Automated Compact Storage Systems:
System Classification and Applications in Food Products

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1. Introduction

Many manufacturers and retailers advertise with product freshness. Freshness is crucial for food products such as bread, vegetables and fruits, meats, fish, and dairy products. Fresh products can be sold at a premium. Customers are not only willing to pay for the extra, but they are also willing to switch suppliers or brands to obtain a fresher product. Maintaining freshness of the product requires storage, handling, and movement of the product under strict temperature, humidity, and air conditions. Material handling technologies play a vital role in realizing time-sensitive deliveries in distributing food products.

In this paper, we discuss variants of multi-deep-lane automated compact storage systems, which are adopted for not only safe and secure handling of produce at the warehouses but also for meeting time-sensitive deadlines for food products distribution. Food products are typically stored in low (often sub-zero) temperatures. In practice, more energy is required to keep the products cool than to heat the warehouse. The new innovations are aligned with the sustainability mission, i.e., multi-deep compact storage system maximizes the storage density and reduces energy requirements for maintaining cooling temperature. Further, a smaller footprint minimizes heat gains from the roof.

The rest of this paper is organized as follows. In Section 2, we describe the key system requirements from storage solutions for food products. In Section 3, we discuss the variants of multi-deep lane automated compact storage systems. In Section 4, we discuss the role of analytical models in system design conceptualization. Finally, we present some results from implementation of such systems in practice.

2. ***Performance Tracking for Storage Solutions***

Some of the Key Performance Indicators for the compact storage systems include:

- *Manage truck waiting times:* The material handling system should retrieve the unit-loads within due-date targets. In several cases, the unit-loads need to be reshuffled, so that they are ready to be retrieved within a limited time and sequenced a priori for loading in the trucks (see Zaerpour et al., 2015). Typically, the pallets are retrieved from the higher pallet locations and stored in the ground pallet locations in preparation for quick dispatch.
- *Reduce produce damage:* Automated handling with standardized pallet sizes ensure that all pallets are handled uniformly, which reduces damage to the pallets. Further, the pallets are stored in standardized racks which prevent any damage.
- *Maintain high-density in storage:* Multi-deep lane storage ensures that the pallet storage area is densely packed (implying high space utilization). High storage density minimizes the heat losses and reduces the energy consumption for maintaining the cooling temperature.
- *Accommodate flexibility in throughput capacity:* The material handling system should accommodate the fluctuations in handling demands. For instance, when the demand for the product increases, the system should be flexible enough to adjust its throughput capacity.
- *Maintain cooling temperature:* Depending on the product storage requirements, the storage system should control the temperature and air moisture for product storage.

Another important KPI for the WMS is to manage product shelf life: The shelf life of the produce is limited; hence, to maintain food safety, the remaining shelf life of the products should be tracked to minimize wastages. This feature is typically present within the warehouse management system.

In the next section, we discuss the available technologies for multi-deep compact storage systems.

3. Classification of Multi-deep Lane Compact Storage Systems

Multi-deep-lane compact storage systems do not have aisles but only cross-aisles between the multi-deep storage locations for movement of the vertical transfer (and) or horizontal transfer unit movement. The storage depth depends on the type of product; e.g. 5-15 loads. Typically, the number of food product SKUs that are handled are rather small, e.g. hundreds. Further, they are received and stored in batches (one batch per lane and all loads in a batch have the same expiry date). A multi-deep lane compact storage system can be classified based on the mechanism for vertical and horizontal transfer of the unit load. Based on the vertical transfer mechanism, a compact storage system can be broadly classified into a crane-based or a vehicle-based system. Shuttles are used for handling the pallets in the depth dimension in most systems. The mechanism of shuttle charging can also be an important contributor to the throughput capacity of such systems, see Figure 1.

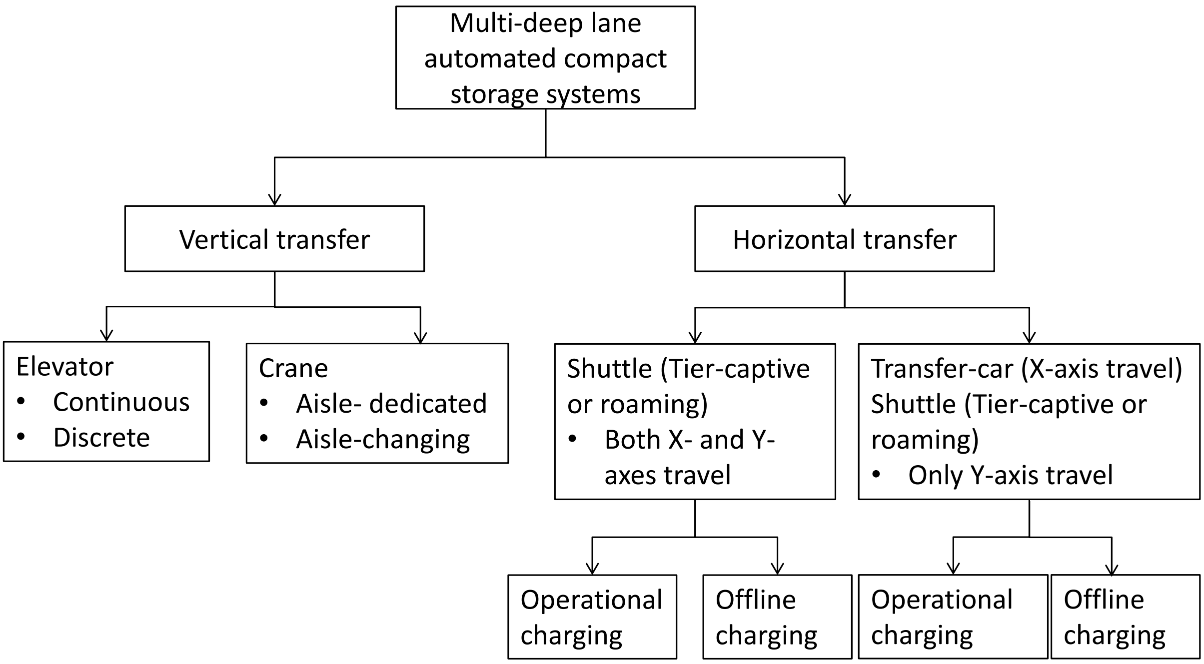

Figure 1: Classification of multi-deep lane automated compact storage system

3.1 System Description

Crane-based system: In a crane-based system, the crane with shuttle (a transfer unit) picks up a storage pallet and travels in a Tchebychev motion (along z- and x-direction) to reach the storage location.Then the crane (or storage/ retrieval machine) releases the shuttle (also known as a satellite or mole) to the rack. The shuttle travels along the y-axis to store the load. Likewise to retrieve, the shuttle reaches underneath the load to retrieve the pallet and completes the remaining operations in a reverse sequence. The shuttles can be charged during the crane's Tchebychev travel, which we refer as operational charging (in Figure 1). In some systems, the cranes can also change aisles. Note that in such systems, typically the cranes are the bottleneck resource and its throughput capacity determines the overall system's throughput capacity. Further, if the cranes are aisle-changing, then the system flexibility increases, however the maximum throughput per aisle decreases, as the crane spends a substantial amount of time travelling between the aisles. In some cases, the shuttles could be dedicated to lanes.

Vehicle-based system: In the vehicle-based system, a load is moved in the vertical direction using a continuous (typically totes) or discrete elevator (typically pallets) and by a shuttle or a combination of a transfer car and a shuttle to reach the storage location (see Figure 2). Transfer-cars are typically captive to a cross-aisle within a tier. However, the shuttles could be tier-captive (dedicated to a tier) or roaming (tier-to-tier shuttles). Again, the shuttle could be charged during movement on the rails, or offline (after regular hour of operation). Charging the shuttles offline may add delays to the pallet handling times because the wait time to access a shuttle increases. In such systems, typically the throughput capacity of the vertical transfer system determines the overall throughput capacity of the system. If a system has fewer shuttles than storage lanes, the transfer car moves the shuttles between the lanes. In so-called live-cube compact storage systems, each load is stored on a shuttle that can move along the x- and y- directions at each level, independently of the movements of other loads at the same or other levels, as long there is an empty space next to the load.

Crane-based compact storage systems lack flexibility in the volumes they can handle, whereas vehicle-based compact storage systems using lifts instead of cranes enhance the flexibility of vehicle-based systems (created by adding or removing shuttles) with the space efficiency of compact storage. They consist of multiple tiers of multiple-deep storage lanes, each of which holds one type of product. The loads in a lane are managed using a last-in-first-out (LIFO) policy unless the retrieval is allowed from both sides.

3.2 Design Variables

The throughput time and the cost performance of compact storage systems depend on several design variables. For example, the number of lanes, the depth of each lane, the number of tiers, the speed of vertical transfer, type of shuttle (shuttles self-powered to move in one direction (x-axis) or both directions (x- and y axis)), number of cross-aisles, number of vertical transfer systems, the location of the load/ unload point, the dwell-point of the shuttles, i.e., the location where a vehicle without job is parked, the acceleration and deceleration of the shuttles, cranes, elevators, and transfer cars affect the performance. Analytical models may be an attractive option to narrow the set of potential set of configurations (see Tappia et al., 2015).

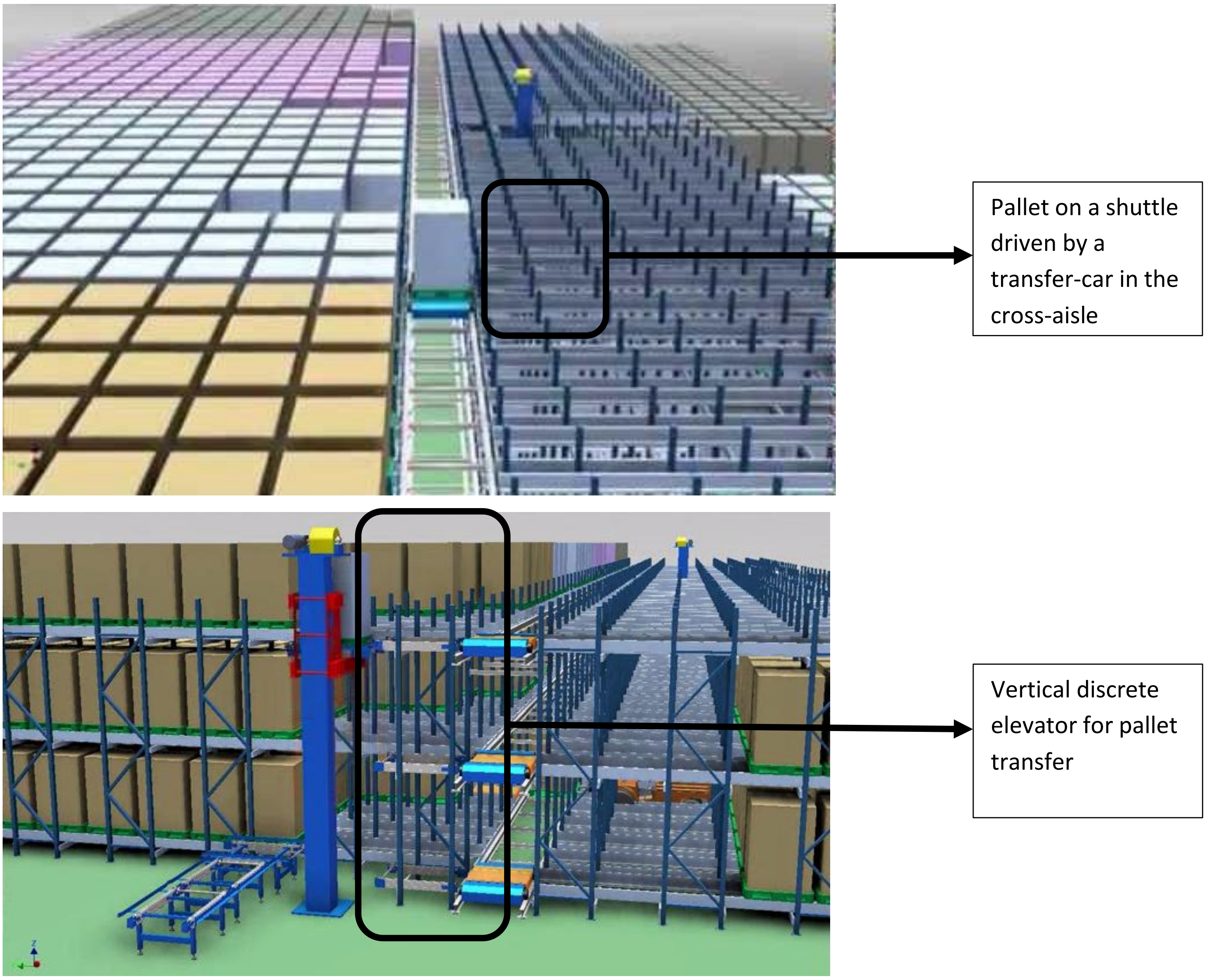

Figure 2: A tier of a vehicle-based compact storage system (top) and the vertical transfer system (bottom). In this figure the horizontal movement uses both transfer cars and shuttles. (source: Total solution provider group, https://www.youtube.com/watch?v=TYbxHBZ8KDk)

4. Analytical Models: An Attractive Alternative to Simulation

During the design conceptualization phase, material handling designers would like to evaluate many possible design configurations based on the demand profile, storage time of the pallets, retrieval time windows, and other key performance indicators for food products handling. There are multiple design variables that need to be optimized to maximize the performance in the multi-deep compact storage systems. For example, the number of storage positions per lane, the length of the cross-aisle, number of shuttles (see Section 3.2). Typically, analytical models are very useful for design conceptualization phase i.e., to reduce the design search space and identify few potential configurations for detailed simulation. The design conceptualization phase has room for tolerating a certain error percentage in the estimates, since these serve only as rough estimates. Analytical models are not only computationally less expensive but they also allow for easy enumeration of design parameter settings. Detailed simulation typically takes more than 3 months to develop a new design, and about 1-2 weeks for small changes in design configuration (for example a change in lane depth).

In sum, analytical models offer an attractive option to reduce the design search space and arrive at potential design configuration choices. The design configurations chosen from the analytical model are then subjected to detailed simulations for obtaining accurate performance measures and fine tuning the configuration settings.

Analytical models can also provide design insights such as which type of shuttle optimizes the throughput time? What is the advantage of one system over another in terms of throughput capacity? What is the effect of multiple shuttles in a single tier on throughput time performance? What is a good dwell point for shuttles? What is a good layout dimension for such systems?

Similar studies have been done in the context of single-deep lane vehicle-based storage and retrieval systems using analytical models. Roy et al. (2012) studied the effect of horizontal and vertical partitioning of the system into storage zones and dedicating vehicles to each zone. They found that horizontal partitioning of a tier into two to three zones is better in terms of throughput time performance because it balances between the transaction waiting times for vehicles and the travel time for vehicles. In terms of vertical partitioning, Kumar et al. (2014) found that vertical partitioning of tiers into two zones (zone 1 consisting of tier 1 and zone 2 including the remaining tiers) minimizes the overall transaction throughput time. Note that the vehicles that need to access tier 1 do not need to use the vertical elevator and hence their movement can be restricted to tier 1. Optimal zoning can yield throughput time reductions up to 30%.

5. System benefits and conclusions

Several companies that have implemented multi-deep lane compact storage system have reported benefits from such system implementations. For example, Gehl Foods

(Germantown, WI, USA), a manufacturer of dairy products, implemented Westfalia's 6-11 deep compact storage automated storage and retrieval system (AS/RS) in a 7m high warehouse. The system has three levels, 6 cranes and space for 10,000 pallets. They saw a 300% increase in storage space on the same footprint in comparison to single deep storage. While crane-based and vehicle-based compact storage give almost identical storage capacity, a vehicle-based system substantially increases the throughput capacity of the system.

Likewise, Suncup Juice (www.suncupjuice.com) uses AS/RSs in its high-bay deep freeze warehouses. These have 10-deep storage positions. They significantly reduced travel time by workers, wrong picks, and product and rack damage with automated material handling solution. The stacker cranes can go three pallets deep with a telescopic fork and, additionally, the satellite unit can store or retrieve a pallet 12m deep into the rack. Suncup uses aisle-changing cranes. Further, the cranes can generate electricity from lowering their lift carriages, using their motor as a generator. The system also generates energy from friction when braking downwards, which can account up to 40% of the AS/RS total power usage.

In sum, automated compact storage systems hold tremendous promise for food products storage and handling from both the perspective of throughput flexibility and sustainability.

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