Fraunhofer IML

Efficient solutions for high-density pallet storage: A detailed comparison of

Pallet Flow and Pallet Shuttle Rack Systems

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Introduction

Motivation and objective

In the dynamic and constantly evolving world of intralogistics, it is of great importance to make well-informed decisions when selecting technologies for a specific application. This whitepaper examines two rack systems for high-density storage: the Pallet Flow System and the semi-automatic Pallet Shuttle System. Both solutions cover a similar range of applications and offer different advantages and disadvantages through their functions and mechanisms. In addition to budget considerations, relevant factors for technology selection include throughput requirements, operational strategies, and product or industry-specific requirements. Often, the degree of automation is also highlighted as a key consideration in decision-making. However, automation alone should not be the sole reason for implementation. It should be justified by other factors such as increased efficiency or reduced operating costs. The goal of this whitepaper is to comprehensively compare both technologies and present the strengths, limitations, and application opportunities of each storage system. Furthermore, decision-makers will be provided with meaningful examples of technology implementation through a calculation model.

Methodology

This study is based on insights gained in semi-structured expert interviews with vendors of both technologies, the Fraunhofer IML employees' expertise, supplementary literature research, and a developed calculation model for validation and presentation of the results.

Table of contents

1. Technologies

1.1 Overview

Both the Pallet Flow and Pallet Shuttle systems are classified as "high-density storage systems". In contrast to conventional single or double-deep rack systems with "direct access", these systems offer the advantage of utilizing the available space more efficiently. By storing numerous pallets densely in channels, they significantly reduce the number of required aisles.

The channel depth (i.e., the number of pallets stored behind each other) varies greatly depending on the use case and technology. A storage system typically consists of one or more storage blocks, with each storage block comprising multiple channels arranged side by side and on top of each other. The relevance of high-density storage is evident from the variety of applications found in almost every industry. An overview of best-practice examples is provided in Appendix 1.

1.2 Pallet Flow System

The Pallet Flow system is characterized by the use of mechanical roller conveyors for transporting pallets within the channels. With a 4% incline of the roller conveyors, gravity is utilized to transport the pallets from the input to the retrieval point. Typically, the pallets are transported longitudinally, but in exceptional cases (with significantly more effort), transportation in the transverse direction is also possible

As shown in Figure 1, the main components of a Pallet Flow channel include: the rack structure, conveyor roller, brake rollers, pallet centering rails, exit beams or pallet stops (stopping mechanisms or pallet push-through protection), and optionally, pallet retainers. Foldable roller conveyors can also be used to facilitate maintenance work. These are moveably fixed on one side of the channel but can be released and folded open on the opposite side, similar to a door.

The rack structure and conveyor rollers are largely of industry standard. Depending on the type of pallets used, the dimensions of the rack structure and the width of the rollers can be adjusted.

The brake rollers control the speed of the pallets in the rack. They are configured to the pallets' weight to provide the optimal braking force. The number of brake rollers per channel is defined by the channel depth. Another component that enhances safety and ensures gentle transport of the palletized goods is the pallet retainer. Employing these devices in certain intervals reduces the ram pressure on the individual pallets.

The Pallet Flow system offers the possibility to operate according to both, the FIFO (First-In, First-Out) and LIFO (Last-In, First-Out), principles. Following the FIFO principle, the rack is served from two opposite sides - pallets are feed from one side and retrieved from the other side. In contrast, following the LIFO principle, pallets are loaded and unloaded from the same side of the rack. In this case, the roller conveyor is inclined towards the transfer point. Hence, a forklift, that wants to store a pallet, needs to push the storage channel's entire contents, which are under ram pressure, against the inclination. When a pallet is retrieved, the remaining pallets roll towards the retrieval point. Due to the ram pressure that needs to be overcome, the maximum possible channel depth with the LIFO principle is usually six to eight pallets.

A Pallet Flow System

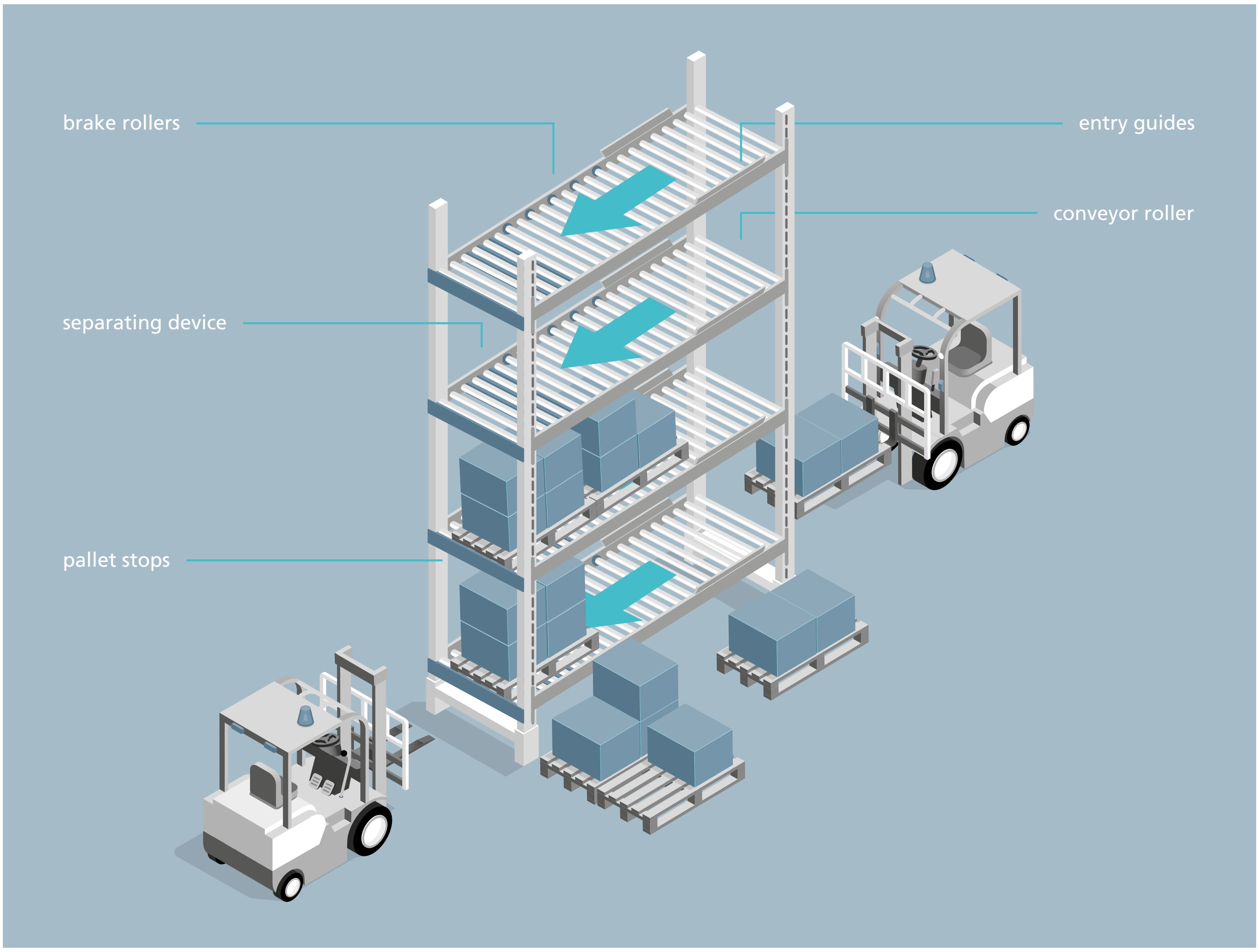

Figure 1: A Pallet Flow System (FIFO)

1.3 Pallet Shuttle System

The Pallet Shuttle System is a semi-automatic, high-density storage solution for handling pallets within rack channels. Unlike the Pallet Flow system, this system does not rely on gravity but instead utilizes the shuttle technology. The shuttle vehicles operate (semi-) automatically within the channels and transport the pallets. It does not require a material-intensive steel roller construction and hence no inclination. The functionality of the system is illustrated in Figure 2.

As shown in Figure 2, the main components of the Pallet Shuttle System include the rack structure, shuttle vehicles, and guiding rails beneath each rack channel. Built-in sensors and mechanical safeguards ensure precise positioning and process reliability.

The system is typically used for Euro pallets. The shuttle's design limits the range of suitable pallets.

The shuttle also influences the direction in which the pallet is conveyed. The pallets are being transported in the lateral direction and a pickup from the load carrier's side is required for storage and retrieval.

The shuttle is controlled using a remote control or a tablet, depending on the shuttle's configuration and the provider. The control unit is worn directly on the body or attached to the forklift. After placing the shuttle in the channel, the operator can activate various functions using the remote control. The most common functions include "picking up a certain number of pallets at the starting point and delivering them to the end of the channel" or "filling or emptying entire channels". Modern systems also offer functions such as counting pallets in a channel for inventory or performing condensing.

The storage process is as follows:

1. A shuttle vehicle is placed in the corresponding channel using a forklift.
2. Then, a pallet is placed over the shuttle's guiding rail at the transfer position.
3. The operator initiates the storage command, upon which the shuttle lifts the pallet, moves to the next available position, and drops the pallet.
4. Afterwards, the shuttle returns to the transfer position, where it picks up the new pallet and automatically places it in the rack.
5. This process is repeated until only the transfer position is left vacant. The shuttle is removed from the channel and the last pallet is placed in the channel by the forklift.

The retrieval process is carried out in reverse order. Simultaneous storage and retrieval within a channel are possible. However, they result in significant throughput capacity limitations since typically only one shuttle is used per channel.

Using the remote control, the operator can switch between multiple shuttle vehicles and can thus work on multiple channels in parallel.

Since the Pallet Shuttle System does not rely on gravity, the storage and retrieval points can be flexibly defined. Both the FIFO and LIFO principles can be applied as storage and retrieval strategies if there is access to both sides of the rack. With single-side access, only the LIFO principle can be applied. Unlike the Pallet Flow system, there is no defined maximum channel depth from a technical perspective.

A Pallet Shuttle System

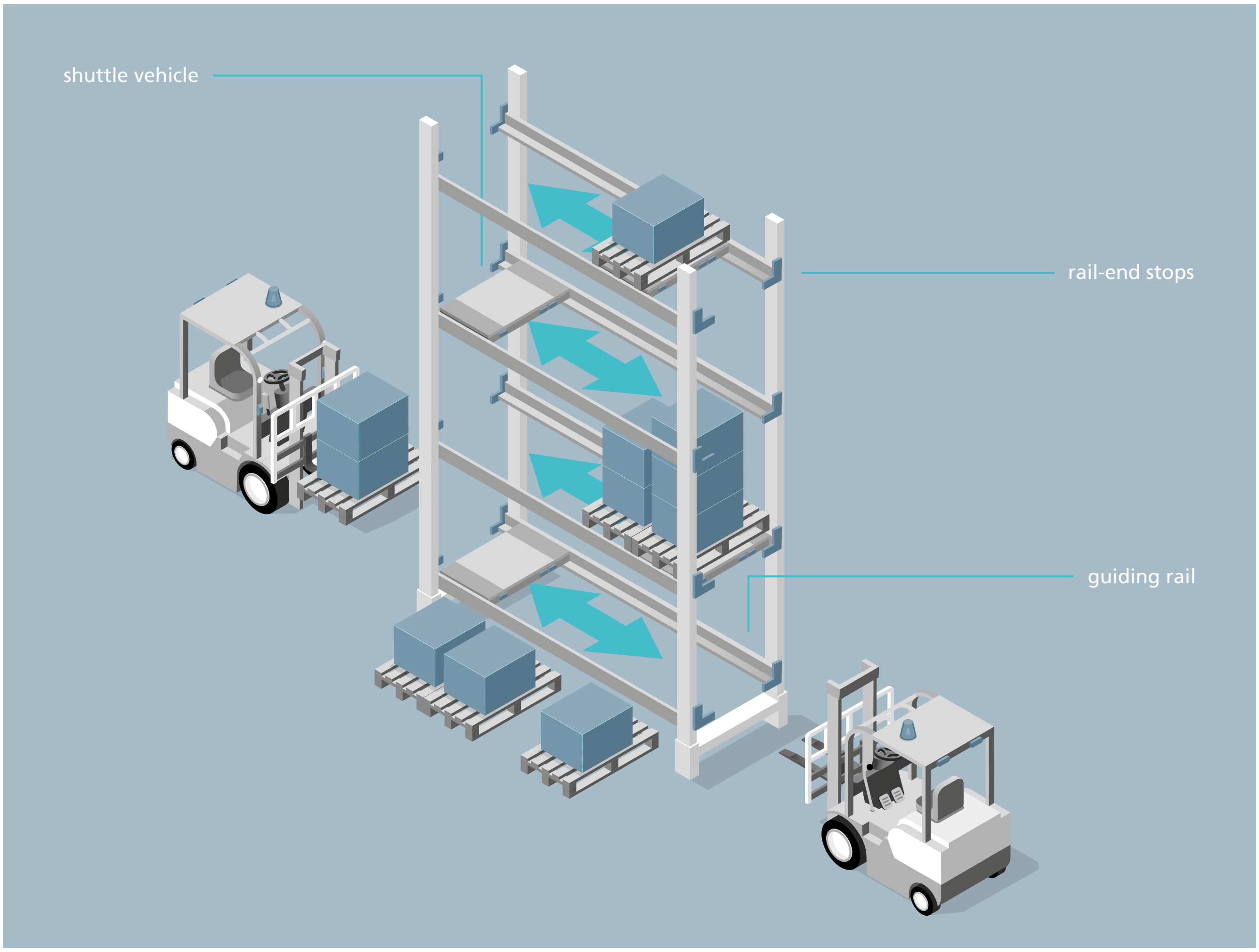

Figure 2: A Pallet Shuttle System

2. Comparing the technologies

After the introduction of both storage systems, they will now be compared and discussed based on relevant qualitative and quantitative factors.

2.1 Qualitative factors

The qualitative factors can be divided into the following eight focus areas: required condition of the conveyed goods and load carriers, space requirements, process integration, automation potential, external influences, availability, safety, and sustainability.

2.1.1 Required condition of conveyed goods and load carriers

Both technologies require a minimum level of load carrier quality and load securing. Defective or poorly secured pallets can quickly lead to costly disruptions in the rack. Due to the high physical impacts on the pallets during transportation on the rollers, it is important, especially in the Pallet Flow technology, to use suitable load carriers. The gentle transport of the pallets on the shuttle vehicle allows for more flexibility in terms of pallet quality.

For sensitive goods, the "gentler" transport can be a pro-argument for the Pallet Shuttle System. By setting an appropriate minimum distance between the pallets in the channel, contact can be avoided. In the Pallet Flow System, a distance between the goods can only be ensured if the goods do not exceed the pallet dimensions.

In addition to the quality of the pallets, other characteristics of the load carriers are also crucial. Due to the dimensions of the shuttle vehicle, the Pallet Shuttle System is more restricted in terms of the load carriers' dimensions compared to the Pallet Flow System. However, the shuttle technology allows for the transport of plastic or metal Euro pallets without any restrictions. The brake rollers in the Pallet Flow System, on the other hand, require a higher friction, which is only partially met by plastic or metal. Therefore, handling metal and plastic pallets requires a technical adaptation or a process adaptation, such as transferring the pallet onto one made of more suitable material. Special coated brake rollers are used to increase the grip in these cases.

2.1.2 Space requirements

An essential argument for integrating a compact storage system into one's intralogistics is the efficient use of space. Therefore, both systems can be rated as very good in terms of space requirements. Despite slight differences in the construction of the racks and the differing transport of the load carriers within the rack, the space consumption of both systems is nearly equal, when dimensioned comparably.

However, a significant difference still exists - the orientation of the pallets. As described in Chapter 1, within the channel, pallets are typically transported longitudinally in the Pallet Flow system and lateral in the Pallet Shuttle system. For an identical dimensioning of the storage, a Pallet Flow system requires less width but has a greater channel depth. Conversely, in the Pallet Shuttle system the reverse is true for the same number of pallet locations. Depending on the use case and spatial conditions, one technology has advantages over the other.

2.1.3 Process integration

Looking at the whole logistics system, both rack systems need to be integrated into upstream and downstream processes. Therefore, a comparison regarding the procedural integration is also useful.

Besides the core processes, such as pallet injection into the channel and subsequent retrieval, the Pallet Flow system does not require any additional process steps. It thus allows for a very streamlined operation of the rack. The pallets are transported longitudinally within the rack, which eliminates the need for additional handling in many use cases.

The use of the shuttle vehicle in the Pallet Shuttle system results in a higher procedural effort. In addition to supplying and retrieving pallets from the rack, there is additional work involved in managing the shuttle vehicles themselves. This includes moving the shuttle vehicles between the storage channels, transporting the shuttles to the charging stations and back to the rack, as well as rotating the pallets before storage and after retrieval. The latter is necessary when upstream or downstream processes do not allow for pick up on the pallet's longitudinal side.

2.1.4 Automation potential

Both systems provide opportunities for integrating complementary automation technologies with the respective rack system.

In practice, the supply for the Pallet Flow system is increasingly performed by automated storage and retrieval systems (AS/RS) or automated guided vehicles (AGVs). The corresponding retrieval of pallets from the roller conveyors is also possible, given that the pallet's accurate positioning on the roller conveyor in the channels is ensured.

Numerous solutions already exist for the automation of the Pallet Shuttle system, especially in combination with the use of AGVs. However, it should be noted that the synchronization between the shuttle and, for example, an AGV is not trivial, depending on the required process and material flow. Reductions in the throughput capacity may occur if the pallet transfer between the shuttle and AGV is not aligned. Additionally, the AGV must be able to handle a transversely oriented pallet, as otherwise an intermediate step for rotation after the Pallet Shuttle system is required.

2.1.5 External influences

Both Pallet Flow and Pallet Shuttle are established on the market and have been in use at numerous logistics sites for an extended period. As a result, the providers have a wealth of experience which allowed them to further develop the technologies and to design them to be highly robust.

Both technologies can be implemented at temperatures ranging from -30°C to 50°C without significant hardware modifications and with only minor additional costs. Similarly, there are no special requirements regarding humidity. However, if shuttle devices switch between different storage zones with varying humidity and temperatures, problems may occur during the transition, such as fogged or ice-covered sensors.

Cleanliness, maintenance, and careful handling of the system has a significant impact on the components' longevity and the susceptibility to disruptions. In both systems, attention should be paid to the fact that left behind garbage or hanging parts, such as packaging materials or wood residue from a pallet, can cause the pallet or shuttle to get stuck in the channel.

However, a much more frequent cause of damage to the system is the operating personnel. In the case of the Pallet Flow system, most defects to the roller conveyor or the rack structure occur at the channel transfer points due to the forklift forks. Pallet retainers are particularly vulnerable in this regard.

In the Pallet Shuttle, disruptions in the shuttle operation due to contamination or misalignment of sensors and light barriers can occur more frequently.

2.1.6 Availability

In line with the previous chapter, it should be noted that both technologies can achieve a high level of availability given the proper maintenance and care.

In the Pallet Shuttle system, the loss of productivity due to a shuttle's charging time or failure can be offset by acquiring multiple vehicles and thus creating redundancy in the system.

In the event of disruptions in the Pallet Flow system, usually only the disturbed channels are affected. Neighboring channels might be influenced too if they are needed to retrieve the pallet. The operation of the remaining system continues.

Maintenance and inspection work should be scheduled during planned maintenance windows or periods of low demand. They are an essential factor for the availability and safety of both systems.

2.1.7 Safety

Both systems are typically equipped with sufficient safety devices to protect people and goods. The safety standards comply with common norms and regulations, at least in the European region. However, it is important to note that the functionality of safety devices is only guaranteed if they are properly maintained and serviced. In the Pallet Shuttle, the focus should be on the sensors and their cleanliness to minimize errors and safety risks. The same applies to components of the Pallet Flow system, such as the pallet stops.

2.1.8 Sustainability

The topic of sustainability is gaining increasing importance in intralogistics.

During operation, the Pallet Flow technology scores points as its pallet movement driven by gravity, resulting in no energy consumption. Additionally, it avoids the use of batteries and other electronics.

In contrast, Pallet Shuttle systems have a lower steel consumption since no additional roller conveyor technology is installed for this storage technology.

2.2 Quantitative factors

The quantitative factors can be divided into the following three focus areas: throughput capacity, investment costs, and operating costs.

2.2.1 Throughput capacity

An important metric for technology comparison is the throughput capacity, especially considering peak load.

The attainable throughput is influenced by various factors. Both the configuration of the rack system (such as the channel depth, the number of storage levels, or the number of shuttle vehicles) as well as the upstream and downstream processes are relevant. For this whitepaper, a calculation model has been developed. It considers various influencing factors and allows for a generalized comparison of both technologies through numerous configuration variations. An overview of the model and its assumptions can be found in Appendix 2.

Capacity deviations in all scenarios

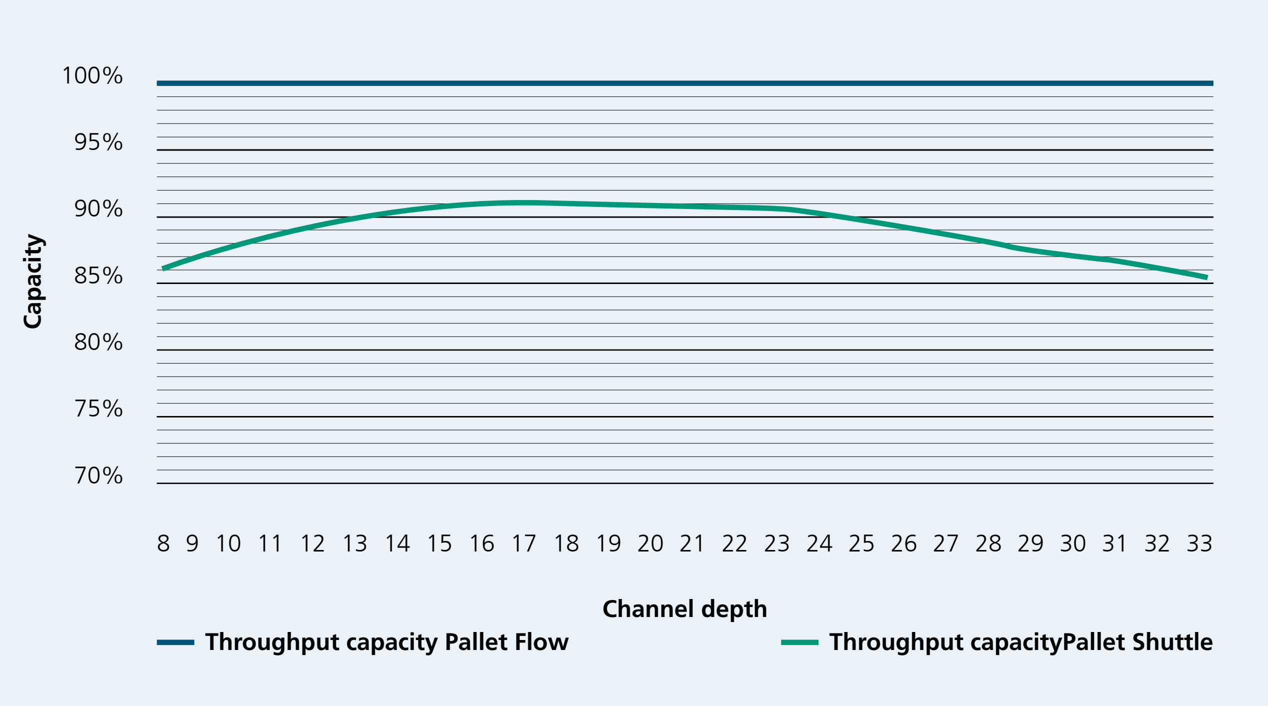

Figure 3: Capacity deviations in all scenarios

As can be seen in Figure 3, a Pallet Flow system generally allows for a higher throughput than a Pallet Shuttle system in every comparable configuration. This is due to the nature of their operation. The transport of pallets within the rack in the Pallet Flow system is continuous and decoupled from the forklift. Therefore, the throughput of the system is determined solely by the number of forklifts used for storage and retrieval. The continuous and uninterrupted transport of the pallets can be represented by a straight line, as the channel depth does not affect the throughput capacity. However, the storage block's height or width directly influences the throughput and shifts the line along the Y-axis.

In contrast, the throughput graph for the Pallet Shuttle system is curved. Due to the interaction between the forklift and the shuttle vehicle, different waiting times arise depending on the configuration. A shallow channel depth results in the shuttle vehicle needing to be relocated more frequently, impacting the throughput significantly, as shown in Figure 3. Moreover, the throughput capacity of the Pallet Shuttle system declines with increasing channel depth, as the deeper the channel, the longer the shuttle takes to travel the distances within the rack. The longer travel time results in waiting time for the forklift wanting to pick up or deposit a pallet. This reduces the overall throughput capacity of the rack system.

In summary, based on the calculation model of Fraunhofer IML, the Pallet Flow system's throughput capacity is between 9% and 15% higher than that of the Pallet Shuttle system, assuming a common channel depth of 8 to 33 storage locations. This calculation does not consider simultaneous storage and retrieval of pallets within the same channel. In that case, the throughput capacity of the Pallet Shuttle system is significantly reduced. Only when the shuttle vehicle is used to completely fill or empty a channel, the throughput capacity is not affected by frequent relocations of the shuttle.

2.2.2 Investment costs

Investment costs are often a significant factor in decision-making. When comparing the costs per storage location of common configurations in isolation, the Pallet Flow technology is usually the more expensive alternative.

For the Pallet Flow system, the investment costs increase almost linearly with each storage location. This is because each storage location includes both, the rack construction and the roller conveyor technology. The Pallet Shuttle's rack construction is cheaper due to the absence of the roller conveyors. However, there are additional costs for the shuttle vehicles. Therefore, the price per storage location in the Pallet Shuttle technology varies greatly depending on the system configuration.

If the previously discussed throughput capacity is important, the isolated consideration of investment costs can be put into perspective. By calculating a cost-throughput coefficient, the difference between the technologies can be illustrated. This coefficient indicates the cost associated with storing a single pallet. For example, for short channels, a "throughput capacity unit" of the Pallet Flow system is significantly cheaper, as shown in Figure 4.

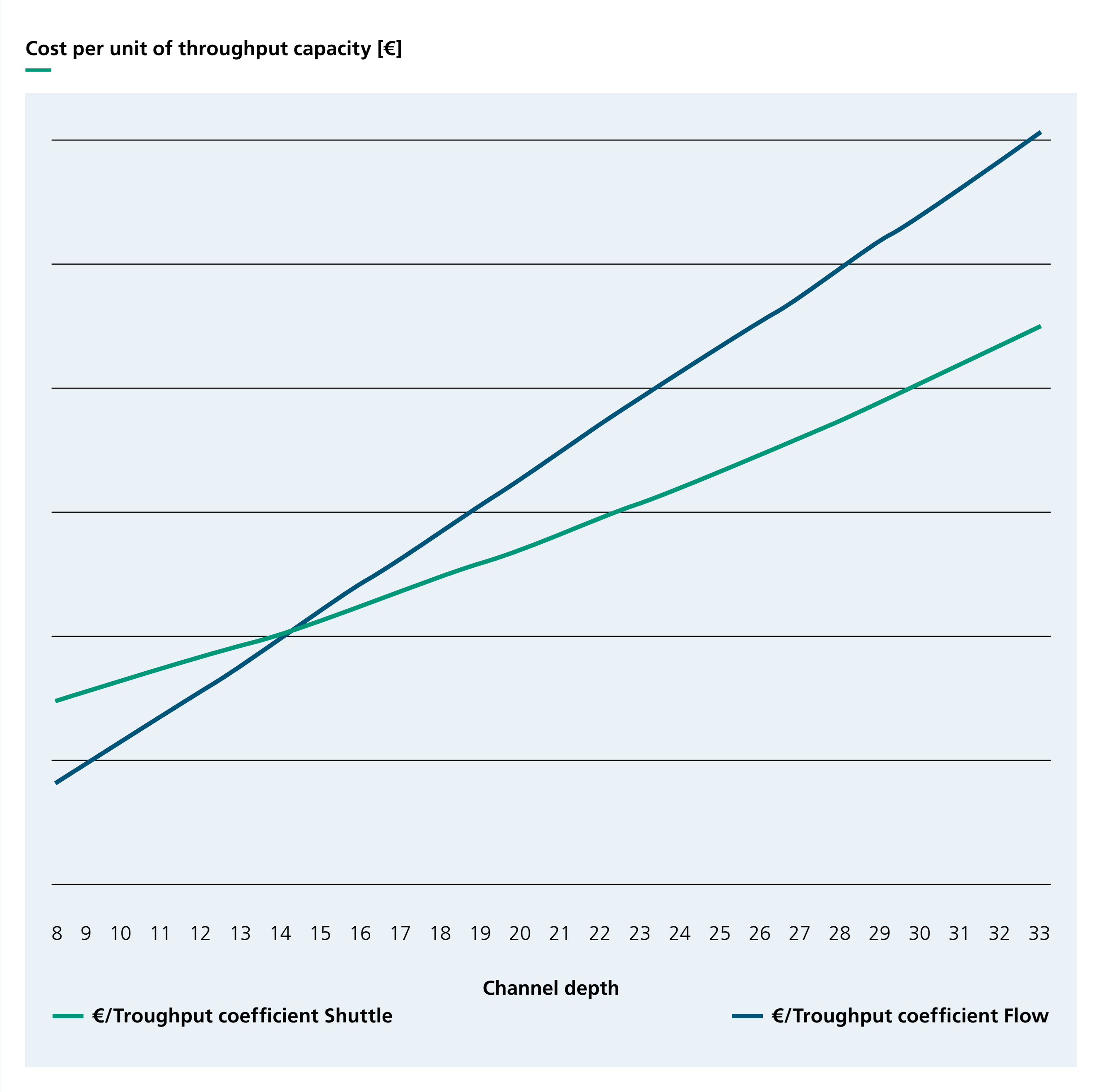

Figure 4: The cost-throughput coefficient

This can be explained by the significantly higher throughput capacity of the Pallet Flow system and the relatively high investment costs per storage location in the Pallet Shuttle system. The costs for shuttle vehicles have a strong impact on the Pallet Shuttle's overall cost. Pallet Shuttle systems with a small number of storage locations are rarely competitive in terms of costs.

As the channel depth increases and thus more storage locations are available, the relationship shifts, as shown in Figure 4. From a channel depth of about 15 pallets, a throughput capacity unit in the Pallet Shuttle system can become more cost-effective. With a larger number of pallet storage locations, the costs of shuttle vehicles become less significant. Furthermore, the development of the Pallet Shuttle's throughput capacity (Figure 3) reduces the costs per throughput capacity unit.

This described trend of the cost-throughput coefficient is also depicted in the following Figure 5. It shows the positive deviation of the coefficient for both systems. As mentioned above, for shorter channels the coefficient for the Pallet Flow system is up to 29% more cost-effective. From about 15 storage locations per channel, this relationship reverses, and the Pallet Shuttle system achieves a cost-throughput coefficient that is up to 20% more favorable.

Average deviation of the cost-throughput coefficient for Pallet Flow and Pallet Shuttle Systems

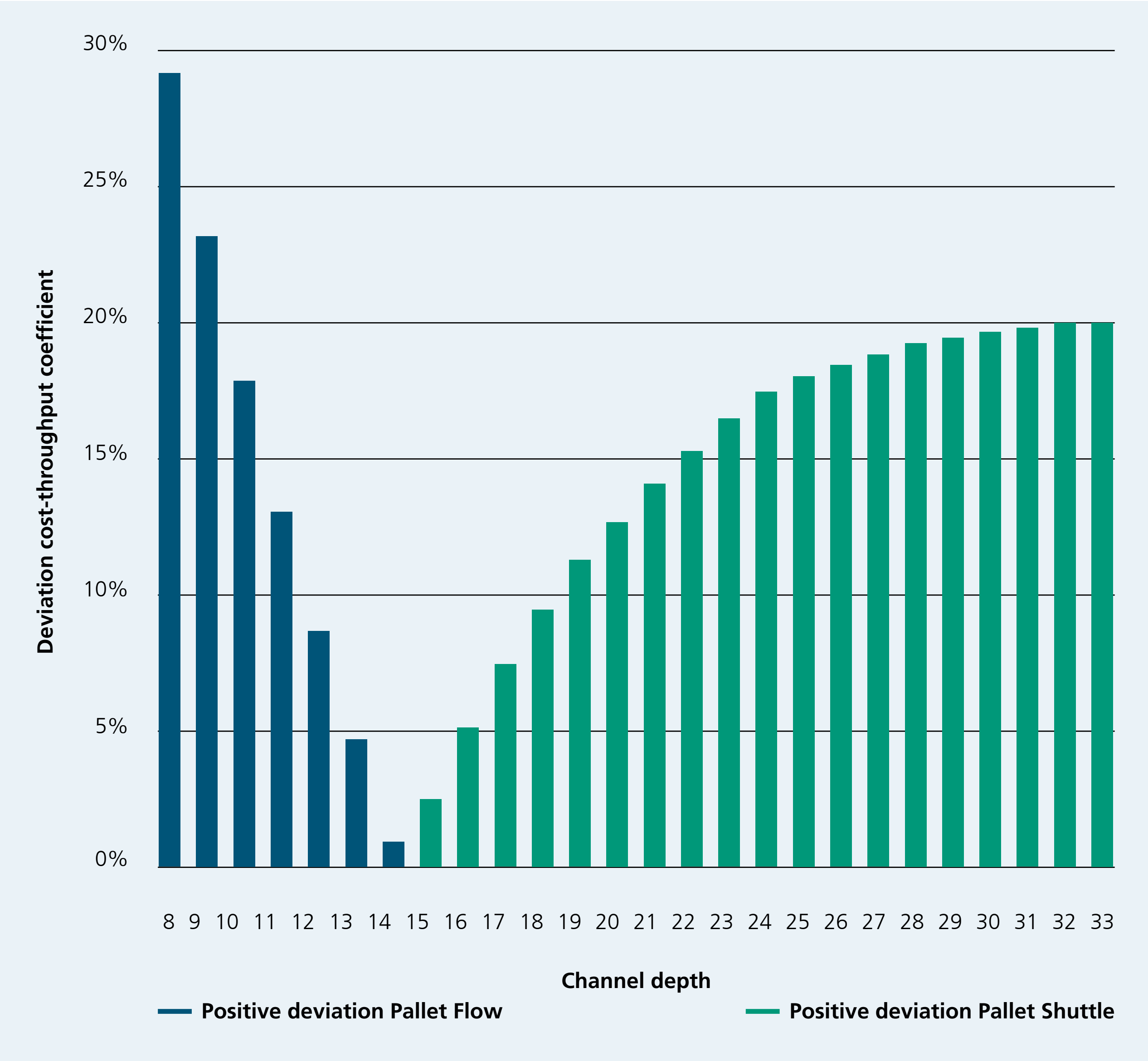

Figure 5: Average deviation of the cost-throughput coefficient for Pallet Flow and Pallet Shuttle Systems

2.2.3 Operating cost

Although investment costs are often in focus, companies should also consider the importance of operating costs in their decision-making process. Over a longer period, the operating costs can change the initial cost advantage of one system significantly.

To provide a comprehensive view of costs, a calculation model was established using average values of common warehouse configurations. Both the investment costs and operating costs were determined for a 15-year period. Operational costs include annual service and maintenance of the facility, which are relevant for both technologies. In addition, Pallet Shuttle-specific expenses such as shuttle vehicles replacements, after 5 to 8 years, and battery replacements, after approximately 1,000 charging cycles, were considered. Furthermore, energy costs for operating the shuttle vehicles were included. To facilitate better comparison between the technologies, the calculation model was based on the same throughput volume. Hence, higher personnel costs in the Pallet Shuttle technology are considered as the process and waiting times are longer.

The overall cost development for both technologies is summarized in Figure 6. Despite significantly higher investment costs, the Pallet Flow technology can convince by lower operating costs in the long run. The point at which the two total cost curves intersect varies for each specific case. Numerous individual factors come into play, making it necessary to analyze each case individually. As described in the previous paragraph, these factors include the system's availability due to maintenance, as well as additional process times due to pallet rotation and the geographical location of the site. In particular, the latter point can lead to significant uncertainties, when quick response times and spare parts are required during disruptions. Especially in the case of the Shuttle system, availability is directly dependent on the shuttle vehicles. Therefore, adequate redundancies must be ensured (see 2.1.6), and a failure concept must be in place, as otherwise, high costs may arise from disruptions. As depicted in Figure 6, the outlined aspects lead to diverse trajectories in the cost development of the systems, necessitating individual examination in each case.

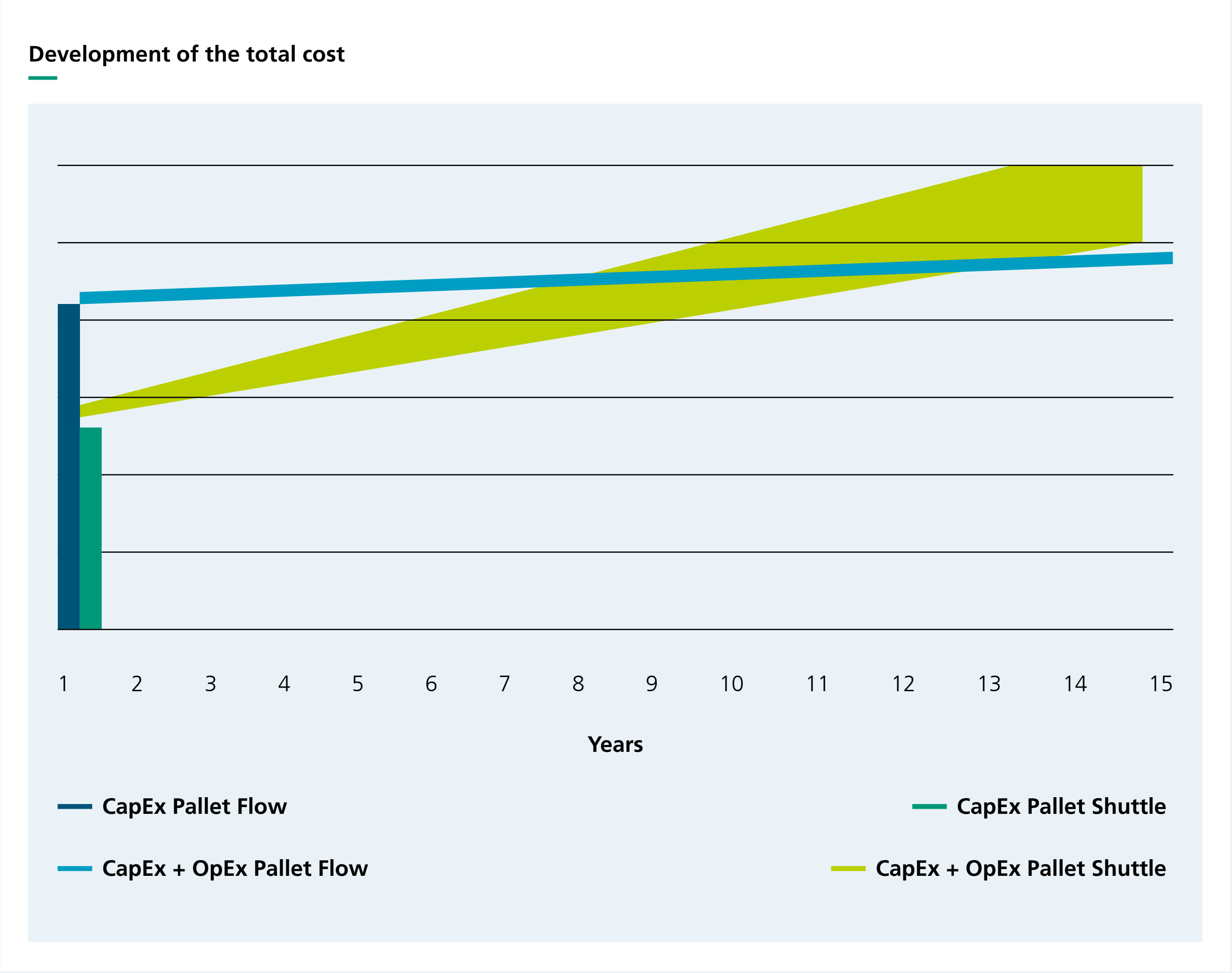

Figure 6: Development of the total cost (based on the Fraunhofer IML's calculation model)

3. Conclusion

As evident in the previous chapters, both technologies have different strengths and weaknesses, making the recommendation for a system heavily dependent on the specific scenario. The following Figure 7 summarizes the key factors and rates the technologies accordingly.

The indications shown in Figure 7 provide an initial tendency for each specific factor. A scale from zero to three is used, with zero corresponding to the lowest level and three to the highest level, indicating the greatest advantage of that technology.

Strengths and weaknesses

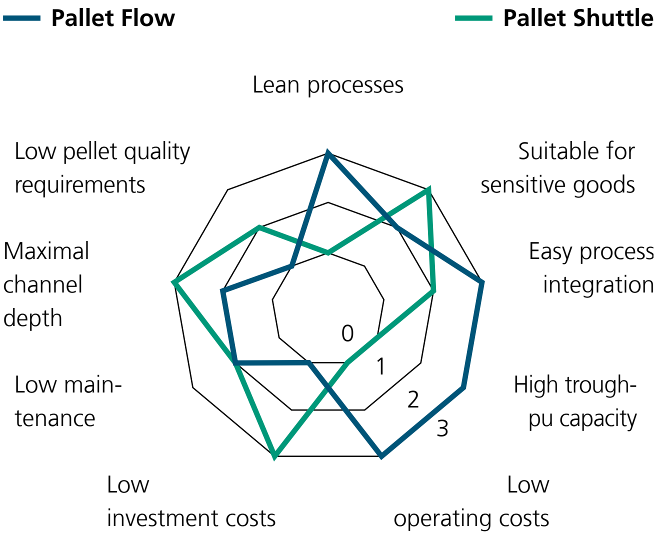

Figure 7: Summary of strengths and weaknesses of Pallet Flow and Pallet Shuttle Systems

Sweetspots
In most cases, Pallet Flow systems are the preferred choice from a technical and process perspective. They are characterized by a high throughput capacity, an easy integration into the other warehouse processes, and lean processes. These advantages are reflected in lower operating costs, compared to other systems.

The Pallet Flow system is particularly suitable for companies with high throughput and material flows that have a continuous longitudinal pallet alignment. Typically, channel lengths of up to approximately 14 pallet storage locations are suitable for this type of system.

Pallet Shuttle systems distinguish themselves by their low initial investment costs and are the preferred choice for very large storage systems. The system is especially suitable for storage areas with lower throughput requirements and long channels. Additionally, the Shuttle system is used when goods need to be stored for longer periods and require gentle handling.

This system is particularly suitable for companies that want to store numerous pallets of the same product type with a comparatively low investment, and where the cross-alignment of pallets does not pose a disadvantage for material flow.

Summary
Both systems, with proper maintenance, cleanliness, and adherence to pallet quality standards, provide robust and durable solutions for high-density pallet storage. They also offer significant opportunities within the context of integration with automation technologies.

Furthermore, these technologies do not necessarily exclude each other. The strengths of both systems can be combined in a hybrid construction. For example, the lowest level could be designed as a Pallet Flow system, while the upper levels could be configured as a Pallet Shuttle system. This way, pallets with high a throughput can be handled in lean processes on the lowest level during peak times. The upper levels can be utilized for pallets with lower turnover rates, resulting in lower investment costs.

Before deciding on the system to be used, logistics processes, the desired operational lifespan, and the availability of services for each technology should generally be thoroughly examined. The combination of traditional logistics technology and automation technology will also play an increasingly significant role. Therefore, the ongoing development in the AGV market should also be considered in future planning.

4. Appendix

Appendix 1 - Best Practice Examples from the Industry

Food Industry
Storage and picking of perishable goods, such as fruits, vegetables, or dairy products. The FIFO principle allows for optimal and efficient flow of goods.
The high-density storage enables efficient space utilization in frozen/cold storage facilities.

Beverage Industry
Acceleration of storage and picking processes through quick access to large quantities of pallets in conjunction with a high-density storage

Consumer Goods
High-density storage for household products, cosmetics, or electronics ensures efficient picking and space utilization, and enables fast delivery of products.

E-Commerce
The ability to handle high throughputs and to manage large quantities of goods easily enables meeting short delivery times for online orders.

Automotive Industry
Storage of parts and components maintaining a FIFO structure and ensuring an organized material flow. This is the basis for efficient supply to assembly lines.

Chemical Industry/ Production
High-density and fast storage of large pallet quantities of the same product from a batch.

Appendix 2 - Model for Throughput Calculation

Methodology and Assumptions
A calculation model with a largely comparable basis for both technologies was developed. The assumptions were made to enable a realistic and general comparison. The model represents the smallest possible (meaningful) storage unit to allow for simple extrapolation to larger use cases. Certain model parameters were defined as fixed values, while the factors, that were analyzed, are variable.

The following fixed values define the model:

- A rack block consisting of ten channels side by side (in width) is considered.
- The rack is operated by a forklift. In the case of Pallet Shuttle technology, it is also assumed that one forklift continuously serves one shuttle (1:1 assignment). However, a second shuttle to ensure availability is considered in the costs.
- Manufacturer-independent technical parameters are used for both the forklift and the shuttle.
- The model does not include simultaneous storage and retrieval in the system/channels. In this case, the Pallet Shuttle technology is not competitive with Pallet Flow systems in terms of storage/retrieval throughput capacity.

The following (examined) variable values are considered in the model:

- The number of rack levels includes the values 1, 3, and 5.
- The channel depth ranges from 3 to 50, with the higher values being more theoretical in nature and only relevant for the investigation. For the final presentation of the results, the value range has been specified as 8 to 33.
- The distance between the pallets' origin and the rack (average distance for the forklift) includes the values of 10m, 20m, and 30m.

Average market prices (2023) were used for the monetary evaluation of the technologies.

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