design a generic planning and control architecture for automated material handling systems (AMHSs). We illustrate the relevance of this research direction, and then address three different market sectors where AMHSs are used, i.e., baggage handling, distribution, and parcel & postal. The research in this paper is heavily motivated by a collaboration between the authors and a major global company supplying AMHSs. We analyze requirements from practice for a generic control architecture, and then review the literature to investigate whether these practical requirements have been met. From this confrontation of theory with practice, we conclude that many practical issues are not yet covered in the current literature. We take the initiative to define a research direction in concrete terms, pinpoint problems to work on, and propose an agenda for future research. Moreover, we take a step to propose a concept control architecture.

Contents

1. Introduction

In this paper, we focus 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

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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 are 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' supplier 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, 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 satisfies the requirements of AMHSs designed for distinct market sectors. In this context, we emphasize that our focus is on *control architectures* and not *on software architectures*. Although the advantages and disadvantages of centralization versus decentralization in both domains are very much alike, we have to make a distinction because, e.g., a decentralized control architecture can be implemented by a single-tiered software architecture.

Before presenting the structure of this paper, we outline our scope boundaries. Fig. 1 shows three possible scopes of analysis, along with the party mainly responsible for decision making within each scope, i.e., the customer or the supplier. The research direction that we introduce excludes Scope 3, because the focus then shifts toward network optimization. A shift toward network optimization will limit 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 mostly the analysis within Scope 1. However, we may have to deal with problems at Scope 2, which are closely related to the operation of the AMHS. An example is the scheduling 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. Section 5 provides more details on different problems to work on.

This paper proceeds as follows: we first analyze the functionality and requirements of AMHSs installed in different market sectors from a practice-oriented point of view (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. In Section 5, we next propose a concept for a generic control architecture. We end with concluding remarks in Section 6.

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, 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 various forms and 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 we clarify later on. Fig. 2 shows the generic scheme of a simple sorting system.

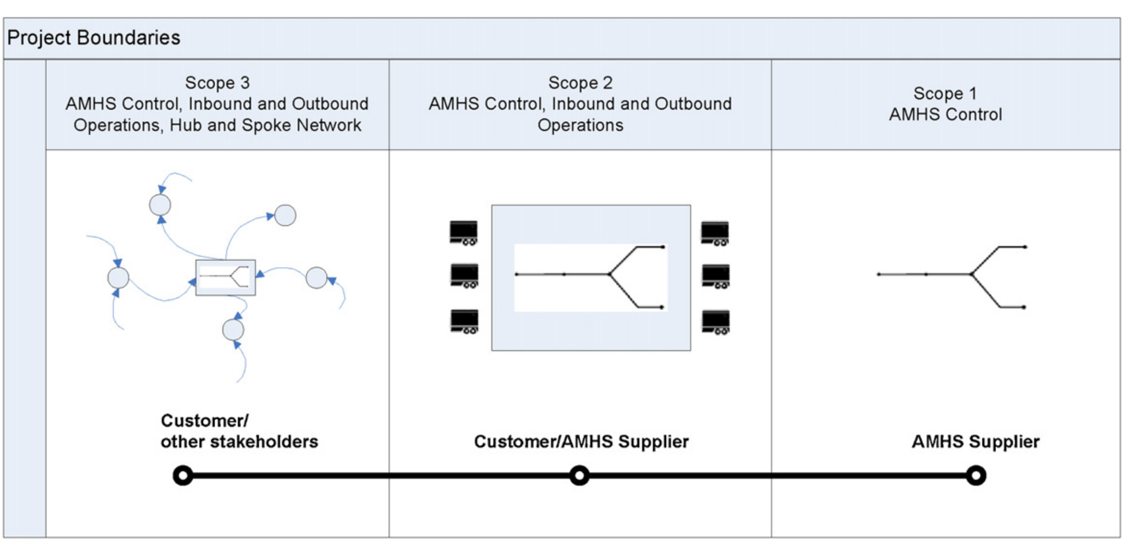

Fig. 1. Scope boundaries.

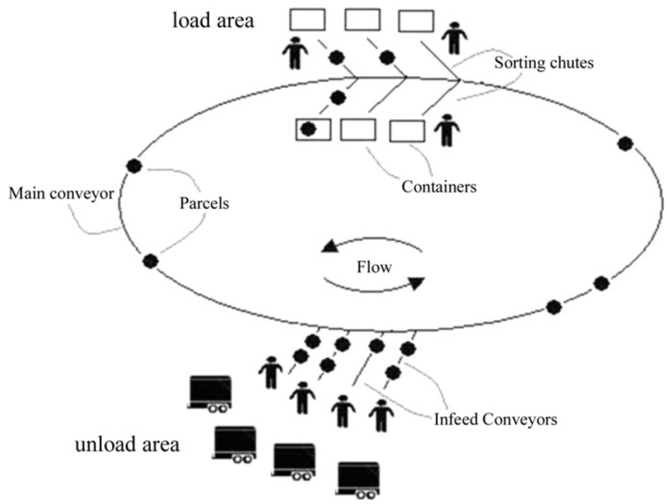

Fig. 2. Generic scheme of a closed-loop parcels sorting system.

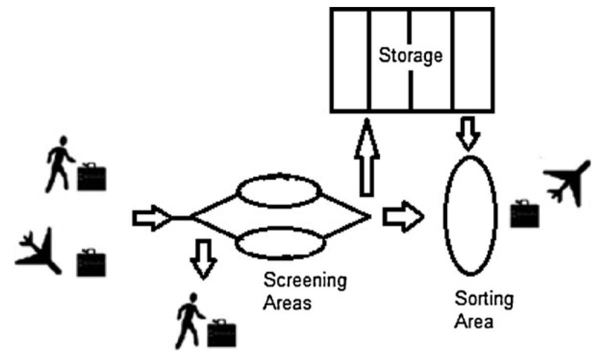

Fig. 3. Generic scheme of a baggage handling system.

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 Fig. 2. The merge operation takes place when the parcels transported on the infeeds reach the main conveyor. Once on the main conveyor, the parcels are transported until they 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 Fig. 2). At the end of these chutes, operators gather the parcels in containers. In the layout given in Fig. 2, some parcels may flow back into the unload area, which means that they have passed the load area without being sorted. This may happen 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. Note that the system depicted in Fig. 2 is a relatively 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 BHS. 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 Fig. 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 or her final destination. In a BHS, there is an early bag storage (EBS), where bags that arrive early to the system are temporarily stored.

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 its own desires, which affect its 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 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, planes 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 smallest. 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 completing the overall transportation operation within the time limits, which requires a smooth process that is able to avoid disruptions or 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

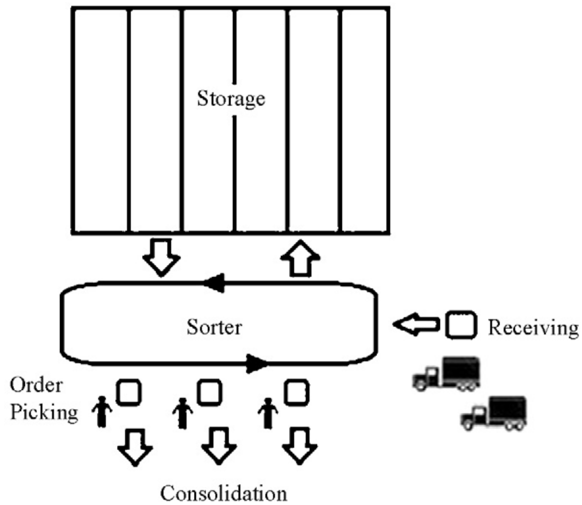

Fig. 4. Generic scheme of a distribution center/warehouse.

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. Fig. 4 shows a schematic view of a warehouse with a goods receiving area, a storage area where an automated storage and retrieval system (ASRS) is installed, an order picking area (with three pick stations), and a consolidation area.

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 normally is a set of parallel stations performing the same tasks, for example, parallel order pick stations, parallel aisle cranes, etc. Therefore, it is crucial to balance the workloads within the system. There should be a generic control approach that entails generic algorithms, allowing for applications in different types of systems. However, the current control of distribution centers is highly customized and often includes quite a number of relatively complicated rules to realize as much throughput as possible at the AMHS.

As a general remark, according to observations from practice, there is an increasing interest from system architects, toward control solutions that are more robust and generic, at the expense of sacrificing the maximum attainable throughput from AMHSs. 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, we take the challenge to deal with the differences in order to model the AMHSs in different sectors in a generic way that 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 at 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 BHSs and parcel & postal systems, 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 on 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 a BHS or parcel & postal 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 characteristics of the tote change. 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 a BHS or parcel & postal 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 or tote.
- Heterogeneous items: bags and parcels may be of different shapes, weights, dimensions, which affects 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, based on the study of some distribution centers in practice, we observe 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 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 for instance parallel screening machines, or to *laterals*. Laterals are areas where bags for a certain flight are consolidated for loading.

We believe it makes sense 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. Fig. 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 we are interested in, is to develop 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.

Based on our experiences at 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. In this section we first discuss functional requirements, followed by 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. Throughput has to conform to the *functional capacity requirements that specify* the number of items the AMHS is able to handle per unit of time while operating, according to design specifications. This presents a constraint to meet 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 the completion of an urgent order in a distribution center, or the handling of 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.

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 a 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:

$$\begin{aligned}&\text{Minimize Response time}\\&\text{Subject to}\\&\text{Throughput} \geq \text{prescribed target} \quad (\text{functional capacity})\\&\text{Labor Efficiency} \geq \text{prescribed target}\end{aligned}$$

The decision variables in the model above are basically the rules implemented in the control architecture. Examples of such rules are how to determine in which aisle to store a certain item, on which workstation to activate a certain order, when to release bags from storage to destination, and which route to take to the destination.

As a matter of fact, our collaboration with experts from industry 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 aim at a 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 items do not move on a certain transportation resource or are 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.

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 infeed 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 miniload 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.

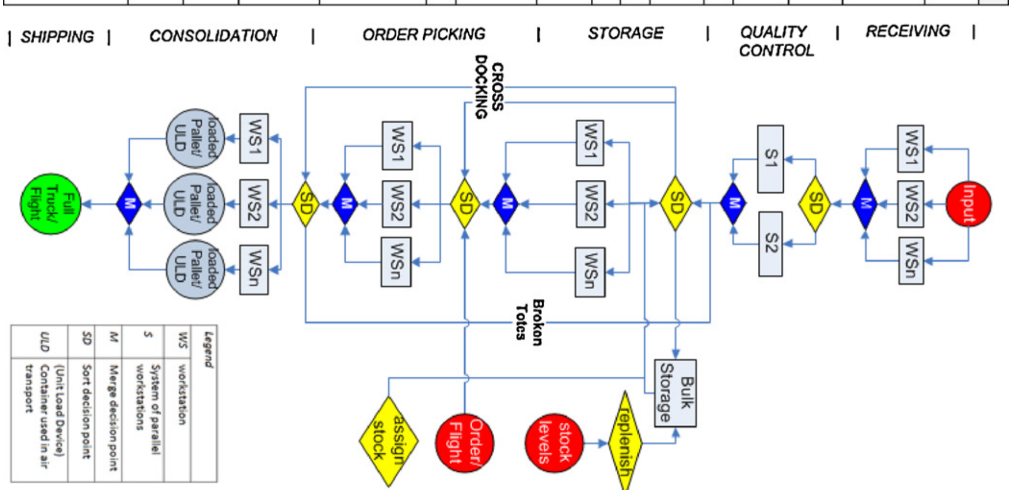

Fig. 5. Generic material flow model with the description of process stages per sector.

- 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., it should 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 toward 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 (assuming there is at least one crane at each aisle). Moreover, the time needed to retrieve all bags for a certain flight is minimized when bags of this flight are distributed among 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., the *water fall principle*. This strategy would result in even quantities across 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 when 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 [1] to define them 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*: a modular design 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*: a 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, it entails the ability to take action when disruptions occur.

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

3. Theory: literature review

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

3.1. 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. [2], who review the evolution of control architectures grouped in the major four forms of control (see Fig. 6, where control units are represented by squares and resources by circles). In the following, we briefly discuss the main characteristics of these forms:

1. Centralized form: in this form 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. The main advantages of centralized control are: access to global information, possibility of global optimization, and a single source for system-status information. The disadvantages include: a 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. The 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

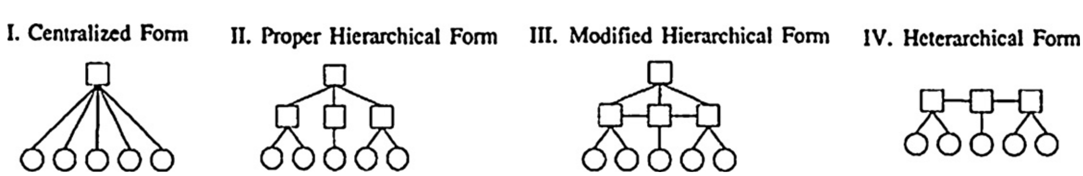

Fig. 6. Evolution of control architectures [2].

decisions. We notice that control decisions are executed top-down, while status reporting goes bottom-up. The 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 last but not least delegation of lower level decisions to lower levels in the hierarchy so that not all details are at the highest level. The disadvantages include: making future modifications in the design is difficult, because the structure tends to be rigid and fixed in the early design stages [2], 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. Some 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 locally distributed and 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. This 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 discussed later in this paper. The 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. The disadvantages are primarily due to technical limits of controllers, lack of standards for communication protocols, and the likelihood of local optimization.

Babiceanu et al. [23] 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 there are very few papers considering material handling systems. 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 [3] 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 represents a manufacturing-specific approach for distributed intelligent control. On the other hand, a multi-agent system represents a broad software approach, where one of its uses is distributed intelligent control. For more details, we refer to Giret and Botti [3].

Lau and Woo [4] 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 routing*.

Mo et al. [5] 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 [1] 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 the 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. [6] present a modular simulation approach for the evaluation of AMHSs. Babiceanu and Chen [7] use simulation to justify the use of a decentralized agent-based approach and assess its performance compared to conventional scheduling systems. Jahangirian et al. [8] 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. Finally, Hunter [9] presents a model evolution analysis for simulating AMHSs.

3.2. Baggage handling systems

Tařau et al. [10] 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 [11], 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 impractical 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. [12] 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, their 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 and Demazeau [13] use multi-agent technology in generic software components to replace traditional system-specific centralized control software. In their approach, the first agent on the route of a bag entering the system 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 [14] 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.

3.3. Distribution and warehousing systems

Amato et al. [15] state that control systems of warehouses consist of three main hierarchical subsystems: a planning system, a management system, and a 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 cranes and shuttle handling devices.

Kim et al. [16] 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, useful literature reviews are found in Van den Berg [17], Rouwenhorst et al. [18], and Gu et al. [19].

3.4. Express parcel systems

McWilliams et al. [20] introduce the parcel hub scheduling problem (PHSP); this problem concerns the scheduling of a set of inbound trailers to a fixed number of unload docks at an express parcel sorting hub. The objective is to minimize the makespan (i.e. total required time) 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 [21]. A very useful result of his studies is that a balanced flow within the system results in minimizing the time required to accomplish the transfer operation.

3.5. 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. In our view, the most relevant study is the holonic architecture proposed by Babiceanu et al. [23]. 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 deal with complex systems.

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 [10,11]. 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 we stress that *distributed control* means *making decisions at the right level*, and thus that it can be realized with other forms of control, e.g., the hierarchical form, and not only with 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 the design aspects, or throughput maximization through the use of advanced algorithms for warehousing activities such as: storage and retrieval sequencing, and order pick concepts. Our experience in industry however made clear that other requirements are necessary to make the control architecture applicable in a practical setting. For example, experts from the material handling industry 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. Most relevant in this context is the parcel hub scheduling problem introduced by McWilliams et al. [20].

4. Planning and control of AMHSs: practice versus theory

4.1. 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: 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 conditions 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 a comprehensive coverage of these requirements is still lacking because the 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., they deal with urgent items/routing at diverts and do not address other problems, such as 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 subsystems functions properly. Therefore, a top-down design approach makes sense, because it allows to deal with the system dynamics at an early stage. Finally, there may be a need to adapt solutions for subsystems in certain sectors to be generic for similar subsystems in all sectors.

4.2. An 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. To the best of our knowledge, we conclude that the 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 contain the following elements:

Propose 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.

Detail the concept in terms of control levels (hierarchies) and control units: in particular, 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 proposals for control rules and algorithms at 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).

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

Prove 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.

Section 5 builds upon our conclusions so far in a first attempt to propose a concept control architecture in more concrete terms.

5. A concept for a generic control architecture

In this section, we take a first step toward the development of a generic control architecture by proposing a concept, and detailing it in terms of control units and hierarchies. To propose a concept for generic control, we build on the experience from our industrial cooperation and on the basic forms of control discussed earlier. First of all, we exclude the centralized approach for reasons concerning both the operational environment, and the design requirements. The arguments for exclusion are:

- It is very rigid when it comes to a dynamic flow of information and to dealing with disruptions in material flows.
- The computation time for a central solution is incompatible with the real-time nature of the AMHSs.
- Information on items transported by the AMHSs flows in real-time and is revealed gradually with a narrow look-ahead horizon. Therefore, making global decisions that affect every resource in the system based on a narrow scope of information is not sensible, especially because it is highly probable that the central solution changes radically when new information becomes available, e.g., about disruptions or new items in transport.
- The software may become very complex to build and would not serve our design requirements of being generic, modular, robust, and flexible.

The centralized approach is one extreme of decision making, the other extreme is purely decentralized decision-making embodied by the heterarchical approach. The main advantage of the heterarchical approach, according to various authors, is that it supports the objectives of modularity, generic structure, and robustness. Modularity is embodied in the possibility to build software components separately, and include some intelligence to manage decision making activities. The control architecture can be composed by configuring the interfaces between software components.

A pure heterarchical form of control results in a cooperative approach to global decision making, where a main concern is the extent of deviation from the optimal solution. Another concern for our problem is the loss of higher level coordination that may be necessary in some cases, e.g., planning orders. Moreover, for our generic control problem, decisions made within AMHSs are not all at the same level. In particular, when looking at the different market sectors we analyze, we find global decisions that impact the overall performance of the system, while others are local decisions with limited global impact.

Based on the aforementioned points and our observations in industry, we propose a control architecture that involves hierarchical control and also a certain degree of intelligence and freedom of controllers at different control levels.

5.1. Concept control architecture

From our analysis of the AMHSs in the three sectors, and the decision-making aspects in particular, we found it necessary to first have a control level that takes care of the planning activities using an aggregate view of the system. Moreover, this control level should provide the interface with the system user, e.g., the receipt of flight schedules in a BHS or of order details in a distribution system. Second, the resources of the system have to be controlled but not, as argued earlier, centrally controlled. Therefore, resource controllers are needed that schedule and execute work considering their own status and the status of other resources involved in the handling operation. Finally, when all decisions on workload control and material flow are taken, the realization of these decisions by the physical equipment has to be taken care of via a dedicated level, e.g.,

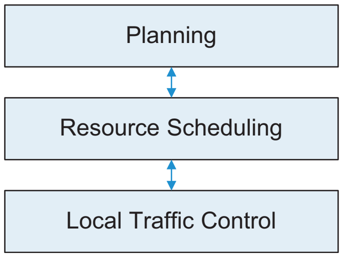

Fig. 7. Levels of control.

to store a TSU[4] within a certain storage aisle, or to induct a TSU on a conveyor belt at a merge junction. Following this discussion, we propose three hierarchical levels of control, where each level contains several generic controllers as will be further described. The three levels of control are as follows (see Fig. 7):

1. *Planning*: The planning function requires a global view of the system regardless of the system size. This is the control level that interacts with the outer environment, e.g., customer orders, plane schedules. As a result, this level is mainly responsible for the assignment of work to resources/system devices. Planning decisions are made by abstract controllers using aggregate system information.
2. *Scheduling*: Given a set of assigned tasks, the scheduling function addresses the problem of when and in what sequence to execute these tasks. Scheduling decisions are made by device controllers as a result of the interaction between system resources. This level deals with executing the tasks assigned by the planning level. Resources can be either workstations, e.g., pick stations in a warehouse, or transport and routing resources, e.g., sorting loops and divert switches. Routing and task sequencing for each resource are decided upon here. In this sense, this level has to deal with the specificities of the system layout, e.g., travel distance to destination, and with dynamic scheduling according to the state of the system, e.g., loads in transport.
3. *Local traffic control*: This function entails algorithms or routing rules executed within defined boundaries of the physical system. There is minimal interaction with other areas in the system, and mostly the aim is local optimization where no global view is needed. Decisions made at this level do not have a global effect on the system. These decisions are implemented at a low level of control or made by resource controllers. Examples include the movement of a crane within its aisle, and prioritizing the movement of items on a conveyor junction.

From a theoretical point of view, and also based on experiences from practice, local traffic control problems are the easiest to deal with, as they do not affect the overall control structure or the communications among different controllers. Control methods for local traffic problems can be integrated in a control architecture with minimal difficulty. The higher levels of control, i.e., planning and scheduling, are the challenging levels of which the functionality is highly dependent on the control structure and communication interfaces.

In our concept architecture, planning control units, referred to as *planners*, have an aggregate view of the system and are not directly connected to system resources. On the other hand, scheduling control units, referred to as *schedulers*, are directly connected to system resources, being workstations or transport resources. Planners communicate with each other, and assign tasks to subordinate schedulers. Schedulers also communicate with each other to schedule the assigned tasks, and report to higher level planners. They are responsible for task sequencing and execution.

[4] Transport Stock Unit (TSU): a generic term to refer to different types of items transported in AMHSs, i.e., bag, parcel, or tote.

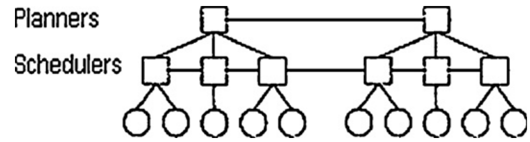

Fig. 8. Control architecture scheme.

Schedulers communicate via standardized interfaces to execute the transportation process and fulfill the tasks assigned, e.g., bag delivery to its destined lateral or crane retrievals.

The proposed control architecture (Fig. 8) has a certain degree of hierarchy combined with flexible decision making for subordinates, as in the modified hierarchical form of control. However, we may define several higher level control units (planners) rather than a single higher level control unit. Therefore, the control architecture is a variant of the modified hierarchical form of control. At this point, we emphasize again that we take the control perspective of the architecture, and not the software implementation perspective (see also Section 1).

Now that we defined the basic structure of our control, we next have to allocate decision functions to the different levels of control and to the different controllers. In doing so, we attempt to locate each decision function at the lowest possible control level and with the narrowest possible scope. Here, the word "possible" means that no direct deterioration in system performance is expected due to making the decision local and with a narrower scope. However, this principle may be violated due to a required synergy in control among different sectors.

In order to apply generic control methods, we have to treat systems that are at the same level of detail similarly. However, due to the varying nature of AMHSs in different market sectors, this is not always the case. Therefore, it is essential for our control architecture to have elements that deal with the differences among systems, to produce a certain level of detail that is then usable by generic control methods. This is further described below.

5.2. Decision-making processes

In the following, we highlight the main decision making processes relevant to our architecture, at each level of control. First, at the planning level (see Fig. 9), there are two main planners we incorporate in our control architecture:

- *Build planner*: responsible for the build area, i.e., workstations. In distribution, this means planning the order picking process, whereas in baggage handling this means planning the *make-up* of flights, i.e., gathering the baggage belonging to the flight at the right make-up point(s). This is a planner as it requires a global view on system information, schedules, and the build area. Moreover, it results in assigning work to system resources (see our definition of the planning level in the concept architecture).
- *Storage planner*: this controller is responsible for the storage area, i.e., the ASRS consisting of cranes and storage aisles. The same arguments as with the build planner hold for this controller to be a planner, where the global view necessary is on the ASRS and operating cranes.

We stress that parcel & postal systems are mainly sorting systems that are controlled at the scheduling and local traffic levels as later described. There are no ASRSs that need the planning level, while the assignment of destinations to chutes is an input parameter to the system that is usually fixed for longer times. For distribution and baggage handling, we identify the following planning processes:

P1. *Inbound flow to the ASRS*: when a TSU requires storage, it is announced to the storage planner, which responds with

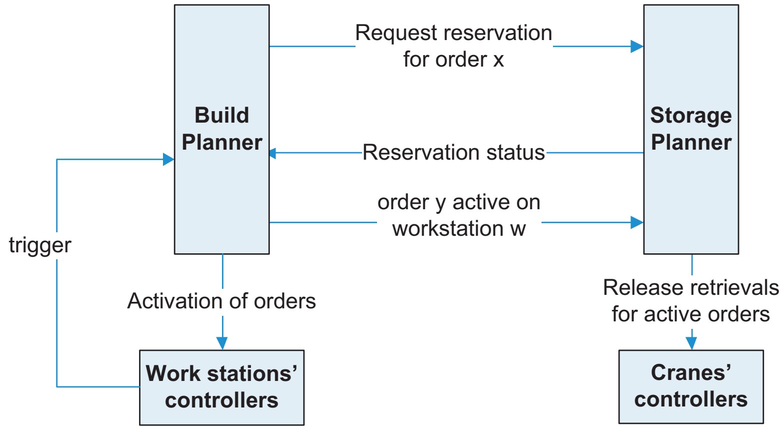

Fig. 9. Communications at the planning level.

indicating a destination aisle and crane to perform the storage operation. The decision can be made according to different business rules. TSUs returning from a workstation in a distribution system (no item integrity) are part of the inbound flow to the ASRS (see Section 2.2).

P2. *Outbound flow from the ASRS*: this process is a planning process as it requires a global view of the ASRS and of the destination workstation(s). Moreover, it results in assigning tasks to resources, i.e., retrieval tasks to cranes. There are two main sub-processes in outbound flow planning:

a. *Stock reservation*: this is a process that brings the distribution system to the same level of detail as a BHS, by assigning TSUs to orders. In distribution, a customer order consists of a set of order lines, each referring to an SKU required with a certain quantity. To build the order, stock is retrieved from the ASRS. Since multiple TSUs may hold the same SKU (TSUs are not unique), it is necessary to decide on which TSU to *reserve* for usage of a certain order. However, in baggage handling we define an order as a set of *bags* required for a certain flight. In this sense, bags are uniquely identified, as each bag entering the system via check-in desks or as transfer baggage is already assigned to a specific *order* (flight). This process is accomplished as the build planner requests stock reservation for certain orders (plans orders) from the storage planner, which in turn looks for TSUs to reserve.

b. *Order release*: workstation controllers trigger the build planner to activate orders. As soon as an order is active on a workstation, stock belonging to this order has to be released from the ASRS. Therefore, the build planner informs the storage planner that a certain order is active. In turn, the storage planner dynamically assigns the reserved TSUs to candidate cranes as retrieval tasks. From this point on, cranes are responsible for executing and sequencing these tasks in the scheduling level of control. Note that the previous process (a) brought the distribution system to the same level of detail as in baggage handling.

Second, at the scheduling level, we identify the following scheduling processes:

S1. *Crane retrievals*: crane controllers have to schedule the released set of TSU retrieval tasks. The pipeline occupation of the TSU destination plays a role in scheduling, in order to support functional requirements such as avoiding blockings and deadlocks. TSUs are normally retrieved to be loaded on the main sorting system in baggage handling and distribution AMHSs. However, in parcel & postal, the sorting system is the main element where no cranes are involved.

S2. *Scheduling inbound containers*: in parcel sorting systems there are no diverts or cranes to load TSUs on a sorting system, as the AMHS is basically the sorting system, which is a sub-system in the other two market sectors. In this case, the loading problem is already at Scope 2 of our analysis (see Fig. 1). This loading problem may also apply to some simple BHSs in small airports where bags from incoming ULDs (see Fig. 5) are loaded immediately on the sorting system with no preceding stages, e.g., routing, and storage. Fikse et al. [22] develop scheduling tools that consider loads in transport within sorting systems in order to schedule incoming containers in parcel & postal, and baggage handling. These scheduling tools are not part of a scheduler within the AMHS, but are tools for the system's user to apply. For sorting systems using conveyors in distribution, this loading problem is not applicable as incoming TSUs are always stored first, so the inflow and outflow are decoupled. Scheduling inbound containers should support our functional requirements, e.g., management of buffers, dealing with urgent items, and starvation avoidance.

S3. *Routing arrivals*: in baggage handling, as mentioned earlier, arrivals are routed either to the sorting system or to the ASRS. This choice is made by the arrivals' divert controllers, using system information and status of destinations.

S4. *Routing in parallel systems*: in large scale AMHSs, there are often service points, e.g., screening machines (Fig. 10), which are available at different alternative systems. In such configurations, a divert controller has to decide to which system to divert an incoming TSU.

Our control logic for these routing problems is dynamic and based on the status of the system. Machine cluster controllers post expected throughput time to pass through. Upstream controllers use

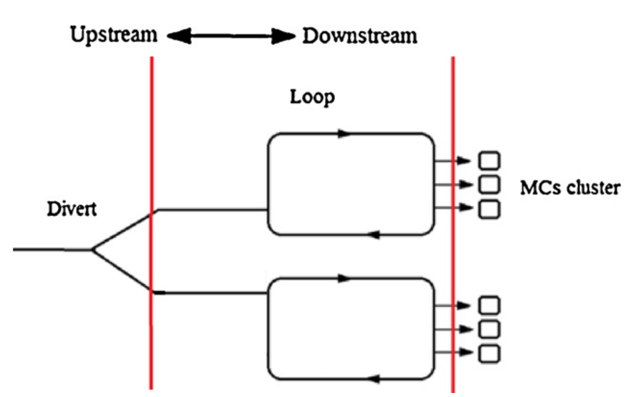

Fig. 10. Routing in parallel systems.

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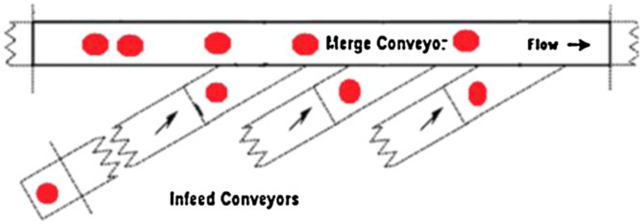

Fig. 11. Merge configuration.

this information to make routing decisions. In this dynamic control, downstream controllers need information about TSUs in the pipeline from upstream controllers, in order to estimate throughout times. This control logic helps in our functional requirements of saturation management, prevention of imbalanced queues and recirculation, management of buffers, and dealing with disruptions.

Third, local traffic control deals with processes such as:

L1. *Space allocation in merge configurations*: in merge configuration we have to allocate free spaces on the loop to TSUs waiting to enter the loop from several infeeds (Fig. 11). The scheduling processes 1, 2, and 3 mentioned above, result in decisions to load infeeds. Once infeed loading decisions are taken at the scheduling level, then we can use a generic local traffic control algorithm in such a configuration, e.g., by a loop controller. This problem is particularly important for parcel & postal sorting systems, which handle large numbers of TSUs within strict time limits, and so need an efficient merge operation. This local traffic problem has to satisfy several functional requirements, e.g., labor efficiency for operators loading the infeeds.

L2. *Crane storage cycles*: the crane executes storage cycles to store TSUs waiting on its inbound buffer. Higher levels of control assign TSUs to a certain crane, and route them to the crane. However, regardless of these higher level decisions, once TSUs arrive at a certain crane to store them, then the storage operation is similar for all relevant sectors, which allows the application of a generic control logic at the local traffic level. Storage does not need to communicate with other system components for information, and can execute this process locally.

We note that schedulers are the controllers responsible for workload control, because they decide on task execution times, e.g., retrievals. Pipeline size limitations reflect a pull system for material flow, which is used to avoid congestions, overflow of buffers, saturation, imbalances in loads among buffers or parallel systems, and to support other functional requirements. Traffic controllers have to deal with materials physically moving as a result of scheduling decisions, and do not influence the amount of materials in transport.

In the first part of this section, we analyzed the forms of control that are the basic structure of any control architecture, while keeping in mind hybrid forms that can result in variants from the basic forms of control. We then evaluated the suitability of these alternative forms of control to our problem, and excluded the two extremes (centralized control and heterarchical control). Next, we built upon the nature of decision-making in AMHSs to propose a concept control architecture that entails hierarchical levels of control and generic controllers on different levels. Our concept control architecture is a variant of the modified hierarchical form of control, which uses the strong points of heterarchical control architectures (e.g., modular and robust design), and of hierarchical control architectures (e.g., delegation of lower level decision to lower levels in the hierarchy).

In the second part of this section, we presented the main decision-making processes and indicated the potential to model them generically. In future studies, we gradually detail our concept control architecture further, and test its applicability in AMHSs in different settings reflecting the different market sectors. Then we analyze the extent to which we manage to maintain a generic control that conforms to our functional requirements and design requirements.

6. Conclusion

In this paper, we have discussed the possibility to design a generic planning and control architecture for AMHSs that occur in different market sectors. In Section 2 we analyzed the synergy among the different sectors. Furthermore, the process flows in the different sectors were modeled in an analogous way given a certain level of abstraction. This analysis, partly based on close experience with the materials handling industry, led to a list of general requirements for a generic control architecture. These requirements concern both the design and functionality of the control architecture and are valuable for all market sectors. Subsequently, we reviewed the literature in Section 3 to investigate the availability of answers to the requirements from practice. Consequently, Section 4 weighed the requirements from practice against the existing literature and highlighted the missing links to propose an agenda for future research in the field of planning and control of AMHSs. Finally, in Section 5 a concept for generic control of AMHSs in the three market sectors has been proposed, in light of our design and functional requirements.

Our main message 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 relax this requirement 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' supplier 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.

We find our concept control architecture (Section 5) capable of dealing with our functional and design requirements. In subsequent studies, we build on this concept further to develop a full-blown generic planning and control system.

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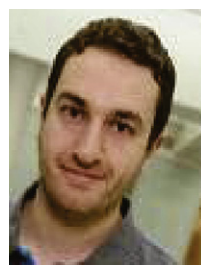
Glossary

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
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
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
TSU: transport stock unit, a generic terms for loads handled in AMHSs
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
ULD: unit load device, standard container used in the baggage handling industry
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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