Assessing the performance in automated loading and unloading of autonomous trucks and the implications for the logistics system

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Abstract
The logistics industry is changing due to the introduction of autonomous trucks (ATs). Although there are many promising benefits associated with ATs, there is a limited exploration into automating the loading and unloading (L/UL) process that was performed manually. However, for autonomous transport to be fully realized, the L/UL processes at shipping and receiving facilities must also be automated. Despite automation being a solution to address the challenges, the broader impacts of automating L/UL are not well explored. This study assesses the effects of automating L/UL with AT on a broader system level using context-intervention-mechanism-outcome logic (CIMO).

Keywords: Autonomous trucks, Loading and Unloading, Performance evaluation

Introduction
The impact of electrification and automation in the logistics sector is evident with widespread transformation occurring in the field (Dong et al., 2021). One such transformation is the development and introduction of autonomous trucks (ATs) for

freight transport. ATs serve the purpose of connecting supply chain nodes such as warehouses and terminals, enabling new possibilities and potential benefits for the transport of materials. The potential benefits include economic, environmental, and social factors, together with higher transparency in the supply chain, and the presumed ability to carry out 24/7 operations (Engesser et al., 2023).

Having ATs in operation will only automate the transport itself, but to fully realize some of the stated benefits, it is necessary to also automate some of the related activities. One such activity is the process of loading and unloading (L/UL) the goods. The L/UL is currently in most cases performed manually by the truck driver (Fritschy and Spinler, 2019), or manually by personnel at the sending or receiving facilities. However, in the case of ATs there is no driver physically present who can perform the L/UL activity. Also, considering the ongoing development towards increased automation in warehouses and production processes, there may not be personnel available at the sending or receiving facilities either. Additionally, a development towards automation of L/UL may be promoted also by conditions such as a shortage of workforce and increasing volumes of goods handled (Dekhne et al., 2019).

The removal of the truck driver or warehouse operators will require the L/UL to be performed by help of automation. This may have other benefits as well, as manual L/UL processes are prone to goods damage and accidents (Carlan et al., 2023). In combination with AT, automating L/UL holds the potential to improve flows in terms of shorter truck turnaround times, and minimized disruptions (Kersten et al., 2017).

Despite the potential benefits of automating L/UL, especially considering the emerging transition to AT, industrial development has been slow and research initiatives supporting such development have been few. A possible reason for this could be the lack of clarity regarding expected performance when such automated solutions are implemented.

Previous research on automated L/UL evaluates the performance of individual hardware components such as sensors and load handling mechanisms (Doliotis et al., 2016), as well as the overall performance of an automated L/UL solution (Stoyanov et al., 2016). Furthermore, these studies evaluate the performance of automated L/UL solutions within controlled environments such as laboratories, thereby making actual impact assessment under regular operating conditions difficult. Also, existing literature indicates a gap between the benefits that are stated to be expected from implementing such automated solutions and published evidence justifying these statements. An example is the statements from Mörth et al. (2020) that states automated solutions are expected to improve truck turnaround times, minimize disruptions and associated handling costs. On the contrary, Cao and Dou (2021) state that automated L/UL solutions have low operating speeds.

A possible reason for this limited understanding of performance could be the complexities present within and between organisations involved in the automated process, limiting in capturing the system-wide benefits. Irrespective, knowledge regarding performance, expected benefits and any negative effect of implementing automated L/UL solutions becomes essential for making informed decisions.

Therefore, the purpose of this paper is to identify the potential performance impacts of automating L/UL in the context of AT on the logistics system. The significant contribution of this study lies in providing an understanding of the validity of benefits mentioned in automated L/UL and AT literature such as efficiency, safety, and 24/7 operations. This paper is based on the information gathered using a single case (detailed below) that involves the use of automated L/UL solutions in the context of ATs.

Research Design

Design Science Approach

Studying the impact of new solutions where the theoretical concepts and problem contexts are yet to be structured proves cumbersome from a methodology perspective (Khajavi et al., 2018). Handfield and Melnyk (1998) stated that such problems where knowledge is still in its developing phase could be handled by using exploratory and descriptive approaches. Design science research (DSR) methodology in such cases comes in as a solution for developing knowledge to solve real-life field problems that are still developing (Denyer et al., 2008). DSR combines methods from exploratory case studies in organizing the collaboration of researchers with industrial practitioners. By doing this, the DSR methodology helps in explicitly developing an "artifact" that can be used as a decision-making tool or a framework.

To structure the DSR and to develop actionable knowledge, this study follows the Context, Intervention, Mechanism, Outcomes (CIMO) framework (Denyer et al., 2008). The CIMO logic provides information on what actions to take (intervention), in which specific situations (context), with some understanding of the underlying reasons (mechanisms), and what outcomes are expected (outcome) (Pawson and Tilley, 1997). Therefore, the CIMO-logic allows for a comprehensive understanding of both the social and technological components of a system that, in turn, enables researchers to enhance system performance in practice (Denyer et al., 2008).

As the objective of this study is to assess the performance efficiency of automated L/UL of ATs and its implications for the logistics system, the DSR approach using CIMO logic is adopted. This method helps in identifying outcomes from the introduction of automated L/UL solutions, outcomes from the introduction of ATs, and outcomes resulted from the introduction of both automated L/UL and AT. This understanding can explain how interventions such as the use of automated L/UL for ATs can improve performance and the mechanisms that trigger such an outcome.

Case Study Approach

Case studies aid in capturing the complexities of the studied research object and include an in-depth investigation of an event (Yin et al., 2012). The case addressed is a unit, entity or phenomenon that is governed by boundaries defined by a researcher, limiting what will or will not be studied (Gaya and Smith, 2016). By performing such investigations, case studies can aid as an inspiration for new ideas and new theory development (Thomas, 2011).

This study uses a single case study approach to analyse in depth how the implementation of automated L/UL solutions, when using AT, can influence performance, to reveal a deep understanding of requirements, material flow, information flow etc., and capture the interests of various parties involved in the process.

The choice of a single case study approach is further justified by three aspects pointed out by Yin (2009). First, the case being unique, thereby adding to the limited literature of system-level performance evaluations. Second, the context of the case being typical, meaning that lessons learned are assumed to be informative to a broad set of actors. Third, the rationale of the case being a revelatory case is sufficed since the authors had an opportunity to physically observe and analyse the implementation of an automated L/UL solution along with AT.

Data Collection

Data were collected throughout a two-year research and innovation project that involved researchers and industry parties, including a provider of ATs, a provider of automated materials handling equipment, a provider of load-securing solutions, and a company within the mechanical engineering industry at which the automated L/UL operation is intended to take place. Data were gathered in various ways, mainly by observations at site, regular project meetings, semi-structured interviews with single actors, and during pilot tests that involved the use of automated L/UL solutions and AT which is under development. The study involved collecting data in various steps. i) Collecting secondary data collected from literature reviews that supported in identifying and understanding the potential benefits that automated L/UL solutions and ATs provide. ii) Primary data collection by participating in project meetings, analysing project documents, mapping various flows in the system via direct observations and conducting semi-structured interviews.

While the introductions of the AT and the automated L/UL solutions were not permanent and not fully integrated into existing processes, this study utilizes the pilot to assess the implications of a permanent transition to automated L/UL of ATs. The study thereby considers two simultaneous, highly interrelated changes: both the introduction of automated L/UL and the introduction of ATs operating between a production facility and a nearby warehouse.

Interviews and observations provided an understanding of both the current system and the potential advantages the future AT system could provide, thereby also enabling the identification of requirements set by the interaction between various sub-systems. Participating in a pilot study aimed at testing the developed automated L/UL solutions. The tests enabled an understanding of the feasibility of adopting ATs and automated L/UL in the targeted operation at the participating mechanical engineering company.

The professionals involved in the development process were senior professionals, having extensive experience within their respective fields. This comprised, e.g., the senior logistics manager of the mechanical engineering company, the senior lead innovation engineer of the materials handling solution company, a project manager of the AT company, a senior project manager of the load-securing solutions company, and senior researchers working in the field of logistics for more than 10 years.

Data Analysis

The problem addressed (*context)* includes internal and external factors that influence behaviour, organizational settings, uncertainty, and system interdependencies (Denyer et al., 2008). In this study, the *context* is the transition occurring in the current transport setup, from manual transport and handling operated by a truck driver to ATs and AGVs for L/UL, to overcome the difference in operation times existing between the transport and the nodes. The nodes are operating 24/7 but the transport operates only for 15 hours a day. The transport getting automated, the environment that this transformation generates, with the absence of a driver who is involved in many activities (such as L/UL), is the context addressed. The reason we say this is to make a proper comparison between the existing transport setup (driver-operated transport and L/UL) and the future transport setup (ATs and AGVs).

The *intervention* is aligning the operation of the transport setup (i.e. AT) with the shifts at the nodes by introducing automated L/UL solutions to handle L/UL operations in the absence of a truck driver who is generally responsible for these operations.

The *outcome* is the performance expected from the implementation of automated L/UL solutions with AT on the logistics system.

The *mechanism* provides the logic as to how the intervention causes a certain outcome in a particular context such as reduced inventory, shorter lead times, improved profits, etc. The generative mechanisms are determined by identifying the capability that automated L/UL poses, which aids in achieving improved performance when used with AT.

As an outcome of this intervention, we see the combined implementation of AT and automated L/UL solutions enhances the overall performance of the logistics system. This coheres with the statement of Denyer et al. (2008), stating that outcomes encompass various aspects fostering effectiveness and efficiency.

Applying the CIMO Logic on the Case

This section analyses the case using the CIMO logic and explores its various aspects. In this course, the section presents the main topics that emerge from the analysis.

Context

The mechanical engineering company addressed in this study is a manufacturing company that exports its products globally. Partly in response to the rising production volumes, the company has adopted a high level of automation, both in the manufacturing processes and in the internal logistics processes. This case study focuses on the flow of finished goods from the highly automated factory to a nearby warehouse, located around 1 km from the factory.

The company faces a problem with its existing setup for transporting manufactured products from the factory to the nearby warehouse. Though the production facilities and warehouses operate 24/7 (3 shifts per day), the transport that connects these facilities within the confined area operates only 15 hours per day (2 shifts). This leads to inventory pileup at the production facility during the nights, especially during peak production volumes. To overcome this problem, the mechanical engineering company anticipated benefits of using AT for 24/7 operations to match the operations of the production facility and warehouse.

Figure 1 illustrates the mechanical engineering companies logistics process occurring from the production of pallets at the production factory, the transport system and a nearby warehouse located at around 1 km to which the pallets are transported. The system boundary considered in this study comprises the outbound flow at the production factory and the inbound flow at the warehouse. The figure also signifies various interfaces involved during the logistics processes including information systems, transport systems and human interaction.

The operations at the mechanical engineering company follow a make-to-stock type of production where products of various types and sizes are produced based on forecasts. Once a production order is received, products are produced and dispatched on pallets to the warehouse. The pallets are produced based on the production orders received on the SAP system. This trigger of producing pallets based on the requirement is fed into the production system as a production order detail. The pallets produced by the production system (not indicated in the figure) arrive on conveyors. All conveyor system, hydraulic systems and AGVs (automated guided vehicle) used for internal material transport in the facility is managed by a PLS system that synchronizes these systems to maintain smooth operations. For example, once the pallets are produced and arrive on the conveyor, this information is sent via sensors to the PLS system which in turn controls the AGVs through a fleet sync system for maintaining the required intralogistics operations. The AGV transports these pallets to a stacking area. At the same instance, the fleet-sync system (that controls the AGVs) also tracks the number of pallets that the AGV has transported and indicates this information through a display to the human operator (driver). The operator based on the information received via the display begins stacking the pallets transported by the AGVs. Pallet stacking is performed manually both based on the intuitive experience of the operator and based on the information identified from a barcode sticker on the pallet indicating whether the pallet is stackable or non-stackable type. Once this is done, the driver scans the pallets to be loaded. This information is sent to the warehouse management system (WMS) available at the warehouse generating an expected receipt information (ERI). Once the pallets are scanned, the operator plans how the pallets need to be loaded into the truck.

Once loading is complete, the driver secures the load and transports the pallets from the production factory to the warehouse. The pallets on reaching the warehouse are unloaded from the truck, scanned, and placed on the floor. The scan during arrival confirms the ERI received and updates the WMS. This confirmation is sent to the SAP, which then pulls orders out of stock as required to fulfil the product demand.

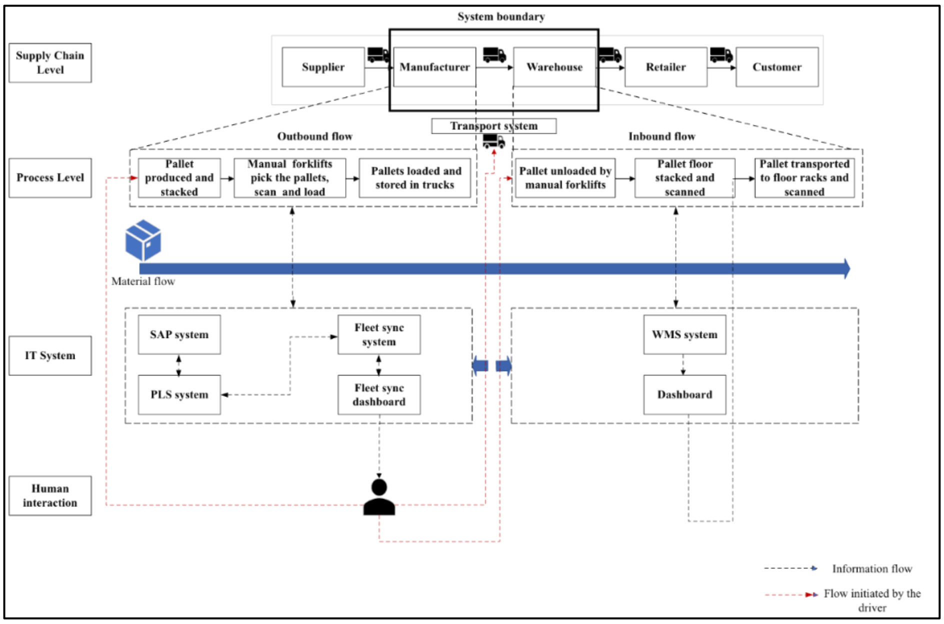

Figure 1- Snapshot of logistics process in the mechanical engineering company

Intervention

The intervention in focus in this study is comprised by the introduction of an AT to replace conventional, manually operated trucks, and the associated introduction of automated L/UL, which was seen as a prerequisite for the introduction of the AT. As described in the methodology section, the two introductions were not permanent but only tested during a pilot.

The objective of the introduction of the AT was to create more continuous flows between the factory and the warehouse, thereby improving the logistics performance. However, the transition in the transport system also required solutions for managing the tasks currently performed by the truck driver, also beyond the driving of the truck. These tasks included the L/UL, and it also included operations such as opening/closing the gates of the truck/facility/warehouse, maintaining material flows, stacking the pallets, load securing and un-securing. Each of these tasks required continuous information exchange, making the management of these information flows crucial to the success of these interventions.

As mentioned in the earlier section, when the transport and L/UL process was done manually, the driver was an interface in initiating the various flows. This involved the driver interacting with the various systems available at the transport, factory and the warehouse to facilitate material flows. However, with the intervention, managing the information flows and material flows in the absence of a driver becomes essential.

This facilitation process involves managing the information flows during the following stages: i) Arrival of the AT: ensuring that the AT has arrived, is safely parked, the loading gates are open and is ready for loading. ii) Loading: ensuring the pallets are prepared and properly loaded into the truck by either completely filling the truck or loading the produced pallets and securing them. iii) Pre-transport checks: confirming that loading and securing has been done properly and the AT is ready for transport to the warehouse. iv) Transportation: Moving pallets from the factory to the warehouse, notifying the WMS system that the AT has arrived (or is going to arrive); the gates are open, and the truck is ready for unloading. V) Unloading: Safely unloading all the pallets from the AT.

The AT solution that was introduced included a remote operator who was able to perform some tasks. By use of a camera system and a remote interface, the remote operator managed the docking of the AT with the loading bays at the sending and receiving facilities to ensure precision. Moreover, the remote operator supervised many processes and initiated activities such as opening and closing of gates as well as L/UL.

The L/UL was performed by a forklift AGV, navigating by use of a laser scanner and reflectors located in the sending and receiving facilities. During loading, the AGV picked up the pallets from a predetermined location within the shipping area of the factory and transported them onto the AT. Once all pallets were loaded, or the AT was full, the cargo was secured on the AT, in anticipation of the transport. Similarly, during unloading the AGV transferred the pallets from the AT to a predefined area. In the preparation of the pilot test, the cargo securing, and un-securing was found to be a challenging task to automate, but by use of careful planning, so that the pallets could be placed in even rows on the AT, it was possible for the AGV to secure and unsecure the pallets on the AT by use of locking bars.

Mechanisms and Outcomes

Based on the pilot test, the transition to an AT and automated L/UL had several impacts on the performance of the production and logistics systems of the mechanical engineering company.

The elimination of a driver to operate the truck presented a clear potential for reducing the amount of manual labour required in the system. During the pilot test, the remote operator was fully focused on the specific case considered in this study. However, the long-term plan for that role, as described by the company developing and operating the AT, is for a single remote operator to manage multiple ATs simultaneously, thereby significantly increasing efficiency from a man-hour perspective.

Another benefit that resulted from the introduction of the AT and automated L/UL was the smoothening of the material flows between the factory and the warehouse. This was an anticipated effect that was part of the motive for introducing the AT, as described in Section 3.1: the introduction of the AT made it possible to run the transports between the factory and the warehouse around the clock, thus aligning them with the operations in the factory and the warehouse.

The fact that the AT could be utilised around the clock also meant that the utilisation w.r.t time is high. The increased utilization according to the mechanical engineering company was critical for the permanent application of the electric AT due to its high investment cost, requiring continuous utilization to be practical.

However, while time utilization could be optimal (up to 100%), the utilization of available space might not be efficient. In other words, although the trucks can operate around the clock, they may not always make the best use of their cargo space. This inefficiency becomes more pronounced when considering volume, indicating that the trucks might not be fully maximizing their capacity in terms of both time and space. This draws us to the fact of taking the benefits spread over the entire logistics system into account rather than solely focusing on the individual performance efficiencies of the AGV forklift or AT for comprehensive improvements.

Continuous operation enhances flexibility and efficiency, addressing the operational complexities, and minimising peak-related system requirements. The continuous flow achieved from the intervention prevents the logistics system from becoming dimensioned to handle peaks (as evident in the existing operating setup) and reducing idle periods during non-functional transport hours. This could help the mechanical engineering company prioritise outbound pallets impacting customer delivery lead times positively.

Additionally, the intervention also impacts the capital costs by reducing the inventory and associated holding costs. Continuous flows minimise warehouse storage time, freeing up tied-up capital stored as inventory and leading to cost savings. Implementing even flows also improves warehouse space utilization, especially during peak production volumes reducing storage needs and influencing capacity requirements at the receiving ends.

Furthermore, the flexibility achieved from the intervention acts as a catalyst for re-evaluating long-standing suboptimal processes. The intervention will require organisations to reassess and potentially redesign their processes to better integrate with automated systems. Consequently, this shift towards automation can enhance efficiency in material handling and logistics operations.

Despite the potential benefits, the study also indicates challenges. One such challenge was the pre-planning of pallets required before loading as the introduction of intervention, i.e. the automation, resulted in the elimination of on-spot decision-making by a driver.

The pilot revealed limitations in the AGV forklift loading capacity and speed compared to manual operations. The loading capacity of the AGV forklift solution used in this study is limited to only placing two rows of pallets owing to handling constraints. Additionally, the L/UL processes, as well as associated processes of for example cargo securing, took considerably longer time to perform in the automated setup compared to the manual setup. Because the AGVs move much slower than the manually operated forklifts, it took one minute to load one stack of pallets (comprising two pallets) onto to the truck with the manually operated forklift, whereas it took close to two and a half minutes in the automated setup. In addition, the cargo securing was more cumbersome and time-consuming in the automated setup. Accordingly, the turnaround times of the AT at the sending and receiving facilities were much longer than those of the manually operated trucks.

Discussion

The paper has provided new insights into the topic of automated L/UL and has thereby made several valuable contributions. The L/UL processes have not received much attention in the context of AT, even though they constitute a critical element of a transport setup. Hence, there is a risk that the implementation of AT is hampered by difficulties in effectively managing the L/UL. Some research efforts have been directed towards automated L/UL but often with a focus on hardware and technical solutions. By providing a process perspective, outlining the process steps of L/UL and putting them into a context of the logistics system, the current paper has provided a valuable addition to the literature and, at the same time, it has provided insights that can be of value to practitioners involved in the development of autonomous transport solutions.

In the studied case, a main benefit of the introduction of the AT and automated L/UL was the smoothening of the material flows between the sending and receiving facilities which was enabled by the transition to round the clock deliveries. This outcome highlights the need to consider the links between processes steps rather than viewing each process step in isolation. This applies both to industry, where scope that is too narrow could result in sub-optimisations, and to academic research, where important effects could otherwise be overlooked.

Furthermore, while the intervention discussed in this study demonstrates the potential benefits of automated systems such as AGV and AT. However, for these systems to function effectively, there needs to be improved information visibility across all interacting systems. This enhanced visibility allows for better production planning by leveraging transport availability. By exchanging information and functioning in an interconnected manner, there are opportunities for efficient planning and optimization, which in turn reduces the reliance on manpower. Such optimization is especially crucial for continuous operations.

There are indications in the existing literature that automated L/UL can reduce turnaround times by enabling faster handling (Kersten et al., 2017). The findings of the current paper, which are based on an L/UL solution utilising AGVs for the L/UL process, do not support this claim. In contrast, the automated L/UL observed in the studied was considerably slower than the manually operated processes. There exist multiple technologies for automating L/UL, and the time for L/UL is likely to vary depending on which technology is used. For example, there are technologies where the entire truck load is loaded or unloaded in one move, by use of solutions such as conveyors, and it seems likely that such technologies hold a potential to enable a much faster loading and unloading than the AGV setup that was applied in the case studied in the current paper. On the other hand, if the entire truck load is loaded in one move, this requires that the unit loads have been arranged in advance, which arguably requires more preparation than the AGV setup that was studied in this paper, which was relatively flexible. It thus seems that different technologies for automated L/UL have different advantages and drawbacks, and that they should therefore be carefully matched against the area of application before a decision is made of which technology to apply. There is also a need for further studies, considering also other technologies for automated L/UL, in order to fully understand the performance impacts of automating L/UL in the context of AT.

The studied case displays a relative simplicity in that the unit loads are relatively homogeneous and in that all the unit loads are shipped between the same two locations, both of which belong to the same company. A greater diversity of unit loads would have created a more complex and thus challenging context, as would a transport setup with multiple pick-up and drop-off locations belonging to different companies. Future studies could address the application of AT and automated L/UL in contexts with a higher degree of complexity to discern if the performance impact of automating L/UL in a setting of AT is different compared to the findings of the current paper.

Conclusions

This research is unique in contributing to the emerging field of automation in L/UL because it involves evaluating the performance of automated L/UL at a system level that, according to the knowledge of the authors, no other research has done. To practitioners, this study provides valuable insights and will help understand the scope of not individually assessing the performance of L/UL or AT but considering the overall benefits achieved at the system level. Academic researchers can benefit from the results of this study as it provides practical implications that can help drive future research in technical, operational, and socioeconomic aspects. This, in turn, can contribute to evidence-based policymaking and industry best practices.

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