Research Article

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Proposal of Methodology to Calculate Necessary Number of Autonomous Trucks for Trolleys and Efficiency Evaluation

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Abstract: The introduction of the paper highlights best practice in the area of deploying autonomous trucks in warehouses and the automotive industry, including the current technical possibilities of selected autonomous trucks. The next chapter presents the selected outputs of the scientific project “Center of Excellence for Intelligent Transport Systems” focused on a proposal of the methodology for calculating the necessary number of autonomous trucks and trolleys deployed in logistics warehouses. The methodology is based on the requirement that autonomous trucks do not have downtime. This represents a model solution with possible application in warehouse logistics but also in the automotive industry. The follow-up chapter proposes a methodological procedure to evaluate the efficiency of introducing autonomous trucks to pull trolleys in a logistics warehouse compared to conventional trucks operated by trained personnel. Autonomous trucks can theoretically be operated 365 days and 24 hours depending on the technology of their operation, battery charging, etc. On the other hand, there is generally a shortage of logistics personnel in the European Union as well as reliability and performance have been declining in recent years. The conclusion of the paper includes a discussion of the research results obtained and possibilities for future research.

Keywords: autonomous vehicles, technology, efficiency, logistics

1 Introduction

The concept of the fourth industrial revolution (Industry 4.0) emerged about ten years ago in Germany with the aim to create the so-called Smart Factory. The technological basis for this smart factory was to be Cyber-Physical Systems and “Internet of Things” (IoT) [1–4]. After ten years, we can state that these factories already exist at present. Logistics becomes, of course, one of the important part of production for such a factory to be able to operate and produce finished products. We can have available the world’s most sophisticated robots and equipment but if, for example, the components do not come to the plant, the production will ultimately produce nothing. As another example, if we have necessary components supplied to the plant, but we are no able to prepare them in the right quantities and at the right time for delivery to individual production workplaces, unwanted downtimes will occur and a production company may ultimately achieve losses.

Logistics was not once considered very important. Many times, it was underestimated and it was something to look at as the last in most cases. In today’s continuous increasing level of automation of logistics and warehouse systems, a great emphasis is placed on the effective level of logistics. Currently, companies are trying to automate their processes not only to save labour but also due to the speed of individual processes and elimination of errors *e.g.* when picking up goods. The consequence of this increasing level of process automation is seen in the continuous increasing pressure from the side of customers on reliable supplies of goods and materials to production plants. This also requires the application of the latest methods of inventory planning and management, *e.g.* TOPSIS [5–11]. The demand for automated logistics solution is expected to continuously increase with increasing number of plants mainly in the automotive industry but also in other segments, *e.g.* retail chains, logistics warehouses.

Delivering materials and components to the production plant is, in the broader sense, ensured by logistics itself or individual suppliers who are a part of a given

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supply chain. Nowadays especially in the automotive industry, a common standard for delivering parts and components represents supplies within Just-In-Time or Just-in-Sequence regime. This represents the supply of components to the production lines in time they are actually needed in the production process (JIT) and in the order of the sequence of individual products on the production lines (JIS). In most cases, large components such as seats, bumpers and various other parts, which would normally take up a lot of space along the production lines and would represent a limitation for the supply of other components, are supplied to the production lines in this way.

An important part of these processes is a man itself. The vision of Logistics 4.0 is to automate a given process and also other processes as much as possible and thus to eliminate the human factor. A key element in the smart factories is a perfect overview of the flow of individual materials and components throughout the entire production plant. Nowadays, some automobile manufacturers require 100% movement traceability of individual products and components and the strategy for the future expects that they will even require also 100% movement traceability of persons (operators) working on the products. In other words, we need to have a perfect overview of not only where each pallet or item is but also it will be necessary in the future to know whoever that pallet manipulates, where moves it, why moves it and what is caused by this movement. This traceability will not be achieved unless perfect information systems filled with correct and quality data are employed. These “master data” are currently considered to be a very crucial thing not only for traceability but also for all other logistics activities whether we talk about warehouse operations, deliveries of materials to production lines and workplaces as well as backflow from the production to the warehouse [4, 12–15]. Another vision or challenge to face is that online traceability and immediate access to information can greatly improve logistics processes. Nowadays, modern logistics companies already have software that allows to specify the place and time of unloading in addition to scheduling carriage itself. Based on the data gathered, this software can effectively plan the route of trucks also with regard to traffic congestion, various traffic restrictions, driving bans during holidays, weather, ordering places at secure parking lots, etc. As a result, companies save not only operating costs but also they can shorten delivery times and increase security of shipment carriage.

Another thing to focus on within Logistics 4.0 is the data itself that are generated by individual devices. When expanding the production, *e.g.* in terms of new orders, insufficient capacity of the existing machines, it is nec-

essary to focus on integration. In this sense, integration means the possibility of linking a new device to others that are already situated in the plant. At present, every device (machine) is able to count produced pieces, produce products according to production orders or every forklift is able to count the number of kilometres travelled, manipulated tonnes and record individual movements during a work shift. The amount of the data will even multiply with new more modern systems being introduced. According to a study, the volume of daily generated data represents 2.5 – 3 exabytes [16]. With increasing amount of the data, the question is where and how to store this data. Various cloud storages can be taken into consideration, however, the question of the protection of personal data may represent an issue in the case of some companies. In addition to the growth of the data generated by various devices and machines, the electronic data exchange or EDI between customers and suppliers is also important step on the way to Logistics 4.0. Some companies often mistakenly believe that EDI also involves writing emails and sending order by emails. According to the data from the Czech Statistical Office, only 10% of all small enterprises, 15% of all small and medium-sized enterprises and around 30% of all large enterprises currently use EDI to exchange data with their suppliers [12, 16–21].

2 Nomenclature

As the paper deal with the calculation of the necessary number of autonomous trucks and trolleys deployed in logistics warehouses and the calculation of economic return of AGV trucks, Table 1 provides the list of symbols used throughout this paper.

3 Methodology for Calculating the Number of AGV Trucks and Trolleys in Logistics

Most companies are not yet fully ready for the application of ideas and technologies within the concept of Logistics 4.0. The automotive industry is, of course, the driving force in this area. Automatic supply of parts for assembly production lines by using AGV, robotized workplaces, fully automatic welding lines are applied, for example, in Volkswagen Slovakia Bratislava. An AGV automated logistics system (Automatic Guided Vehicles) is a complex automation solution determined for various industries. The AGV

Table 1: The list of symbols used in this paper.

Symbol	Description
ce	electricity price [€/kWh]
cz	unit price of handling equipment [€]
$FN1.year$	financial intensity of the implementation in the first year
$FNn-year$	financial intensity in the n-year from the implementation [€]
I	interval of arrival of AGV logistics trucks to the place of loading and unloading
i	interest rate
K	capital that expresses the degree of technological equipment
L	labour, it may be expressed by the number of workers
l_{A-B}	distance from place A to B [km]
l_z	transport distance [km]
m	wage rate per unit of labour
NI	costs for AGV implementation (infrastructure, software, etc.) [€]
No	annual costs per an operator [€]
no	number of operators
Ns	annual service and maintenance costs [€]
nz	number of acquired equipment [pcs]
$P_{No.}$	the total number of trolleys
$P_{No.,L}$	the number of trolleys at the place of loading
$P_{No.,U}$	the number of trolleys at the place of unloading
P_{to}	turnover time of a trolley (a peripheral) [min]
Q	production function
$Sel24hod$	electricity consumption of handling equipment per 24 hours [kWh]
TC	total costs
t_c	duration of connection
t_{cd}	duration of connection and disconnection [min]
t_d	duration of disconnection
t_L	time of loading [min]
$t_{L,U}$	time of loading and unloading of trolleys [min]
$T_{No.}$	number of trucks
T_{to}	turnover time of a truck [min]
t_U	time of unloading [min]
v_t	technical speed of AGV truck with trolleys [km·h ⁻¹]

Table 2: Selected technical parameters of AGV CEITruck [23].

Tractor modification	Maximum towable weight in kg	Maximum speed m·s ⁻¹
CEITruck 500A	500	2
CEITruck 1300A	1 300	2
CEITruck 2000A	2 000	1
CEITruck 3000A	3 000	1
Under-run modification	Maximum towable weight in kg	Maximum speed m·s ⁻¹
CEITruck 800AF	500 kg on truck; 800 kg on trolley (wagon)	2
CEITruck 1300AF-BD	1 000 kg on truck; 1300 kg on trolley (wagon)	1

system automates the pulling of trolleys (peripherals) with material along to the predefined path (by using a magnetic tape fixed on the floor) and by using the commands (start, accelerate, wait, connect a peripheral, etc.) stored on the tags (RFID tags) placed throughout the path. AGV trucks enable to solve the issue of labour shortages that relates to the GDP growth in the EU countries in recent years and the demand for freight transport [22].

CEIT company from Žilina (Slovakia), a member of the Asseco Central Europe group, succeeded in the European competition of Automotive Logistics Awards Europe 2018 with a complex solution for internal logistics of industrial plants in the category of Packaging & materials handling automation.

CEIT company developed also OEE (Overall Equipment Effectiveness) that is a complex production indicator designed to assess production efficiency and can be implemented in AGV MCS (AGV Monitor & ControlSystem). By using the OEE tool, unique data on the utilization and productivity of the logistics and production system in the form of graphs and visualizations can be gathered. The result of the analysis is the calculation of “all-in” indicator that indicates the overall efficiency of the device.

Technological aspects of deploying AGVs in warehousing and picking up the shipments as an important part of logistics processes are discussed, e.g. in [24].

3.1 Calculation of Necessary Number of Trolleys for AGV Trucks

In relation to the issue of implementing AGV trucks, it is necessary to propose a procedure for calculating the number of trolleys that is to be loaded at the loading place and unloaded at the unloading place in order to downtime of AGV trucks does not occur.

Turnover time of a trolley (a peripheral) – P_{to} is longer than turnover time of an AGV truck because it includes also loading/unloading operation.

$$P_{to} = T_{to} + t_L + t_U \text{ [min]} \quad (1)$$

Where:

T_{to} – turnover time of a truck [min]

t_L – time of loading [min]

t_U – time of unloading [min]

Interval of arrival of AGV logistics trucks to the place of loading and unloading (I) is an important indicator for determination of the number of trolleys for one AGV truck.

$$I = \frac{T_{to}}{T_{No.}} \quad (2)$$

Where: $T_{No.}$ – number of trucks

Number of trolleys that have to be loaded and unloaded depends on mutual proportion of the interval of trucks' arrival and time necessary for dispatching of one trolley (dispatch of the trolley also includes loading, unloading, disconnection and connection of the trolley).

The total number of trolleys is set by a sum of trolleys on the route between the places of loading and unloading (corresponds to the number of the AGV trucks) and the number of trolleys at the place of loading and unloading.

Duration of connection (t_c) and disconnection (t_d) of AGV truck:

$$t_{cd} = t_c + t_d \text{ [min]} \quad (3)$$

The number of trolleys at the place of loading:

$$P_{No.,L} = \frac{t_L + t_{cd}}{I} \quad (4)$$

The number of trolleys at the place of unloading:

$$P_{No.,U} = \frac{t_U + t_{cd}}{I} \quad (5)$$

The total number of trolleys:

$$P_{No.} = T_{No.} + P_{No.,L} + P_{No.,U} \quad (6)$$

In the case of shuttles (from place A to B and back), the following relation is applicable for a turnover time of the AGV truck:

$$T_{to} = \frac{2 \cdot l_{A-B}}{v_t} + 2 \cdot t_{cd} \text{ [min]} \quad (7)$$

Where:

l_{A-B} – distance from place A to B [km]

v_t – technical speed of AGV truck with trolleys [$\text{km} \cdot \text{h}^{-1}$]

For the interval of arrival of AGV trucks, it is possible to derive the following relation:

$$I = \frac{2 \cdot (l_z + t_{cd}) \cdot v_t}{T_{No.} \cdot v_t} \text{ [min]} \quad (8)$$

Where:

l_z – transport distance [km]

After adjustment of the relation, total number of trolleys may be calculated by the following relation:

$$P_{No.} = T_{No.} + \frac{(2 \cdot t_{cd} + t_{L,U}) \cdot T_{No.} \cdot v_t}{2 \cdot (l_z + t_{cd}) \cdot v_t} \quad (9)$$

Where:

$t_{L,U}$ – time of loading and unloading of trolleys [min]

The number of trolleys for AGV trucks, calculated by mentioned way, ensures that downtime of AGV trucks does not occur at the place of loading and unloading. This is a simple model which can be used in particular for the first

proposal to deploy AGV trucks and as a basis for calculating economic efficiency.

The mentioned calculation does not take into account safety breaks for drivers such as it is necessary e.g. in scheduling road freight transport [25, 26].

4 Possible Approach to Assess the Deployment of AGV Trucks in Logistics in terms of Increasing Efficiency and Performance of the Logistics System

A very important question is whether the deployment of AGV trucks e.g. in a logistics warehouse will solve the lack of labour, increase efficiency of the logistics process and whether this deployment has prerequisites for increasing efficiency and performance of the logistics system [27, 28]. Some aspects of the comparison between a traditional and autonomous systems and planning of the deployment of AGV trucks are mentioned and discussed e.g. in [29–32].

4.1 Proposal of a Calculation Model to Calculate the Economic Return of AGV Trucks in Logistics

Based on [32, 33], a calculation model proposal to calculate the economic return of AGV trucks in logistics was developed. The calculation of the financial intensity of conventional handling equipment in the first year of its implementation:

$$FN1.year = cz\ nz + No\ no + Ns + sel24hod\ ce\ 365 \quad (10)$$

Where: $FN1.year$ – financial intensity of the implementation in the first year [€]

cz – unit price of handling equipment [€]

nz – number of acquired equipment [pcs]

No – annual costs per an operator [€]

no – number of operators [-]

Ns – annual service and maintenance costs [€] $sel24hod$ – electricity consumption of handling equipment per 24 hours [kWh]

ce – electricity price [€/kWh]

The calculation of the financial intensity of conventional handling equipment in the n-year from the implementation:

$$FNn - year = No\ no + Ns + Sel24hod\ ce\ 365 \quad (11)$$

Where:

$FNn - year$ – financial intensity in the n-year from the implementation [€]

No – annual costs per an operator [€]

no – number of operators [-]

Ns – annual service and maintenance costs [€]

$Sel24hod$ – electricity consumption of handling equipment per 24 hours [kWh]

ce – electricity price [€/kWh]

The calculation of the financial intensity of AGVs in the first year of its implementation:

$$FN1.year = cz\ nz + NI + Ns + Sel24hod\ ce\ 365 \quad (12)$$

Where:

$FN1.year$ – financial intensity of the implementation in the first year [€]

cz – unit price of handling equipment [€]

nz – number of acquired equipment [pcs]

NI – costs for AGV implementation (infrastructure, software, etc.) [€]

Ns – annual service and maintenance costs [€]

$Sel24hod$ – electricity consumption of handling equipment per 24 hours [kWh]

ce – electricity price [€/kWh]

The formula to calculate the financial intensity of AGVs in the n-year from the implementation:

$$FNn - year = Ns + Sel24hod\ ce\ 365 \quad (13)$$

Where:

$FNn - year$ – financial intensity in the n-year from the implementation [€]

Ns – annual service and maintenance costs [€]

$Sel24hod$ – electricity consumption of handling equipment per 24 hours [kWh]

ce – electricity price [€/kWh]

Table 3 and Figure 1 provide the case study outputs from the implementation of AGV trucks in the logistics warehouse. Currently, ten towing trucks and 32 workers work in three 8-hour shifts in the warehouse.

Based on this simplified calculation of the financial intensity for the implementation of AGVs in the logistics warehouse, it can be stated that the increased costs of investing in more expensive AGV trucks and related infrastructure return after 2.5 years. If the total labour costs in logistics in EU countries grow by the pace of recent years, the efficiency of introducing AGVs will even increase [34].

Table 3: Input data for the financial intensity calculation for the implementation of AGVs in the logistics warehouse. [authors]

Item	AGV	Conventional equipment
Equipment price	95 000.00 €	35 000.00 €
Number of equipment	10	10
Annual costs per an operator	- €	21 600.00 €
Number of operators	0	32
Annual service and maintenance	7.00%	4.00%
Daily electricity consumption in kWh	72	96
Electricity price per kWh	0.13	0.13
Initial investment	950 000.00 €	
Operation time in days	365	365
Financial intensity 1. year	1 969 916.40 €	1 059 755.20 €
Financial intensity 2. year	2 039 832.80 €	1 769 510.40 €
Financial intensity 3. year	2 109 749.20 €	2 479 265.60 €
Financial intensity 4. year	2 179 665.60 €	3 189 020.80 €
Financial intensity 5. year	2 249 582.00 €	3 898 776.00 €

Figure 1: Graphical representation of the financial intensity calculation. [authors]

5 Discussion and Possibilities of Using the Production Function to Assess the Efficiency of Deploying AGVs

The calculation of the economic efficiency of the deployment of AGV trucks given in chapter 4.1 is relatively simplified and does not take into account all aspects of the deployment of automation and robotization in logistics. Therefore, we deal with the possibilities of using a production function for a more complex assessment of efficiency of AGV trucks deployment in further research. With the advent of robotization, companies are deciding between manpower and the use of new technologies. Changes towards innovation, of course, must mean increasing the ef-

ficiency while lowering the costs. Economic science uses the theory of the production function as described, for example, by Paul Samuelson [35]. Technological innovations that enable to increase production significantly are also an important element. Some examples of technological changes are essential, *e.g.* the introduction of giant jet aircrafts increased the number of passengers expressed per a unit of input by almost 50%, optical fibres reduced costs and increased credibility of telecommunications, improvements in computer technology increased a capacity more than a thousand times over the past thirty years [12]. Bedrich Duchon is one of Czech authors that deal with the production function [36]. In terms of the whole economy growth, the concept of an aggregate production function that describes the relationship between a product and individual inputs is introduced. For instance, Cobb Douglas production function is used to estimate GDP development [37].

In order to apply the production function theory to the case considered in this paper, it is necessary to consider the production function in the long term because technological changes do not occur in the short term. The production function is the relationship between the number of different input production factors used per certain time period and the output size over the same time period. It is necessary to emphasize the technology applied and its impact on the output while assuming two factors influencing the output in the case of the production function Q in the long term. This function may be expressed by the following relation:

$$Q = f(K, L) \quad (14)$$

Figure 2: Optimal combination of inputs K and L of the production function Q. [36]

Where:

K – capital that expresses the degree of technological equipment

L – labour, it may be expressed by the number of workers

The economic theory expresses the production function in the long term in the form of isoquants. An isoquant is a curve showing such combinations of inputs K and L for which the volume of production is the same (similarly as indifference curves depict such combination of two goods by purchasing of which a buyer has the same benefit). This represents a concave and declining function. In the case of innovation introduced into production, the curve shifts away from the axis origin.

The economy further deals with the optimal combination of inputs of variables K and L, which is based on budget constraints. This is depicted by so-called isocosts *i.e.* a straight line that expresses always such combinations of capital and labour that can be acquired at the total costs available to the company. The costs (TC) are influenced by the costs of capital which are determined by the interest rate and labour costs *i.e.* wages. The total costs function is expressed by the following relation:

$$TC = m \cdot L + i \cdot K \quad (15)$$

Where:

m – wage rate per unit of labour,

i – interest rate

The optimal combination of inputs then lies at the point where the isocost touches the isoquant; mathematically where the isoquants equal to isocosts. If an enterprise wants to increase its production *i.e.* to move to a higher isoquant, it must incur higher total costs. This is graphically shown in Figure 2. The following applies:

$$Q_3 > Q_2 > Q_1 \quad (16)$$

$$TC_2 > TC_1 \quad (17)$$

Figure 3: Optimal combination of inputs K and L of the production function Q. [36]

The company can use new technologies instead of manpower (it often does not have to be necessarily unambiguous because robotization also requires workforce, even far more skilled) for several reasons:

- lack of human labour,
- replacement of unreliable human factor by machinery (including robotization),
- need to reduce specific production costs,
- productivity increase.

To increase productivity, it is necessary to achieve increasing returns to scale. This essentially means that the percentage increase in costs is lower than the percentage increase in production, as shown in Figure 3.

Figure 3a) depicts increasing returns to scale – the spacing between individual isoquants decreases. On contrary, Figure 3b) depicts declining returns to scale – the increase in production is always lower than the increase in costs. The increased number of AGV systems in logistics is likely to reduce the costs for production of these systems and related infrastructure. This can significantly affect a decrease of costs of these systems compared to traditional (conventional) systems.

In this chapter, we outlined the possibilities of our future research into the efficiency of deploying AGV trucks and robots in logistics compared to the published literature.

6 Conclusion

Significant progress is currently being made in the field of autonomous transport. In the area of warehouse logistics, the question is whether higher capital expenditures will also be associated with the necessity of higher wage costs for skilled labour [38]. At the same time, this is a question

of changes in production in relation to automation of operation or possible savings (e.g. time savings). The results of such an analysis may be different for each investor or operator. In chapter 4 and 5, the authors did not deal with all the factors affecting the complex assessment of efficiency of long-term deployment of AGV trucks in logistics warehouses. In chapter 4, the case study described a basic approach to assessing the financial return of AGV trucks, on which our research will continue with taking account the possibilities of using a production function (chapter 5).

AGV systems as well as learning-capable robots can increase the efficiency but also address labour shortages in logistics in economically developed countries. However, this is a long-term process. The development towards a high degree of automation of logistics warehouses can be expected within 10 years. The application of a high degree of automation is most conditional on a reasonable return on investment as well as the availability of a solution for the automation of not only newly built warehouses but also already built ones. The paper does not deal with all aspects of the given issue, but it focuses mainly on the application of AGV trucks in the logistics warehouse. The use of AGV trucks as well as robots in logistics warehouses is justified mainly in the case of continuous operation connected to continuous production, e.g. car manufacturers. In such cases, it is possible to save a significant number of employees and to use potential of AGV systems. A thorough assessment of the deployment of AGV trucks in logistics would require to apply a multi-criteria evaluation [39–41]. In future research, the authors want to develop a simulation model for assessing the deployment of different AGV trucks with different maximum towing weights and different maximum speeds used in logistics (see Table 1). The aim of the simulation will be to determine the relationship between a particular type of AGV truck and the number of trolleys in closed queuing systems. Chapter 3.1 containing the proposed calculation of the necessary number of trolleys for AGV trucks represents only a static model but it explains the principle of the mathematical task that needs to be solved in the deployment of these technologies.

The concept of Logistics 4.0 is based on a complex interconnection of freight vehicles, trains, planning, production and warehouse software together with e.g. online data on traffic situation including the weather and its development. This would allow planning all the process fully automatically. The necessity of this system is thus a perfect overview of where and in what quantity a given component is located. It is also necessary to count on autonomous trucks in the future. Logistics 4.0 will also significantly affect road freight transport technology [26?]. In the selected distribution centres and warehouses of DHL,

robots that assist in picking the shipments or providing services with value added are tested within pilot projects for several years. This represents, e.g. so-called cracking, manual work but at the same time highly standardized type of work. The increase of efficiency lies in the fact that a given operation can be performed only by two workers and one robot instead of five workers [?]. Robots could be a solution to labour shortages in logistics in economically developed countries because it is not possible to cope with the growth associated with the e-commerce development when considering the existing or future available labour given to unfavourable demographic trends. Based on this, it is obvious that the development towards Industry 4.0 based on digitization and automation represents not only huge challenges for Logistics 4.0 but also opportunities for the efficiency increase.

As it is obvious from the cited literature, the deployment of AGV trucks and robots in logistics significantly increases. In this regard, it would also require to deal with determination of the most suitable layout of space for handling of loading units [?]. Major manufacturers of forklifts offer various types, e.g. AGV trucks for their customer in logistics. But, the use of this technology is up to the logistics operators, and according to the authors' research there are still no systematic and generally available procedures. The most important output of the paper is a proposal of the implementation procedure of AGV trucks in logistics. The procedure consists of the selection of a suitable AGV truck (chapter 3), calculation of the necessary number of trolleys for AGV trucks in closed queuing systems so that unwanted downtimes do not occur while loading and unloading of trolleys, proposal of the calculation model to determine economic return of AGV trucks in logistics (chapter 4). Within further research, the possibilities of using the production function towards more complex assessment of the efficiency of deploying AGV trucks was addressed (chapter 5). In further step, the authors want to establish a closer cooperation with logistics operators in order to access relevant data for their further research and validation of their results.

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