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Abstract:
Alongside the electrification of vehicles, the automation of vehicle fleets in logistics is considered one of the most important innovation topics for shaping the change toward climate neutrality and digitization. Automation in the field of logistics requires a close look at the individual process steps and the performance of automated transport systems compared to manual operation. In this paper, a methodology for the assessment of project efficiency of autonomous mobile robots in warehouse logistics is presented based on a case study in the HOPPER project. Besides an insight into the methodology, first results of a comparison of a manual and an automated process of a side loading of tarpaulin trucks with steel plate pallets are presented, which focus on the weighted process work time as well as expected process costs per year.

Keywords:
AUTOMATED MATERIAL TRANSPORT; AUTOMATED TRAILER LOADING; PROCESS EFFICIENCY; AUTONOMOUS MOBILE ROBOTS; PROCESS LEAD TIME

Introduction

In the transition to climate neutrality and digitization, the EU is counting on the leadership of European industry to serve as an accelerator and enabler of change, innovation and growth [1]. In the period 1990-2020, technological change in the industrial sector has already achieved an emissions reduction of almost 40% in the European area. However, the transport sector still faces major challenges, as emissions in this sector have increased by 7% in the same period, despite the decline of domestics transport in the covid crisis in 2020. [2] The creation of green logistics and an associated establishment of sustainable transport management should help to avoid or reduce transports and reduce the harmfulness of transports to the environment [3]. In addition to the often-mentioned measures of increased use of renewable energies, more energy efficiency, and a faster introduction of low-emission modes of transport including the corresponding infrastructure and fuels [4], the automation of fleets in logistics can support the transition towards green logistics. Furthermore, automation can make a decisive contribution to counteract the current shortage of skilled workers in the transport sector [5]. However, automated transport concepts first require a corresponding examination of the process efficiency of automated vehicles compared to manual logistics operations in the respective application to weigh up in advance of implementation whether automation would be technically feasible and sensible.

In the HOPPER project (Handling of man-made objects using automated positioning, planning and enhanced reasoning methods), we worked on creating a methodology to measure the process efficiency of an AMR (autonomous mobile robot) in the process of transporting and loading steel blanks onto tarpaulin trucks. The given use case required the creation of a case-based methodology due to the lack of practical data for measuring the process efficiency in the manual and automated loading process. The developed process variant calculation is based on the determination of the individual process steps as well as a time estimate for the respective work steps in the actual and target process. In addition, the methodology offers the possibility to differentiate the picking cases according to difficulty and frequency of the cases and to weight them accordingly for a first realistic estimation of the working time of the manual and automated process. In combination with determined cost factors, this methodology can also be used to create an initial process cost comparison.

This technical paper gives an insight into the methodology of the process-variant calculation for measuring the process efficiency of automated vehicles and provides initial results of a comparison of manual and automated transport in the considered use case.

Method

In the process variant calculation, all work steps of the process under consideration are first recorded during a company visit with the experts on site, which is shown in the following table using an example in order picking.

Table 1: Example of recording of working time with process variant calculation

Recording of working time	% Cases absolute	Simple case		Medium case		Difficult case		"Weighted" working time [min]	
Process/sub-process/activity (function, work step)		Quantity (%)	Time [min]	Quantity (%)	Time [min]	Quantity (%)	Time [min]	Per activity	Per process
Logistics	100%								
Order picking	100%							**44.25**	**30.30**
Pick product articles	100%	15%	8	80%	20	5%	35	18.95	18.95
Check order	100%	15%	2	80%	5	5%	10	4.80	4.80
Correct incorrect picking	10%	5%	10	90%	15	5%	30	15.50	1.55
Pack goods	100%			100%	5			5.00	5.00

An estimate is made of the frequency of occurrence of these work steps (in % absolute). Furthermore, a breakdown can be made for each work step according to the difficulty of the cases. The frequency of the cases as well as the necessary working time per case must be indicated. Based on the data obtained, a weighted working time per activity and per process can be calculated. The results from Table 1 show that the consideration of the difficulty of the cases affects the working time per activity and the frequency of occurrence of these processes (column 2) is considered in the working time per process.

Subsequently, the required executive positions (people) and the required resources (machines) per work step are defined and cost rates are determined together with the experts of the logistics company. Based on the data obtained, the costs per work step can be calculated and an initial business case calculation can be made, which is shown in Table 2 on the basis of the example used in order picking.

Table 2: Example of a business case calculation with process variant calculation

Process/sub-process/activity (function, work step)	"Weighted working time per process [min]	Executing positions	Cost factor position [€/h]	Resources required	Cost factor resource [€/h]	Cost for work step [€]
Logistics						
Order picking						**12.63**
Pick product articles	18.95	Picker	25			7.90
Check order	4.80	Picker	25			2,00
Correct incorrect picking	1.55	Picker	25			0,65
Pack goods	5.00	Picker	25			2,08

Process variant calculation within the use case under consideration

For the application of the process variant calculation in the present use case, a company visit to the logistics operation of a large steel producer took place as part of the HOPPER project. The current process at the production site was recorded in collaboration with the head of operations and a supply chain expert of the logistics service provider and divided into eight sub-processes (see Table 3) with several work steps. As part of this data collection, the experts were interviewed regarding the resources used in the respective process steps and asked to estimate the time required for the individual process steps for a complete loading of a tarpaulin truck. In their time estimates, the experts were asked to distinguish between simple, medium and severe cases in the sub-processes as required and to indicate the probability of occurrence of the cases as a percentage (% cases absolute) to ensure a realistic estimate of the process work time.

Table 3: Sub-processes of the current loading process

Sub-process 1	Forklift driver picks the goods and brings them to the picking station
Sub-process 2	Preparation of the loading plan for the loading of the truck
Sub-process 3	Preparation of loading (removal of tarpaulins, scanning the loading plan)
Sub-process 4	Transport of the goods from the picking station to the truck
Sub-process 5	Side loading of the truck with pallets
Sub-process 6	Load securing
Sub-process 7	Handing over the loading documents
Sub-process 8	Closing the truck (attachment of tarpaulins)

Based on the data obtained, the weighted process working time per truck loading with steel blank pallets was calculated. The weighted process work time takes into account the varying difficulty of the cases and their frequency in each sub-process to consider the high time differences in order picking due to different customer requirements. Only those work steps were taken into account which are associated with a resource expenditure of the loading company (people, machines). Work steps such as the removal and attachment of the tarpaulin from the truck only affect the truck driver and were therefore excluded, as they are not relevant for the subsequent cost comparison of manual and automated operation.

Subsequently, the HOPPER project consortium with 15 experts from the fields of logistics, robotics and automated driving created an automated loading process, which is divided into nine sub-processes. For this target process, a time estimate of the sub-processes was made by the AMR experts based on the speed data of the AMR and the known area of application. Cases of varying difficulty and probability of occurrence were considered for each sub-process and included accordingly in the calculation of the weighted process working time.

Table 4: Sub-processes of the partially automated loading process

Sub-process 1	Forklift driver brings goods to a transfer point, thus starting the loading process by the automated forklift system (AMR)
Sub-process 2	Automated approach to the transfer point
Sub-process 3	Detection of the object to be loaded by the AMR
Sub-process 4	Automated picking up of the goods
Sub-process 5	Automated transport of the goods to the truck
Sub-process 6	Detecting the free loading space in the truck
Sub-process 7	Driving to the loading edge of the truck and lateral positioning
Sub-process 8	Automated positioning of the load at the unloading point
Sub-process 9	Leaving the unloading position and returning to the picking station / waiting point

Sub-processes 2 to 9 correspond in terms of time to the actual manual sub-processes 4 and 5 and **represent the framework of the automatable processes** in this project. Since no automation is planned for the remaining sub-processes of the current loading process due to their complexity, these sub-processes were considered to remain constant and were not included in the process cost comparison.

In addition to the calculation of the weighted working time, it is necessary to determine the associated cost factors of the resources used (machines) and executing positions (people) to be able to carry out a process cost comparison of manual and partially automated operation. For this purpose, average hourly rates of the steel production company under consideration as well as calculated cost rates of an AMR manufacturer were obtained.

Table 5: Cost factors (per h) of the resources used in the manual and automated process

Cost factor		Manual process	Automated process
Forklift + operator		38 €/h	-
AMR	CF 500h	-	180.05 €/h
	CF 1,000h	-	90.05 €/h
	CF 1,500h	-	60.05 €/h
	CF 2,000h	-	45.05 €/h
	CF 2,500h	-	36.05 €/h
	CF 3,000h	-	30.05 €/h
	CF 3,500h	-	25.76 €/h
	CF 4,000h	-	22.55 €/h
	CF 4,500h	-	20.05 €/h
	CF 5,000h	-	18.05 €/h
	CF 5,500h	-	16.41 €/h
	CF 6,000h	-	15.05 €/h

The cost factor of 38€/h in manual operation is mainly caused by the forklift driver with 27€/h. The cost factors of the AMR are mainly due to the high investment costs of the vehicle, which are depreciated over a period of 5 years. The share of electricity costs is rather low and amounts to only 0.2% of the total costs for 500 hours of operation and approx. 2% at 5,000 hours at an assumed electricity price of 0.35 €/kWh. With increased operating time/year, the cost factor decreases accordingly and would have about the same hourly rate as manual operation at about 2,500 h operating time/year. Based on the calculated weighted working time of loading per truck in the manual and automated process and the given cost factors, the process cost comparison was finally carried out.

Results and Evaluation

For the comparison of the weighted process work time of the manual and automated loading process, an average loading of 7 pallets per truck was calculated according to the assessment of the experts of the steel company under consideration. The following table shows the weighted process work time per truck for the automatable current subprocesses 4 and 5 (see also Table 3) and the corresponding automated subprocesses 2 to 9 (see also Table 4).

Table 6: Weighted working times per truck loading (7 pallets) for manual and automated loading

Manual loading (ML)	Weighted process work time [min]	Automated loading (AL)	Weighted process work time [min]	Factor AL/ML
Transport of the goods from the picking station to the truck	7.00	Approach to the transfer point	6.86	
		Detection of the object to be loaded	7.18	
		Automated picking up of the goods	7.04	
		Transport of the goods to the truck	13.84	
Transport total	7.00		34.92	4.99
Side loading of the truck with pallets	11.20	Detection of the free loading space	7.00	
		Travel to the loading edge of the truck and lateral positioning	1.45	
		Positioning of the load at the unloading point	7.56	
		Leaving the unloading position and returning to the picking station/waiting point	10.76	
Loading total	11.20		26.77	2.39
Overall total	**18.20**		**61.68**	**3.39**

The results of the weighted working times of the sub-processes considered show that automated loading, at 61.68 min/truck, has significantly longer process working times than manual loading, at 18.2 min/truck. This is mainly due to the higher transport time for the transport of goods from the picking station to the truck, which is 5 times the manual loading. In the loading process, the ratio of automated and manual loading is significantly lower at 2.39. In the case of automation, one manual forklift operator would have to be replaced by approximately three AMR to achieve a similar loading speed.

Based on the calculated weighted working time per truck loading in the manual and automated process and the given cost factors (Table 5), the costs per sub-process were calculated. The following table shows the process costs per year of the current loading process as well as an automated loading process for the transport of the goods from the picking station to the truck as well as the side loading of the truck with pallets. For the calculation of the process costs per year, the average number of loaded trucks/day as well as the number of working days is required. According to the estimate of the head of operations, a loading of 20 trucks/day can be expected. For the number of working days, 250 working days (=working days of the year 2022, Mon-Fri) were set. Two variants were calculated for the partially automated process. In variant 1, only one AMR is used and the resulting longer working time (see also Table 6) is accepted. Since the annual working time of the AMR here is approximately 5,000 h, the cost factor AMR CF 5,000h with 18.05 €/h was used in this variant. In variant 2, three AMRs are used to ensure approximately the same working time as in manual operation. Since the annual working time of the relevant sub-processes for automation would therefore be around 1,500 h, the cost factor AMR CF 1,500h with 60.05€/h was used for their cost calculation (see also Table 5).

Table 7: Process cost comparison of the manual and automated loading process

Process cost per year (20 trucks/day, 250 working days)	Manual loading process	Automated loading process	
Sub-process	**Costs [€]**	**Costs [€] (1 AMR, CF 5,000h)**	**Costs [€] (3 AMR, CF 1,500h)**
Transport of the goods from the picking station to the truck	22,167	52,509	105,088
Side loading of the truck with pallets	35,467	40,264	168,140
Total	**57,634**	**92,773**	**273,228**

The results of the process cost comparison show that in automated operation, lower additional costs can be expected if the manually operated forklift is only replaced by 1 AMR. The additional costs in this case are around €35,000 per year. In this variant, however, it would have to be checked subsequently whether negative side effects arise due to the longer working time, which could lead to further potential additional costs or even make automated operation impossible (e.g. additional need for truck parking spaces, penalties, etc.). In variant 2, these side effects can be disregarded, since the vehicle ratio of 3:1 ensures approximately the same work rate as in manual operation. However, the use of 3 AMRs leads to considerable additional costs of 215,000€ per year, which is due to both the low operating time of the AMRs and the associated high hourly rate (Table 5, AMR CF 1,500h).

In the given case study, the number of operating hours for the sub-processes that can be automated is currently still low, at approx. 1,500 hours per year. Additional automatable processes (e.g. transport in order picking) could increase the operating hours of the AMRs and thus make them more profitable. However, as a prerequisite it must be given that the longer working time in the process work steps does not negatively influence the daily operation.

Considering the current working speed of the AMR, a cost parity for the considered automatable sub-processes would require an AMR cost factor of 11.2 €/h, which is significantly lower than the 38€/h cost of manual execution (see Table 5). However, it can be assumed that the additional working time of an automated transport system will decrease due to technological progress and thus allow higher AMR cost rates for a parity of process costs.

Conclusions

In this study, a possible approach for the measurability of process efficiency of automated transport systems in the logistics sector is offered. The process-variant calculation used represents an efficient tool for an initial comparison of working time and process costs of automatable processes in logistics, for which only limited initial data are available both for the current process and for the potential automated process. The results of the process variant calculation in the given case study of side loading of steel blank pallets showed that an automation of the transport is currently still associated with additional costs. If a single AMR were used, the additional costs would amount to €35,000 per year. Due to the significantly longer process working time of the AMR, negative side effects for daily operations must be examined and taken into account accordingly. It can be assumed that the additional working time of the AMR compared to manual operation can still be significantly reduced through technological progress and fine-tuning to the operational conditions and thus even more application possibilities will be found for the AMR in the future.

The use of several AMRs to achieve the current manual work rate is not profitable in the considered case study, as the number of operating hours per year of the processes that can be automated is too low to justify the additional investment costs. In this case, a higher degree of utilization of the AMRs would have to be aimed for and the further development of the cost factors of the AMRs would have to be observed, which are currently essentially associated with the high acquisition costs of the AMRs.

This case study represents a first approach to the issue of measurability of process efficiency of automated transport systems in the logistics industry, where limited baseline data is available for both the current and the potentially automated process. Therefore, there is a need to discuss the introduction of more computational scenario planning inputs to demonstrate efficiencies and trade-offs at an end-to-end process level, which is beyond the scope of this paper and will therefore be the subject of future research. Finally, it should be noted that other aspects besides process costs, such as the shortage of skilled labour in the logistics industry, should also be taken into account in a future evaluation of possible process automation. However, these aspects were not the subject of the present cost comparison and should therefore also be pursued in future research.

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