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Autonomously Organized Block Stacking Warehouses: A Review of Decision Problems and Major Challenges

Autonom organisierte Bodenblocklager: Ein Überblick über Entscheidungsprobleme und wesentliche Herausforderungen

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Abstract: In autonomously organized block stacking warehouses, Automated Guided Vehicles (AGVs) control material handling without requiring any technical integration or Warehouse Management System (WMS). In this paper, we present related decision problems and provide a short literature overview for each one. We found that many existing approaches do not exploit the full potential of available flexibility. By focusing on operational decisions, we introduce the Autonomous Block Stacking Warehouse Problem (ABSWP) and discuss major challenges which must be tackled by future solution approaches.

[Keywords: Autonomous Block Stacking Warehouse Problem, Autonomous Transport Vehicles, Block Storage, Unit-load Warehouse]

Kurzbeschreibung: In autonom organisierten Bodenblocklagern übernehmen Fahrerlose Transportfahrzeuge den Materialtransport und benötigen dabei keine technische Anbindung und Lagerverwaltungssystem. In diesem Beitrag präsentieren wir relevante Entscheidungsprobleme und geben für jedes einen kurzen Literaturüberblick. Wir stellen dabei fest, dass viele bestehende Ansätze noch nicht das voll verfügbare Potential an Flexibilität nutzen. Mit der Fokussierung auf operative Entscheidungen, präsentieren wir das Autonomous Block Stacking Warehouse Problem (ABSWP) und diskutieren die größten Herausforderungen, welche durch zukünftige Lösungsansätze zu bewältigen sind.

[Autonom organisiertes Bodenblocklager, Autonome Transportfahrzeuge, Blocklager]

1 INTRODUCTION

Adaptability of production and storage capacities in supply networks is a decisive competitive factor. Frequent changes on the supply and demand side of companies lead to dynamically shifting material flows and require continuous adaptation and relocation of storage capacities. Many forms of technical warehouse infrastructure cannot meet these requirements. A type of warehouse, which is highly flexible, easily expandable and movable are block stacking warehouses. In block stacking warehouses, unit-loads (usually pallet-based) are placed side by side on the floor and stacked on top of each other. This requires no infrastructure and is therefore associated with low investment costs. In today's block stacking warehouses, the efficiency of material handling still depends on the skills of human operators.

In this work, we consider autonomously organized block stacking warehouses, where Automated Guided Vehicles (AGVs) carry out material handling and take over human decision-making without an additional Warehouse Management System (WMS). This autonomous system should be able to adapt to dynamically changing variables like stochastic in- and outbound flow of unit-loads as well as varying warehouse setups.

Compared to other infrastructure-based warehouses with racks, lifts or cranes, the unique feature of block stacking warehouses is that it is generally not mandatory to define any configurations or layout designs. Decisions can be made solely operational, where agents are able to evaluate each new situation and decide accordingly. That is exactly what human operators are skilled at. They are extremely flexible and often act subconsciously. An example is truck loading, where a human operator might place pallets in the middle of a path to speed up an upcoming loading process. Improvising an increase of temporary storage capacity by placing pallets against the storage rule in front of rarely used items is another example. This behavior cannot be easily reproduced by any existing automated systems.

We commence this work by giving an overview and classifying related decision problems. We then describe the considered system decisions and present the state of research of related systems. Based on these findings, we introduce the ABSWP. Afterwards, we discuss major challenges and future research needs in the context of the ABSWP and then provide a conclusion to our findings.

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2 Overview and Classification of Decision Problems in Block Stacking Warehouses

In the past years, several general frameworks on warehouse design and operations with associated decision problems have been presented (e.g. [GGM10], [GGM07] and [RRS00]). In the following, we present major decision problems related to block stacking warehouses. Before introducing these decision problems, we present the warehouse setup. As shown in Figure 1, the setup determines the environment and the available resources, and for the ABSWP we assume that both aspects are given. The system environment is defined by the following aspects:

- Storage space dimensions: The dimensions of the storage space are usually based on the required storage capacities and an estimation of additional free space for vehicle movement, safety areas and spare capacity.
- Building characteristics: This includes characteristics such as surface condition, load bearing capacity of the floor, illumination level and electrical connections for energy supply.
- Number and position of load transfer areas (I/O-points or In- and Outbound docks): I/O-points are the interfaces of the storage system to the outside world. They can be, for example, loading docks for trucks or intralogistical connections to other areas like production.

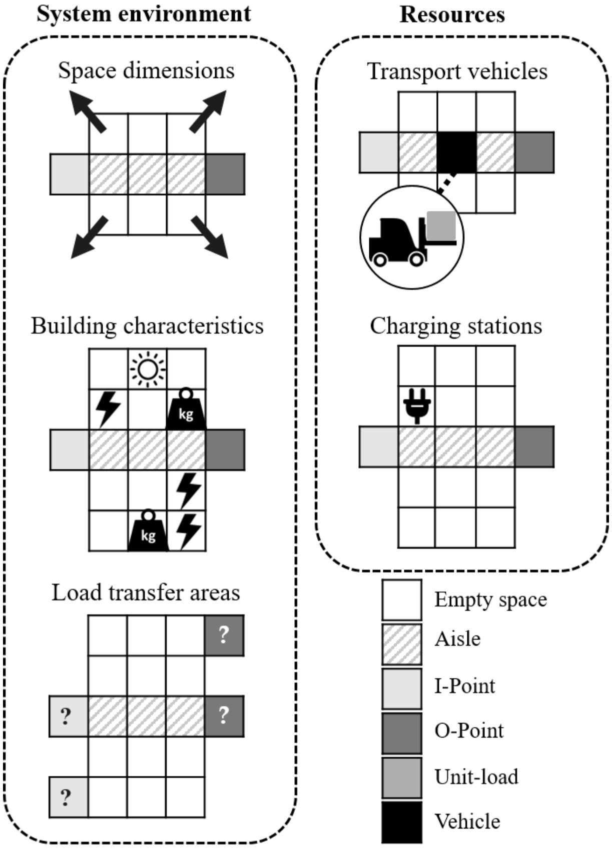

Figure 1. Warehouse setup with specified system environment and resources

For operations in autonomous block stacking warehouses, additional resources as shown in Figure 1 are necessary. These resources substantially define the operational performance of the system. In the case of block stacking warehouses, the subsequent resources have to be determined:

- Number and type of vehicles: The vehicle type (e.g. AGV, robotic forklift or pallet truck) depends on the characteristics of the transport structures and units. The number of vehicles depends on warehouse size and performance requirements.
- Number and Position of charging stations: An adequate capacity of charging stations must be available to recharge vehicles.

A variable number of vehicles is especially important in order to react to changing material flows. In the following we assume that we have just one type of vehicle and that the number of vehicles and charging stations are fixed. Furthermore, we assume that a suitable IT infrastructure is available. In some cases, such as in cross-docking, a flexible assignment of goods to I/O-points might have a positive impact on the system's performance. However, for the ABSWP we assume that the assignment is given and known in advance.

The ABSWP comprises the system decisions within the boundaries of a predefined warehouse setup shown in Figure 2. We start by introducing related decision problems of other warehouse systems including the internal layout design problem, storage location assignment problem (SLAP), unit-load relocation problem, vehicle dispatching problem, unit-load selection problem and vehicle positioning problem.

3 Decision Problems in Block Stacking Warehouses

In this section, we introduce decision problems related to the ABSWP and provide a short literature review for each one. In order to solve those decision problems, many possible objectives can be pursued. For example, these objectives can be cost- or time-related as well as environmental. Some examples include the minimization of travel distance, makespan, task completion times, tardiness, travel times, cost of movement, energy consumption, and expected waiting times, or maximization of throughput and space utilization. Some of these objectives are in conflict (e.g. minimize travel distance and maximize space utilization) and their definition clearly has a major influence on decision-making.

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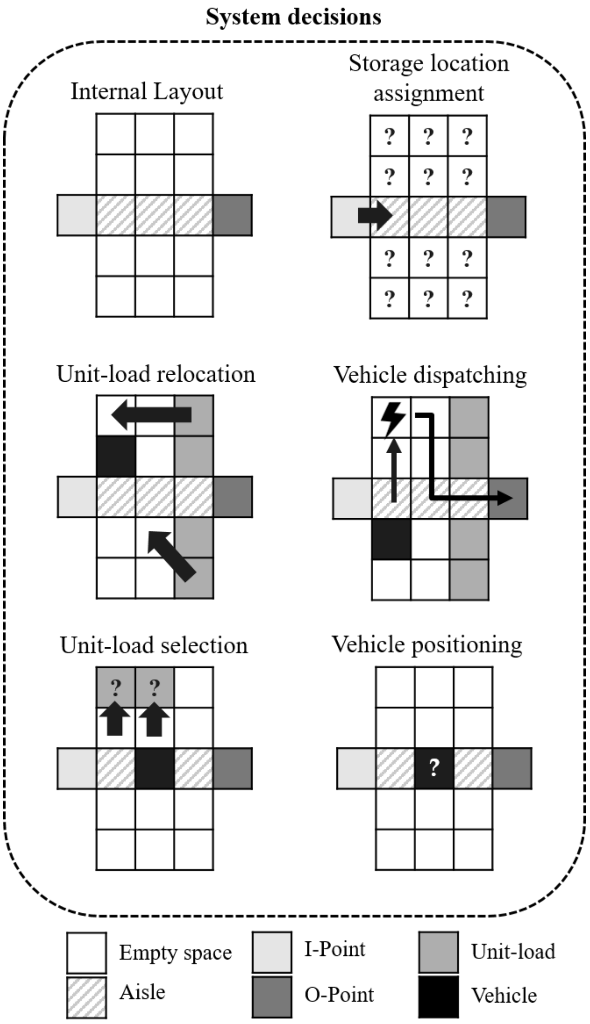

Figure 2. Overview of decision problems related to the ABSWP

3.1 INTERNAL LAYOUT

3.1.1 PROBLEM SETTING

Layout design problems can be classified into external and internal layouts. External layouts define spatial boundaries as well as number and positions of I/O-points and are assumed to be given as described in section 2. Internal layouts define positions and dimensions of aisles for vehicle movement and bays (also referred to as storage areas). Hence, the internal layout problem is also known as the aisle configuration problem. Especially for infrastructure-based systems, these layout problems are typically long-term decisions and not operational (see [GGM10], [GGM07] and [RRS00]).

In internal layouts, four types of locations can be differentiated:

- Inbound dock (I-point; also known as strip door): New unit-loads arrive at inbound docks. The exact position and orientation of inbound docks is given by the external layout.
- Outbound dock (O-point, also known as stack door): The retrieval of unit-loads ends up at an outbound dock, where the unit-load is removed from the system. Specifications of outbound docks are also given by the external layout. Generally in- and outbound docks are interchangeable (e.g. open doors). However, defined in- or outbound docks are often used to simplify processes and achieve a directed material flow.
- Aisle: Aisles are permanently unoccupied cells, which serve as cleared space for fast movement of vehicles. Aisles are usually oriented length- and crosswise towards cardinal directions (orthogonal aisles are cross-aisles). Nevertheless, any diagonal orientation and shape is possible.
- Bay: A bay is a storage area for unit-loads consisting of one or multiple cells of the grid. Depending on the size and shape of a bay, it may not be possible to directly access all unit-loads. It may be necessary to relocate blocking unit-loads on top and in front of the target storage location.

To assess different layout variants, the type of command cycles and storage policies (see section 3.2) are defined. In single command (SC) cycles, the vehicles always return to the starting point after executing a storage (replenishment) or retrieval task. Hence, vehicles travel one way without carrying a load. Dual command (DC) cycles combine storage and retrieval tasks to avoid empty runs, but also require traveling back to the starting point. Thus, it requires alternating receiving and shipping tasks, which is difficult to establish. In continuous multi-command (MC) operations, travelling between any location in the warehouse is possible. This means that the travel time and travel distance depend on the assignment and sequence of transport tasks to the vehicles (see section 3.4).

In infrastructure-based warehouses, all I/O-points are connected via aisles and cross-aisles to guarantee direct access to and from the warehouse. These aisles and cross-aisles can be uni- and bidirectional allowing directional or two-way traffic. High traffic volumes and two-way traffic may also require aisles with multiple lanes. Additionally, space for safety stock and honeycombing (see section 3.2) must be considered as well.

However, with regard to the ABSWP, we are not convinced that it is necessary to determine internal layouts as it is the case for infrastructure-based systems. It must be ensured, that vehicles can move sufficiently within a warehouse. This requires unoccupied areas like permanently free cells in aisles (besides traffic) or temporarily empty cells of bays. Thus, it is possible that a block stacking warehouse consists of only a single bay and temporarily empty cells. On the other hand, internal layouts with aisles could

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be beneficial to reduce complexity and speed up processes in a way humans are already approaching it today. Internal layout designs in block stacking warehouses can be adjusted more frequently than in infrastructure-based warehouses. In order to assess internal layouts in block stacking warehouses with multiple I/O-points properly, MC operations are necessary. Vehicles should be able to perform tasks continuously and travel between any location in the warehouse. Moreover, human drivers would not always run SC or DC cycles and return to a parking or starting position, unless they have to charge batteries or want to avoid congestion.

3.1.2 LITERATURE REVIEW

There have been publications of the internal layout design problem since the 1960s. Berry [Ber68] developed a cost function, where occupation costs (for space utilization) and traveling costs (based on average distance) are considered for horizontally, vertically and diagonally oriented aisles in rectangular prisms. He found that a layout, which minimizes traveled distance differs from a layout where space utilization is maximized. Later Goetschalckx and Ratliff [GoR91] calculated the optimal amount of lanes and the lane depth for single and multiple products to minimize the required warehouse area, but did not consider material handling costs concerning number, length and orientation of aisles. Larson et al. [LMK97] divided a heuristic approach in three phases. In the first phase, a shortest travel time path from an input point to an output point is determined by minimizing the number of turns and maximizing the length of the longest arc. In phase two, the optimal row depth and the required number of storage locations is calculated. Finally, in phase three, a ranking of items is developed based on throughput and storage requirement. Most desirable storage areas in terms of travel distance are assigned to items with the highest ranks. Whereas Larson et al. [LMK97] assumed rectangular travel in a class-based storage, Gue and Meller [GuM09], Gue et al. [GIM12], and Öztürkoglu et al. [ÖGM14] examined diagonal travel for cross-aisles of any shape under a random storage policy. These unconventional cross-aisle designs have been able to significantly reduce expected travel distances compared to traditional designs with orthogonal cross-aisles. Derhami et al. recently published several papers on layout design in block stacking warehouses ([DSG16], [DSG19a] and [DSG19b]). They developed a model for wasted storage space (MBD) and used a simulation-based approach to simultaneously optimize conflicting objectives; space utilization (maximize) and material handling costs (minimize).

3.2 STORAGE LOCATION ASSIGNMENT

3.2.1 PROBLEM SETTING

The storage location assignment problem (SLAP) belongs to the category of assignment problems, where at least two or more elements have to be matched. In case of SLAP, incoming products (here: unit-loads) are assigned to storage locations while considering a certain objective. Gu et al. [GGM07] divided SLAP into three categories based on the amount of available information regarding the arrival and departure times of unit-loads.

- Item information (SLAP-II): All information about the arrival and departure times of each unit-load are available. Hence, storage locations can be determined based on known due times of unit-loads.
- Product information (SLAP-PI): Items (e.g. unit-loads) are instances of products. Thus, information is available on the product-level (as an average) and not for each individual item. Products can be combined to classes. In class-based storage, these classes are assigned to storage locations. If each product builds its own class, this is called dedicated storage. Another possibility is that all products are assigned to only one class. This is called random storage.
- No information (SLAP-NI): In this category no information is available. This can be, for example, the case for new product arrivals without historical demand information.

We assume the transport capacity of vehicles to be one unit-load. If the transport capacity is greater than one (picking of multiple items), probabilities of items occurring in the same order can be examined as part of the correlated storage location assignment problem (CSLAP). In all strategies, a trade-off between objectives like storage space utilization and efficient material handling has to be found. Wasted storage space, which cannot be used, should be prevented. Some storage policies dedicate storage space (e.g. lanes) temporarily to a stock keeping unit (SKU). This prevents that unit-loads of another SKU are obstructing the direct access and require unit-load relocations. However, if the dedicated storage space is not fully occupied and cannot be filled with unit-loads of another SKU, it is a waste of storage space called honeycombing. Honeycombing can only be eliminated by fully emptying or occupying the dedicated storage space.

In the ABSWP the SLAP is a major subject. Solutions (e.g. storage policies) have a substantial impact on warehouse performance (e.g. retrieval time and space utilization) and internal layout decisions. Assessing storage policies especially depends on the type of command cycles. There are situations where a new inbound load arrives and a vehicle solely runs SC cycles from an I/O-point to the target storage locations. Especially in warehouses with only one I/O-point, SC and DC cycles are relevant. However, considering any warehouse setups and all situations over a longer period of time, MC operations are required.

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3.2.2 Literature Review

The application of an appropriate storage policy depends on the availability of data. If the item or product history are available, it is possible to analyze these item or product activities systematically beforehand. This is called profiling. Frazelle [Fra16] describes item activity profiles and possible approaches to warehouse slotting. A very basic principle of pattern recognition is Pareto's law (also referred to as ABC analysis) where, for example, a minority of SKUs may represent the highest total number of picks, indicating their popularity. Based on this, SKUs with highly ranked popularity could be assigned to the best storage locations in terms of shortest travel time. Over many decades, a large number of storage policies and rules have been developed. Reyes et al. [RSM19] provide an overview of recent publications and applied policies and rules regarding the SLAP. They show that class-based (CB) and random-based (RB) policies are most widely used. In the following, a short introduction of most popular storage policies and rules is given.

In the 1960s, Heskett proposed the storage policy cube order per index (COI) ([Hes63]). The COI rule is a turnover-based policy, where unit-loads are ranked based on the ratio of inventory volume to demand rate. Afterwards, unit-loads are sequentially assigned to the most desirable locations. Kallina and Lynn [KaL76] showed that COI is indeed an optimal solution. This is true in the case of single command order picking. However, for MC operations COI can be a bad choice [Sch14]. Hausman et al. [HSG76] compare RB, full turnover-based (TOB) and CB policies. They introduced a CB storage policy based on COI, where locations are assigned randomly within classes. Their approach also considers single command operations. It could be shown that their approach potentially leads to a significant reduction in travel time. In 1990 Goetschalckx and Ratliff [GoR90] developed a shared storage policy based on the duration-of-stay of unit-loads (DOS). Instead of using the average turnover rate, which is a product characteristic (one turnover rate for all unit-loads of the same product), they use the expected duration-of-stay for each unit-load (time in storage for each unit-load of the same product can be different from each other), which is a single unit characteristic (SLAP-II). They distinguished between static and adaptive storage policies and developed solutions for both cases based on DOS.

3.3 Unit-Load Relocation

3.3.1 Problem Setting

We categorize relocations of unit-loads in two types: relocation for unit-load retrieval and relocation to improve future operations.

In order to retrieve a unit-load, it might be necessary to relocate obstructing unit-loads stored on top or in front of it. This can, for example, be the case, if lanes contain a mix of SKUs or storage retrieval rules like due dates, limited duration of stay or "First In, First Out" (FIFO) must be considered. This type of relocations cannot be avoided and should be realized immediately.

Relocation to improve the future warehouse performance deals with the question, of whether existing internal layouts should be rearranged or when stored unit-loads should be repositioned. Thereby, effort for relocation and expected benefit must be continuously investigated. If future benefits in operations surpass required efforts, the relocation process could be triggered. This decision gets more difficult if benefits and efforts cannot be compared directly due to different measurement units. An example is an improved average retrieval time as benefit and additional travel distance as repositioning effort. Finally, also the extent of rearrangement or repositioning actions must be defined. The case of small incremental actions is called healing. Re-warehousing typically involves relocation of goods on a larger scale [KBW11]. Both, relocation for retrieval and relocation to improve future operating efficiency can be combined. A relocation might be necessary for the retrieval of another unit-load and at the same time improve the future efficiency of warehouse operations.

Also in the ABSWP relocation to access blocked unit-loads for retrieval cannot be avoided. This kind of relocation decisions need to be made when solving the SLAP. Relocation to improve the future warehouse performance on the other hand is optional. It can reduce access times in busy hours.

3.3.2 Literature Review

Tasks where relocation is linked to retrieval are similar to the parallel stack loading problem (PSLP) [BoK20], the blocks relocation problem (BRP) [CSV12], and the container relocation problem (CRP) [ZBV19][MGM19], where the objective is to use as few relocation moves as possible.

Studies on relocation to improve future warehouse operating efficiency can be found under terms like warehouse rearrangement [ChC73], restoring policy [LiW90], (re-)shuffling [MLP95], re-warehousing [KBW11], healing [KBW11], reorganization [CaG12], rearrange-while-working (RWW) [CaG12], Dynamic Block Stacking (DBS) [Lee19], repositioning [KXL18][Mer18] or container premarshalling problem (CPMP) [HTT20]. Christofides and Colloff [ChC73] published one of the first approaches which rearranges items from an initial to a desired new location during idle time. Their solution finds a sequence minimizing total costs of operations in a dedicated storage scenario. Linn and Wysk [LiW90] proposed several control policies including a restoring policy in an Automated Storage and Retrieval System (AS/RS). Thereby stored items are rearranged by alternating the two rules; clear the highest turnover zone first (CHTZF) and restore the highest turno-

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ver item first (RHTIF). Marlidharan et al. [MLP95] introduced heuristics for relocation in idle time. Their approach is able to considerably increase operating efficiency and reduce waiting as well as service time in an AS/RS. Kofler et al. [KBW11] compared strategies for re-warehousing and healing. In the case of re-warehousing a warehouse is completely re-slotted. Afterwards, warehouse efficiency decreases over time. Healing on the other side improves existing solutions continuously. In their opinion, healing strategies are generally more appropriate for volatile environments and can be helpful as supplementary measure to maintain operating efficiency after re-warehousing. Carlo and Giraldo [CaG12] are aiming in a similar direction with perpetually organized unit-load warehouses. Their strategy, rearrange-while-working (RWW), optimizes the rearranging process of an AS/RS during operations with the objective to minimize total travel distance. Lee [Lee19] introduced the DBS problem with random demand. Thereby, the row depths are periodically changed in order to balance aisle space and honeycomb loss. They modeled the problem as an infinite-horizon Markov Decision Process (MDP) and utilized a stationary optimal policy. The reward function is calculated as additive inverse of the total storage and material handling costs. Krenzler et al. [KXL18] and Merschformann [Mer18] discussed active and passive repositioning of storage units in robotic mobile fulfillment systems (RMFS). Passive repositioning is the continuous update of a storage location when storage units are brought back after picking. Active repositioning on the other hand deals with the question, if moving storage units from their current location to another without picking could be beneficial in parallel to a running or idle system. Finally, the CPMP deals with container re-ordering to speed up future container retrieval tasks. In a recent publication by Hottung et al. [HTT20], deep neural networks (DNNs) and heuristic tree search (HTS) are combined to tackle the problem with promising results.

3.4 Vehicle Dispatching

3.4.1 Problem Setting

In warehouse operations, storage and retrieval tasks are usually not known for a longer planning period (e.g. a day), but become known dynamically over the course of the day. Whenever more than one vehicle is available, each task needs to be assigned to a vehicle. If more than one task is allowed to be assigned to a vehicle, it needs to be decided in which sequence the assigned tasks are executed. Therefore, typical objective functions are the minimization of travel distances, travel times, task completion times, or tardiness. In order to calculate the distance and the time a vehicle needs for travelling from one point to another, the shortest (or fastest) path must be determined (also referred to as path finding method). In a block stacking warehouse, the graph, which is used to determine the shortest paths, is variable over time. It depends on the current layout, or more precisely, on currently empty bays.

In practice, often relatively simple dispatching rules are applied to assign tasks to vehicles as soon as the tasks become known and an idle vehicle is able to take over the task. A dispatching rule can for example be assigning tasks to the vehicles closest to the starting point of a task. Especially in cases with many vehicles, congestion, live- and deadlocks of vehicles can lead to conflicts. In these scenario, techniques for conflict free routing (e.g. route segment reservation or designated zones) become necessary. In addition, constraints like priorities, time windows and battery levels must be considered.

Another possibility for assigning tasks to vehicles and defining a sequence in an integrated way is to solve a vehicle routing problem (VRP). This involves the consideration of a longer planning horizon and increases the complexity. In the research of the last decades, many variations of VRP (e.g. vehicle routing problem with time windows (VRPTW) and pick-up and delivery problem with time windows (PDPTW)) have been investigated. According to Pillac et al. [PGG13] the problems can be classified into static or dynamic as well as deterministic or stochastic problems. In static and deterministic problems all required information (e.g. travel distance and time) is known prior to the planning period and the data does not change during task execution. Dynamic problems consider the evolution of information, which can be available very late, during the planning period or even during task execution. Stochastic problems take into account the uncertainty of information, which may be expressed as a probability distribution.

Decentralized decision-making is enabled by market-based solutions: In market-based solutions local entities, for example the vehicles, are bidders, which place a bid to an auctioneer (e.g. also a vehicle or a central entity). The auctioneer evaluates all bids and decides on the best allocation. Depending on the auction principle, a sequential single task auction or combined task bundles are auctioned [DVD20].

Vehicle dispatching is interrelated with all other decisions of the ABSWP and is required to evaluate actions. Important objective figures like travel time and distance are based on dispatching decisions.

3.4.2 Literature Review

A common approach in practice of AGV control is to apply a dispatching rule combined with a path finding method. Le-Anh and De Koster [LeD06] divide dispatching systems into decentralized and centralized dispatching methods. An example for a decentralized dispatching method is the first-encountered-first-served (FEFS) rule, where vehicles continuously circulate and pick up the first load encountered as soon as they have available capacity. For central dispatching methods, continuous communication with all vehicles is required. A central control system guides vehicles based on real-time information like their positions and status. Central dispatching approaches are usually myopic and suitable for large instances. Egbelu and

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Tanchoco [EgT84] classified dispatching rules as workstation-initiated (tasks at workstations claim vehicles) and vehicle-initiated (vehicles claim tasks) dispatching rules. Le-Anh and De Koster [LeD06] furthermore divide dispatching rules into single-attribute (e.g. distance or workload-based), multi-attribute (e.g. shortest travel time and remaining queue space), hierarchical (based on added value), look-ahead (short forecast period) and preemption dispatching rules (allow re-assignment). In research, also combined dispatch and conflict-free routing problems (DCFRP) have been addressed (e.g. [DLR03]). Dispatching rules are generally rather easy to implement and especially helpful in highly dynamic and stochastic environments where schedules would have to be updated frequently. However, Meersmans [Mee02] and Yang et al. [YJM04] show that dynamic scheduling is able to outperform dispatching rules, but is only applicable for rather small instances. In order to make a dispatching decision (based on path information), path planning is required. A common approach for path planning is using graph search algorithms. They can also be applied to find a shortest path from a starting point to a destination after a dispatching decision is made.

Research on vehicle routing and scheduling problems is quite extensive. Since operations in block stacking warehouses are often confronted with a highly dynamic environment and stochastic variables like uncertainty in customer demand, this review is focused on dynamic solutions considering uncertainty. Thereby, it can be distinguished between preprocessed and online decision-making [RPH16]. Preprocessed decisions are based on information known prior to task execution. Based on this, general policies and rules (e.g. dispatching rules) or preprocessed rewards for actions and corresponding state representations can be determined. Online decision-making is able to dynamically process a continuous information flow. Therefore, usually a trade-off between decision quality and responsiveness must be found. Look-ahead strategies or rolling horizon procedures typically follow an action plan until a new event occurs. Then, a single decision for the current state or a revised action plan must be calculated. The selection of a suitable solution method depends in particular on the Degree of Dynamism (DOD) and the desired reaction time [RPH16]. In order to make state-dependent decisions with respect to available stochastic information (referred to as policy), problems can be modeled as a Markov decision process (MDP) or multi-stage stochastic models [RPH16]. Pillac et al. [PGG13] divides solution methods for dynamic and stochastic problems in stochastic modeling, sampling and other strategies. A stochastic modeling approach is Approximate Dynamic Programming (ADP), where approximation techniques can be used to overcome the curse of dimensionality (see [Ulm17]). In sampling-based approaches, several scenarios are generated based on random variable distributions. Afterwards, each scenario is evaluated. Well-known is Multiple Scenario Approach (MSA), introduced by Bent and Van Hentenryck [BeV04], which continuously updates a scenario pool by using the time between decisions.

3.5 Unit-Load Selection

3.5.1 Problem Setting

In many cases for the retrieval of unit-loads, not a dedicated unit-load needs to be picked, but a product needs to be provided for a customer. Therefore, usually storage rules or item retrieval policies like "First In, First Out" (FIFO), "Last In, First Out" (LIFO). "First Expiry, First Out" (FEFO) or "Batch First In, First Out" (BFIFO) are applied. If no item-related rules apply or a rule offers a certain degree of freedom , unit-load selection is necessary. In this case, it is possible to select one out of many unit-loads optimizing a given objective function such as minimization of travel distance or travel time.

However, there are also use cases where, for example, a batch of unit-loads is queued up in front of an inbound dock. This represents a waiting queue where all unit-loads have an associated task. The tasks must be assigned to vehicles and sequenced as part of vehicle dispatching (see section 3.4).

In the ABSWP, item retrieval policies have a significant effect on other decisions like the internal layout. Some of the item retrieval policies are rarely found in block stacking warehouses. Often, unit-loads are stored in lanes dedicated to an SKU. In this case, LIFO works well because the unit-load, which has been stored last, can be easily accessed. FIFO, on the other hand, would require relocation of all unit-loads which are stored in front and on top. Item retrieval policies can only be applied correctly, if all information like storage locations and arrival times of unit-loads are available. In block stacking warehouses without additional WMS this is not always the case. An autonomous system can easily collect all required information and correctly apply item retrieval policies.

3.5.2 Literature Review

For unit-load selection, a policy such as shortest process time could be used to select the item with shortest required completion time first.

Item retrieval policies are usually given by product requirements. Thus, unit-load selection is mainly part of larger surveyed scenarios where well-known rules are applied (e.g. [GoR91]).

3.6 Vehicle Positioning

3.6.1 Problem Setting

Idle vehicles have to wait at a certain position until they receive a new task. This parking position (or dwell

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point) should allow them to react efficiently without blocking any other vehicles. A parking position can be, for example, the last position (to minimize travel distance), a charging station (to increase availability) or a central position (to improve response time). Waiting and repositioning decisions as well as battery charging and transport tasks are part of vehicle dispatching problems.

Vehicle positioning can be an area in which human operators are not especially attentive. If there is idle time, some may head to a parking position or charging station, others drive nearby other workstations or the common rooms. Considering waiting and repositioning decisions of vehicles could be another advantage of autonomous block stacking systems and should therefore be part of the ABSWP.

3.6.2 Literature Review

Similar to vehicle routing, static and dynamic methods as well as central and distributed approaches are available. The major rules to select a parking position of AGVs are described by Egbelu and Wu [EgW93] and Van der Meer [Mee00]. These static vehicle positioning rules are central zone positioning, circulatory loop positioning, point of release positioning (or drop-off point positioning) and distributed-positioning. More recently, approaches for dynamic vehicle positioning as well as the investigation of conventional layouts (besides loop layouts) have been proposed [HuE00]. Also, in research related to VRP outside the scope of a warehouse, vehicle positioning and waiting strategies have been addressed ([PGG13]). Essentially, the probability of new tasks coming up in a certain region must be evaluated. Based on this information, waiting strategies for idle vehicles have been developed. Besides waiting strategies, it could be beneficial to actively relocate a vehicle to a new position with a high likelihood for the appearance of a new task. (e.g. [BeV07]).

4 The Autonomous Block Stacking Warehouse Problem (ABSWP)

4.1 Definition of the Problem

After presenting all necessary decisions and solution approaches of related systems, we introduce the Autonomous Block Stacking Warehouse Problem (ABSWP). The ABSWP is influenced by its environment and by its resources, which we assume as given from the outside. Part of the predefined system environment is the storage space, multiple I/O-points and adequate building characteristics with restrictions such as the load bearing capacity. As resources, the number of each vehicle type, and the number and the position of the charging stations are given. In the context of a block stacking warehouse, we consider vehicles, which are able to carry only one unit-load at a time. The vehicles are not restricted to SC or DC cycles and able to process tasks continuously (MC cycles).

As usual for warehousing, the ABSWP must cope with highly dynamic and stochastic input variables as well as heterogeneous available information (e.g. mix of item and product information). Storage and retrieval tasks associated to in- and outbound flow of unit-loads are not known for longer planning periods. They enter the system dynamically from outside throughout the day. Future exact arrival or departure times from production scheduling or notification of logistics service providers are valuable pieces of information. However, usually only product information based on historical data is available for the prediction of in- and outbound loads. In certain cases, no information might be available. For storage and retrieval tasks, we assume that the assignment and sequence of in- or outgoing unit-loads to I/O-points is given.

The ABSWP contains the following decisions. Some of the decisions are optional and not necessarily required for warehouse operations.

- Storage location assignment: Incoming unit-loads must be assigned to storage locations, if they are not directly forwarded to an O-Point. A typical objective is the minimization of travel time. Therefore, it is beneficial to consider future storage, relocation and retrieval tasks within the warehouse. Especially relocations for unit-load retrievals are often time-consuming and should be avoided. To achieve this, the number of required relocations for unit-load retrievals must be minimized. In order to fully utilize the flexibility of an autonomous block stacking warehouse, the assignment decisions should be adapted to the current in- and outbound flow, as well as, to changing product portfolios.
- Internal layout design (optional): Internal layout design decisions define the spatial distribution of storage space and aisles for vehicle movement. In contrast to infrastructure-based systems, in block stacking warehouses, temporarily free cells can be used for vehicle movement. It only needs to be assured that enough space is available to maintain the operability of the system and to avoid a deadlock situation. However, even if aisles reduce the amount of available storage spaces, they are beneficial to increase the material handling efficiency. Thus, also in block stacking warehouses there exists a trade-off between material handling efficiency and storage space utilization. Hence, defining an internal layout is probably beneficial. Nevertheless, it also is implicitly a part of each storage location assignment decision and an internal layout design can be incrementally updated to new requirements.
- Vehicle dispatching: Indispensable is the consideration of vehicle dispatching. It determines the assignment of tasks to vehicles and the definition

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of a sequence. Tasks for vehicles are transport tasks, but also battery charging, waiting or repositioning. Vehicle repositioning decisions are not mandatory for operations, but could improve the efficiency. In the context of larger systems with many vehicles, also conflict free routes need to be ensured. Objective functions for vehicle dispatching are for example the minimization of travel distances, travel times, makespan or tardiness.

- Unit-load selection: The selection of a unit-load for retrieval is necessary, if the unit-load is not determined by item retrieval rules. Then, a unit-load can be selected minimizing material handling effort, for example to achieve DC cycles with pickup and deliveries.
- Improvement relocations (optional): Another optional decision is to change the internal layout or storage location of unit-loads over the course of time to improve the future system performance. The question is when and to which extend improvement relocations are initiated. Improvement relocations are additional effort, but can be realized in off-peak times. For example, the rearrangement of unit-loads during the night based on orders of the next day is reducing the access times.

4.2 Major Challenges of Autonomously Organized Block Storage

Considering the decision problems in section 4.1, solving the ABSWP is challenging. A high computational complexity of the tightly coupled decision problems is already proven. Due to its magnitude, already the formulation of the ABSWP as an integrated mathematical model is difficult.

Different planning horizons and planning hierarchies make the ABSWP more difficult. Some decisions like unit-load selection, storage location assignment or vehicle positioning usually consider shorter planning horizons than finding an internal layout. Today, internal layouts are determined on a tactical level while SLAPs are solved instantly for each storage or relocation task within the boundaries of a fixed internal layout. This classical hierarchical approach could be disrupted: Layouts must not be determined in advance but can evolve incrementally as part of solving SLAPs over time. This requires the extension of the planning horizon of the SLAP while keeping the planning frequency.

Solutions for the SLAP (e.g. storage policies) depend on many variables like the internal layout variant with its I/O-points, defined operation cycles, the product portfolio, arrival and departure times of goods, the degree of available information and the set objectives. Human operators often structure storage locations and form product classes. A known structure helps them to find unit-loads and storage locations easier (especially in case of changing personnel). Hence, they stick to established rules and storage polices. In an autonomous system, a fixed structure would not be necessary anymore, because all the vehicles know about the current state and storage locations of the system. This allows using shared storage policies, which can utilize storage space more flexibly (better utilization of attractive locations leads to reduced travel time) and require less maximum space. Besides, the influencing variables to find a suitable storage policy are not constant. Storage policies should be adjusted continuously over time. Thereby, a challenge is delayed rewards. A storage decision is often made with goals like minimizing order retrieval time, tardiness, or total travel distance. The reward function for these goals includes elements of the future process steps (unit-load relocations and retrieval tasks) until the unit-load has left the system.

After a certain period of time it could be helpful to change a storage location or internal layout. In automated storage systems, concepts to reposition unit-loads in off-peak times are already available and proven to be helpful (e.g. to prepare for known upcoming orders of the next day). In block stacking warehouses however, the internal layout can also be changed. Human operators do not change these internal layouts frequently. It requires additional planning and material handling effort. As a result, while product portfolios evolve, the internal layout often stays the same. The possibility of incrementally adapting the internal layout could be a huge benefit of autonomously organized block stacking warehouses.

Vehicle dispatching plays a key role and major impact in the ABSWP, because all other decisions are strongly interrelated. Today, often simple dispatching rules are applied in AGV systems. They are able to cope with large systems in a dynamic and stochastic environment. However, online solution approaches to solve a VRP with lookaheads could possibly lead to better results. Human drivers are often good in looking ahead. An example of this is the anticipation of peak periods and the preparation by charging vehicles beforehand.

Finally, we see a large number of practical requirements, which have to be met. Some requirements like exception rules or the consideration of due dates are relatively easy to consider. Other requirements significantly increase the complexity of the problem. One example is the variety for sizes and shapes of load carriers. This has an impact on internal layout designs and increases the number of feasible configurations.

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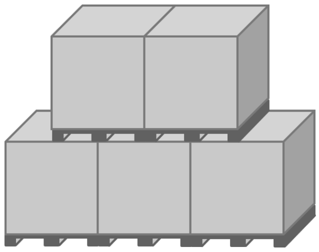

Figure 3. Pyramidal stacking of unit-loads

A product-specific requirement is the stacking capability (height clearance), which depends on the specific material statics and height restrictions of a warehouse. For some products stacking on top of another is not stable. In this case, a different kind of stacking pattern like a pyramidal structure shown in Figure 3, can be highly beneficial. This implies that the consideration of weight and height restrictions would not be enough for SKU-mixed block stacking.

5 Conclusions

We presented decision problems and associated literature related to an autonomously organized block stacking warehouse. Based on these decisions, the novel Autonomous Block Stacking Warehouse Problem (ABSWP) has been introduced. Given the broad field of research and the complexity of all decision problems, developing solutions is ambitious. Nevertheless, we believe solution approaches for the ABSWP are able to disrupt decision-making in block stacking warehouses and are of high practical relevance. Structured storage space in a way humans would organize it (e.g. ABC classification) is not necessary anymore. Internal layouts evolve incrementally when assigning storage locations or can be changed much more frequently. Constant uptime of the system provides more time for relocation of unit-loads in off-peak hours (e.g. during the night). In addition, vehicle dispatching of AGV systems with permanent available information runs more efficiently. However, the flexibility and creativity of humans is outstanding and cannot be matched thus far. We dedicate our future work to develop solution approaches that achieve the abilities and flexibility of human operators.

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