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Transshipment Point Design – Enabling Cooperative Vehicle Routing

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Efficient loading and unloading of trucks is a key challenge in logistics, where long turnaround times and space constraints often limit system performance. Existing solutions either focus on full truckload automation from the rear or rely on forklift-based side access, both of which lack the flexibility and space efficiency required at transshipment points. To address this gap, this paper introduces a novel concept for autonomous side-loading and unloading of boxed pallets using an overhead crane system. The prototype integrates standardized industrial components with custom-designed load handling devices and an AI-based control system capable of detecting, localizing, and handling boxed pallets without human intervention.

In addition to the technical realization, an analytical performance estimation model is developed to quantify travel times and reshuffling operations during pallet transfers. The model explicitly accounts for load security requirements, which distinguish truck-based reshuffling from warehouse-based multi-deep storage systems. Results provide a framework for evaluating the efficiency of the proposed system and offer insights for the design and operation of future automated transshipment points.

[Keywords: autonomous Trucks, Vehicle Routing, Transshipment Points]

1 Introduction

Efficient loading and unloading of trucks is a critical challenge in modern logistics and supply chain management. With the continuous growth of e-commerce, just-in-time production strategies, and globalized trade, the pressure on logistics nodes such as transshipment points has increased substantially. Truck turnaround times directly affect overall supply chain performance, influencing costs, delivery reliability, and resource utilization. As a result, automation of truck loading and unloading processes has received growing attention in both industry and academia.

Current technological solutions in this domain, however, exhibit clear limitations. Existing automatic truck loading systems are capable of handling full truckloads rapidly but operate exclusively from the rear of the truck and are limited to complete batch operations. They lack the flexibility to autonomously handle single pallets, particularly when side access is required. Alternatively, automated forklifts can provide side loading but require large operational space, which makes them unsuitable for compact transshipment facilities. To date, there is no space-efficient automated system that can flexibly load and unload trucks from the side.

Parallel to these technological developments, research on storage and retrieval systems has made significant progress in modelling and analysing system performance. Analytical and simulation-based approaches have been developed for double-deep and multi-deep storage systems, focusing on travel times, throughput, and reshuffling operations. While these insights are valuable, they predominantly address warehouse environments such as automated storage and retrieval systems (AS/RS), shuttle-based systems (SBS/RS), or robotic compact storage systems (RCS/RS). These systems typically require reshuffles only when a blocking load must be removed to access a target item. In contrast, truck-based transshipment operations introduce additional complexity: due to load security requirements, reshuffles may also be necessary after retrieval to ensure stability of the remaining load. This fundamental difference calls for new operating strategies and adapted performance models.

This paper addresses these gaps by introducing a novel concept for automated side-loading and unloading of boxed pallets at transshipment points. The proposed system integrates an overhead crane prototype equipped with AI-based perception and control, enabling fully autonomous handling of boxed pallets between trucks. The system is designed to combine space efficiency with operational flexibility, offering a scalable alternative to conventional solutions. Beyond the technical design, a performance estimation model is developed to quantify travel times and reshuffling requirements, thereby providing analytical insights into system behaviour.

This paper is organized as follows. Section 2 reviews the relevant literature on transshipment points. Section 3 presents a detailed description of their functionality and structural characteristics. In Section 4, we outline the methodology for estimating the throughput of transshipment points. Finally, Section 5 summarizes the findings and concludes the paper.

2 Literature

This section is divided in two parts. First, an overview of automatic truck loading and unloading systems is given. And second, the literature of performance analysis for storage systems such as trucks with double-deep storage of pallets and boxed pallets is given. This section concludes with the research gaps.

First, there are different systems available on the market which can all load and unload a full truck load in relatively short time [1][2][3]. These systems have in common that they can be operated in an automatic mode but only from behind the truck. It is not possible to load and unload single pallets with these systems. An alternative to load and unload pallets and boxed pallets from the side of a truck are (automated) forklifts [4]. However, these forklifts have the disadvantage that they need relatively large space compared to crane based systems. To sum up, there are automatic systems which can efficiently load a full truck load and there are forklift-based systems which can operate a truck from the side. But there is no system on the market which can autonomously load and unload trucks from the side while being space efficient.

Second, the literature for double- or multi-deep storage systems and the performance estimation of such systems is diverse. An extensive literature review is provided by Azadeh et al. [5]. Furthermore, there are travel time and throughput models for multi-deep systems available from ,multiple authors in the last years [6][7][8][9]. However, all this work focus on storage systems such as automated storage and retrieval systems (AS/RS), shuttle based storage and retrieval systems (SBS/RS) or robotic compact storage and retrieval systems (RCS/RS). These systems have in common, that reshuffles are only necessary when a blocking load must be reshuffles before another load can be picked. In trucks, there are additional requirements such as Load security making reshuffles necessary after retrieval, when a load has no load in front of it any more. This makes a new operating strategy necessary which will be introduced in this paper.

3 Structure and Functionality of Transshipment Points

Each transshipment point consists out of one overhead crane system inside a hall or similar building. The hall must be able to house two trucks at the same time and ensure enough space for manoeuvring of the crane. The layout is described in Section 3.1. The crane is described in Section 3.2 and is able to pick one boxed pallet at a time from the side of a truck. It than can either change the boxed pallet to the other truck or rearrange the boxed pallets in the one truck. The transshipment points ensure an autonomous storage and retrieval of boxed pallets, which is ensured by AI supported control system (see Section 3.3). Figure 1 illustrates, that the load handling device of the crane will pick boxed pallets from the side of a truck. It also shows that trucks are able to transport up to 68 boxed pallets, because boxed pallets can be stacked above each other.

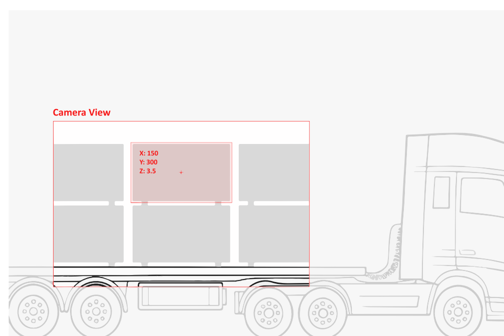

Figure 1: Side view of a truck with two boxed pallets stacked above each other.

3.1 Layout

The layout of the transshipment point is shown in Figure 2. Two trucks are parked next to each other and the overhead crane is operating in the space between the two trucks. Only one side at a time can be operated by the overhead crane. If both sides of a truck must be operated, the truck has to drive outside of the hall and enter it again. With this operating pricicple, the footprint of the transshipment point (and thus also the cost) can be limited to 220 m^2.

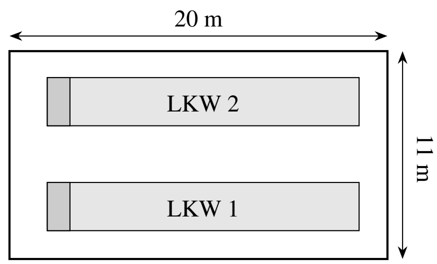

Figure 2: Two trucks in a hall of the transshipment point.

3.2 Overhead Crane Prototype – Structure and Components

The developed prototype crane combines standardized industrial components with custom-designed parts, demonstrating a hybrid of proven technology and application-specific engineering. Structural elements, guide systems, bearings, and connectors are integrated with both commercial modules (e.g., Eepos, Stahl Crane Systems (SCS), SEW, Siemens) and in-house designed brackets and adapter plates to ensure optimal fit within the crane assembly.

The following sections describe the main subsystems and their functions: bridge crane (Section 3.2.1), trolley (Section 3.2.2), fork (Section 3.2.3), guide system (Section 3.2.4), sensor technology (Section 3.2.5), and drive systems (Section 3.2.6). Figure 3 shows the complete crane prototype from two different angles.

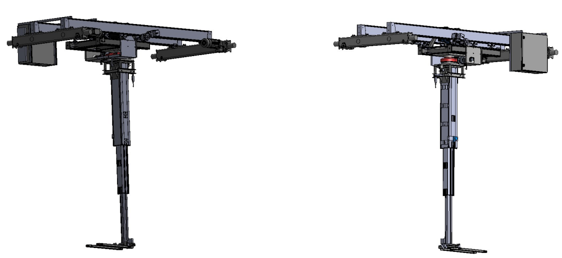

Figure 3: 3D drawings of the crane prototype.

3.2.1 Bridge Crane

The double-girder bridge crane is built from two parallel aluminium profiles (Eepos) that form the primary load-bearing structure. At both ends, these profiles connect to end carriages (SCS), which house the travelling gear and support the bridge.

The connection between profiles and end carriages is realized through precision-formed steel plates welded to the end carriages. The aluminium beams are inserted into these pockets and bolted, creating a rigid, backlash-free joint for reliable force transfer.

3.2.2 Trolley

The trolley frame is assembled from lightweight aluminium profiles (Eepos), providing the base structure for suspended trolley wheels that run inside the bridge profiles. A custom-designed cross beam (traverse) is integrated into the frame to mount the DC-Com chain hoist (Demga). This ensures a central load pickup, secure force transfer, and stable operation during lifting.

3.2.3 Fork (Load Handling Device)

The fork is a custom-built attachment designed specifically for boxed pallets (600 $\times$ 800 mm). It is constructed from hollow profiles for strength and low weight, connected to the telescopic lifting axis (Eepos) via an adapter plate for secure force transmission. Integrated proximity sensors in the fork tips and sidewalls detect obstacles and support collision-free insertion into pallet openings, ensuring both safety and precise automated operation.

3.2.4 Lifting Axis and Guide System

The crane uses a 3-stage telescopic lifting axis (Eepos), enabling a compact design with extended vertical reach. The nested aluminum profiles provide high stiffness and smooth, backlash-free motion. Key features include:

- Grooved side profiles for easy attachment of sensors or brackets with T-slot nuts.
- Low-maintenance linear guidance for uniform motion.
- Integrated rotary unit (servo-driven swivel joint) that allows controlled pivoting of the fork.

3.2.5 Sensor Technology

A comprehensive sensor system enables safe, precise, and automated control:

- **Optical sensors** (SICK) on the fork for obstacle detection and pallet guidance.
- **Wire-draw encoder** (SICK) on the lifting axis (2500 mm range, SSI interface) for vertical position feedback.
- **Absolute positioning system** (VAHLE) for horizontal bridge tracking.
- **Limit switches** (SCHMERSAL) to safeguard rotation end positions.
- **Cross switches** (Telemecanique) to define end stops for trolley and bridge travel.

- **Depth camera** (Intel RealSense) on the fork for 3D environment mapping, supporting navigation and fine positioning.

3.2.6 Drive Systems

The prototype employs a mix of servo drives, geared motors, and frequency inverters for smooth, precise motion:

- **Bridge Travel** (SCS + Magnetek): AC motors with integrated brakes, controlled by inverters (Magnetek) for variable speeds, smooth acceleration, and reduced wear.
- **Trolley Travel** (SEW + Eepos): SEW geared motor with friction wheel system; inverter-controlled for speed regulation and accurate positioning.
- **Hoisting** (Demag DC-Com 500): Chain hoist with 500 kg capacity, two lifting speeds, integrated into the lifting axis.
- **Swivel Drive** (Custom + Servo): Servo motor on a custom bearing frame for precise fork rotation, with end positions safeguarded by limit switches.

3.3 Control System and AI-Based Image Recognition

The prototype crane integrates all drives, sensors, and safety devices into a central PLC- and motion-control architecture. Parameters such as speed profiles, ramp functions, and safety limits are software-configurable, ensuring flexibility for experimental automation and autonomous operation.

3.3.1 PLC-Based Control

The control system is built on a Siemens S7 PLC, which connects and coordinates all electrical and mechanical elements—sensors, motors, and actuators—through industrial fieldbus protocols (PROFINET, SSI). Additional Beckhoff and WAGO modules extend the system via custom-built control cabinets and software blocks.

The PLC processes motion commands across four axes:

- **X-axis:** Bridge travel (longitudinal movement along the Eepos track).
- **Y-axis:** Trolley travel (transverse movement).
- **Z-axis:** Lifting motion of the fork via telescopic axis.
- **α-axis:** Rotational motion of the fork via the swivel drive.

Motion commands are executed via frequency inverters, which allow smooth speed control and enable combined diagonal movements by synchronizing multiple axes. Position feedback from encoders and sensors is processed in real time to avoid collisions and ensure safe operation.

3.3.2 Image Recognition System

At the heart of the automation is an Intel RealSense depth camera, which continuously captures RGB and depth images (640 $\times$ 480 pixels at 30 fps). The visual input is processed by a YOLOv11-based object detection model, trained on annotated datasets of mesh box pallets under varying lighting and environmental conditions.

- Hardware: Nvidia RTX 4060 GPU for training and inference.
- Model Input: 640 $\times$ 640 pixel frames.
- Output: Bounding boxes with object center, width, and height.

The system fuses bounding box data with depth information, enabling precise spatial localization of pallets in three dimensions (X, Y, Z).

3.3.3 Hardware–AI Integration

The data pipeline operates as follows:

1. Intel RealSense camera delivers synchronized RGB and depth frames.
2. YOLOv11 detects pallet boxes and generates bounding boxes.
3. Depth information is combined with bounding boxes to compute real-world coordinates (X, Y, Z).
4. Coordinates are sent via the Siemens S7 interface to the PLC.
5. The PLC translates these into motion commands for the crane along the X, Y, Z, and α axes.

This integration allows the crane to autonomously align itself and pick pallets with high accuracy.

3.3.4 System Architecture and Web Interface

The overall software architecture is based on a .NET 9.0 backend and a Vue.js frontend, communicating via WebSockets:

- The backend processes camera data, executes YOLOv11 detection, and streams results.
- The frontend visualizes the live video feed, overlays bounding boxes in real time, and displays distance and position information (horizontal/vertical midpoints, depth in meters).

This setup provides both autonomous control and transparent operator feedback for monitoring and validation of crane operations.

4 Performance Estimation

The transfer of one boxed pallet at a transshipment point consists out of the following movements and sums up to the travel time of a transfer of an order t_{order}:

1. The load handling device drives from an idle point to the position of the boxed palletin the first truck (t_{Idle}).
2. If a boxed pallet is unloaded from the first truck and is blocked by another boxed pallet, these boxes must be reshuffled first. This leads to either no or one reshuffle and in average β reshuffles will be necessary. Any reshuffle has the following time components which sum up to t_β: First the load handling device drives to the reshuffle boxed pallet (t_{quer}), then the load handling device picks the reshuffle boxed pallet (t_h), followed by driving to the new position (t_{quer}) and the load handling device drops reshuffle boxed pallet (t_h).
3. For every boxed pallet in an order (γ boxed pallets are in an order) we have to transfer, the following steps are executed: First the load handling device picks the boxed pallet (t_h) then the load handling device drives to the new position in the second truck ($t_{transfer}$) and finally the load handling device drops boxed pallet(t_h).
4. The load handling device drives back to the idle point (t_{Idle}).

The total expected travel time for the transfer of an order is $E(t_{order})$ and can be calculated with:

$$E(t_{order}) = 2 \cdot t_{Idle} + E(t_\beta) + \gamma \cdot (2 \cdot t_h + t_{transfer}) \quad (1)$$

$$E(t_\beta) = \beta \cdot (2 \cdot t_{quer} + 2 \cdot t_h) \quad (2)$$

t_h is a given parameter the variables t_{Idle}, t_{quer}, $t_{transfer}$, and β can be calculated as follows. t_{Idle} is the average distance the crane has to cover from the idle point which is in the middle between two trucks and any position in the truck, which yields in $t_{Idle} = \frac{1}{4} \cdot \frac{length_{truck}}{v_{truck}} + \frac{v_{truck}}{a_{truck}}$. The time t_{quer} is the average time the crane needs from one position in the truck to any other position in the truck and can be calculated with $t_{quer} = \frac{1}{3} \cdot \frac{length_{truck}}{v_{truck}} + \frac{v_{truck}}{a_{truck}}$ [10]. $t_{transfer}$ is t_{quer} plus the time the load handling device needs to rotate t_{rotate} to be able to serve the second truck (t_{rotate} is a given parameter).

β is the share of old orders (ω) multiplied with each old order (μ) and the average number of boxes per order (γ). These boxed pallets block boxed pallets of earlier orders and must be unloaded before the earlier order can be executed:

$$\beta = \frac{\omega}{\mu} \cdot \omega \cdot \gamma \quad (3)$$

5 Conclusion and Outlook

This paper introduced a novel concept for the autonomous side-loading and unloading of boxed pallets at transshipment points. By integrating an overhead crane prototype with standardized industrial components, custom-designed load handling devices, and AI-based perception and control, the system enables flexible, space-efficient operations that current solutions cannot provide. In contrast to existing rear-loading systems or forklift-based side access, the proposed approach supports autonomous pallet-level handling under compact spatial conditions.

To complement the technical realization, a performance estimation model was developed that captures travel times and reshuffling requirements in truck-based operations. The model extends established analytical approaches from warehouse storage systems by explicitly considering load security requirements, which necessitate additional reshuffles after retrieval. In doing so, it provides a more realistic representation of truck transshipment processes and enables quantitative evaluation of system efficiency.

Future work will focus on applying this model to identify and evaluate use cases for automated transshipment points. By linking performance estimates with operational data from logistics networks, promising application scenarios can be derived in which the proposed system offers significant benefits over conventional handling methods. This will support both system design decisions and the strategic integration of autonomous transshipment points into larger supply chains. It also enables us to develop sophisticated split delivery vehicle routing problem with transshipment (SDVRP-T).

REFERENCES

[1] TRAPO GmbH, "Autonome Lkw Be- und Entladung," https://www.trapo.de/produkte/fahrerlose-transportsysteme/autonome-lkw-be-und-entladung/, 2025, accessed 9.11.2025.

[2] S. L. GmbH, "LKW Beladesystem – Maximiert die Ladevorgänge," https://simply-logistic.com/produkte/lkw-beladesystem/, 2025, accessed 9.11.2025.

[3] CLSi Logispeed (Complete Logistics Systems international GmbH), "Logispeed expresslader – das automatische lkw-verladesystem

für das europaletten-handling," https://clsi-logispeed.de/produkte/logispeed-expresslader-2/, 2025, accessed 9.11.2025.

[4] enabl Technologies GmbH, "enabl – Autonomes Materialhandling / Material Handling as a Service," https://www.enabl-tech.de/de, 2025, accessed 9.11.2025.

[5] K. Azadeh, R. De Koster, and D. Roy, "Robotized and automated warehouse systems: Review and recent developments," *Transportation Science*, vol. 53, no. 4, pp. 917–945, 2019.

[6] M. Eder, "An analytical approach for a performance calculation of shuttle-based storage and retrieval systems with multiple-deep and class-based storage," *Production & Manufacturing Research*, vol. 10, no. 1, pp. 321–336, 2022.

[7] T. Lehmann and J. Hussmann, "Travel time model for multi-deep automated storage and retrieval systems with different storage strategies," *International Journal of Production Research*, vol. 61, no. 16, pp. 5676–5691, 2023.

[8] J. Marolt, N. Kosanić, and T. Lerher, "Relocation and storage assignment strategy evaluation in a multiple-deep tier captive automated vehicle storage and retrieval system with undetermined retrieval sequence," *The International Journal of Advanced Manufacturing Technology*, vol. 118, no. 9, pp. 3403–3420, 2022.

[9] P. Trost and M. Eder, "A performance calculation approach for a robotic compact storage and retrieval system (RCS/RS) serving one picking station," *Production & Manufacturing Research*, vol. 12, no. 1, p. 2336056, 2024.

[10] R. Manzini, R. Accorsi, G. Baruffaldi, T. Cennerazzo, and M. Gamberi, "Travel time models for deep-lane unit-load autonomous vehicle storage and retrieval system (AVS/RS)," *International Journal of Production Research*, vol. 54, no. 14, pp. 4286–4304, 2016.

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