DOI: 10.2195/lj_edrev_morgenstern_en_202409_01

Evaluation of current influencing factors and assessment of opportunities and risks of a cloud approach for the use of autonomous mobile robots – A Delphi study

Bewertung aktueller Einflussfaktoren und eine Einschätzung von Chancen und Risiken eines Cloud-Ansatzes für den Einsatz autonomer mobiler Roboter – Delphi-Studie

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The number of automated guided vehicles (AGV) is constantly increasing on the way to flexible and adaptable material flows. The growing capabilities of these vehicles, which include a higher degree of autonomy, have led to them being increasingly referred to as autonomous mobile robots (AMR). A side effect of the integration of autonomy functions is a higher demand for computing power. On the IT side, cloud computing is a proven way to handle high computing power. For data transmission and the connection of AMR/AGV to a cloud, the introduction of the 5G mobile communication standard opens new possibilities for joint operation. Therefore, the aim of this work is to measure the importance of the influencing factors playing a role in the use of AMR/AGV and to identify the potential that arises from connecting these robots to a cloud. A Delphi study was designed and conducted to determine the ranking of the factors and to open a solution space for cloud-based AMR/AGV operation.

[Keywords: autonomous mobile robots, cloud robotics, delphi method, material handling, logistics]

Auf dem Weg zu flexiblen und anpassungsfähigen Materialflüssen in der Intralogistik nimmt die Anzahl fahrerloser Transportsysteme (FTS) stetig zu. Das steigende Fähigkeitsspektrum der Geräte, das auch einen höheren Autonomiegrad mit sich bringt, hat dazu geführt, dass diese vermehrt auch als autonome mobile Roboter (AMR) bezeichnet werden. Ein Nebeneffekt der Integration von Autonomiefunktionen ist ein erhöhter Bedarf an Rechenleistung. IT-seitig ist Cloud-Computing ein probates Mittel, um hohe Rechenleistungen zu bewältigen. Für die Datenübertragung und die Anbindung von AMR/AGV an eine Cloud ergeben sich durch die Einführung des Mobilfunkstandards 5G neue Möglichkeiten des gemeinsamen Betriebs. Aus diesem Grund besteht das Ziel dieser Arbeit darin, die Bedeutung der Einflussfaktoren, die beim Einsatz von AMR/AGV eine Rolle spielen, zu messen und darauf aufbauend Potenziale zu identifizieren, die sich aus der Verbindung der Roboter mit einer Cloud ergeben. Zur Erreichung der Ziele wurde eine Delphi-Studie konzipiert und durchgeführt, die die Bewertung der Faktoren ermittelt und einen Lösungsraum für den cloudbasierten AMR/AGV-Betrieb eröffnet.

[Schlüsselwörter: Autonome Mobile Roboter, Cloud Robotics, Delphi-Methode, Transportprozesse, Logistik]

1 Introduction

The Fourth Industrial Revolution focuses primarily on the autonomization and networking of production facilities and systems [1], [2]. This differs significantly from the Third Industrial Revolution, which focused on the automation of factory equipment [3]. Due to its close integration with production, logistics is also subject to these overarching trends. In intralogistics, which deals with the internal flow of materials from goods receipt to goods issue, transportation processes are one of the core tasks [4]. Automated guided vehicles (AGVs) are used to automate these transport processes [5]. The exponential market growth in recent years and the predicted further market growth justify the continued relevance of AGVs [6]. In the context of technological progress in sensor technology and software of AGVs, e.g. in the form of laser-based free navigation or camera-based object recognition, AGVs are increasingly referred to as autonomous mobile robots (AMR) [7]. The Robotic Industries Association provides a high-level definition of the distinction between AGVs and AMRs based on the navigation methods employed [8]. Others make a more nuanced distinction, for example, specifying different autonomy functions [9] or differentiating the degree of autonomy of a transportation system at different levels [7].

DOI: 10.2195/lj_edrev_morgenstern_en_202409_01

Since, from the user's point of view, AMR and AGV are mainly used for transport processes, both terms will be used synonymously in this paper. Overall, it can be said that general technological progress increases the performance of automated transport systems.

At the same time, the increasing automation of production places greater demands on the IT system landscape [10]. Increasing process complexity (e.g., process time, container variance, etc.), increased transport volumes, and the desire for demand-driven and rapidly adaptable material flows require the exchange of large amounts of data between network participants [11]. Cloud computing is being used more and more frequently to cope with increased computing requirements and the processing of large amounts of data [12]. It involves powerful, flexible hardware and software infrastructures that users can access on demand [13].

Overall, the consideration of challenges such as process complexity, safety-related aspects and the influence of external environmental factors is a limiting, cost-relevant factor for AMR/AGV automation [14]. The networked exploitation of the potential of Industry 4.0, e.g. by connecting an AMR/AGV to a cloud, represents an alternative way to overcome these challenges and to ensure the competitiveness of the manufacturing industry in Germany as a high-wage location compared to developing and emerging countries with lower production costs [15], [16]. The link between such a connection of AMRs/AGVs and a cloud can be realized via wireless technology. With the introduction of the 5G mobile communication standard and future generations, more powerful capabilities are emerging in the field of wireless technology that can enable new applications when considered together with AMRs/AGVs and the cloud [17].

The networked use of AMRs/AGVs with a cloud is the subject of this scientific paper. The continuous updating of AMR/AGV applications requires a constant review of the current use of AMRs/AGVs and the search for optimization potential, which can, for example, be provided by the combination with a cloud. In addition to the opportunities offered by the combined use of the cloud and AMRs/AGVs, there are also risks that need to be identified. In the best case, the new cloud approach can mitigate and improve identified weaknesses in current AMR/AGV deployments. Against this background, the following research questions arise for this scientific work:

- What factors influence the use of AMR/AGV and what is their significance??
- How can AMR/AGV be combined with a cloud?

To answer both questions, a Delphi survey was conducted. The survey was divided into two rounds of questions and involved logistics and IT experts from academia and industry. In addition to the transparency provided by listing the factors influencing the use of AMR/AGV, the results of the Delphi survey also provide the user with a precise evaluation and ranking of the influencing factors based on expert opinion. In addition, the answers to the second research question help to provide concrete guidance for the design of cloud-based AMR/AGV systems and to optimize their current use.

2 Research methodology

The combination of AMR and cloud represents a new operating concept for this automation solution that could be widely used in the future. The Delphi method is a tool for identifying opinions about future trends. The following chapter describes the method and its specific application to the research questions of this paper.

2.1 Delphi-method

The Delphi method was first used in the 1950s by the RAND Corporation and was initially used for military purposes [18]. The similarity in name to the ancient Oracle of Delphi is no coincidence, as the Delphi Method is also used to predict future developments.

Since its first appearance, the Delphi method has undergone a variety of different applications [19]. The individual differentiation of the method, combined with its broad application, makes it difficult to formulate a clear definition. Instead, it makes sense to describe the method in terms of its consistent core elements and characteristics, which are also understood as the classic design of a Delphi survey [19]. In addition, Delphi surveys that have already been carried out and are frequently cited in scientific contexts provide a good orientation. The core elements are the use of a standardized questionnaire, the questioning of experts whose answers are anonymized, the formation of an aggregated group opinion, the mutual information of the experts about this group opinion, and finally a multi-stage questioning of the group of experts [20]. The variants of the Delphi method are formed mainly by different options for the type of implementation, the selection of experts, the number of rounds of questions and the design of the questionnaire.

After knowing the basic elements and characteristics of the Delphi method, the overriding goal of the method is to determine a well-founded consensus or dissent among experts on a specific question in a structured manner in at least two rounds of questions [19], [21], [22]. The concrete design can be adapted to the specific question and its requirements.

Against the background of the objectives of this scientific work and on the basis of Delphi studies already successfully carried out, the core elements of this Delphi survey - procedure, structure, form and expert selection - are as follows [21], [23–30]. The procedure is characterized by a total of two rounds of questions, a pretest of the questionnaire, the implementation of the first round of questions with subsequent interim analysis, the implementation of a second round of questions taking into account the results of the first round of questions, and finally the final evaluation.

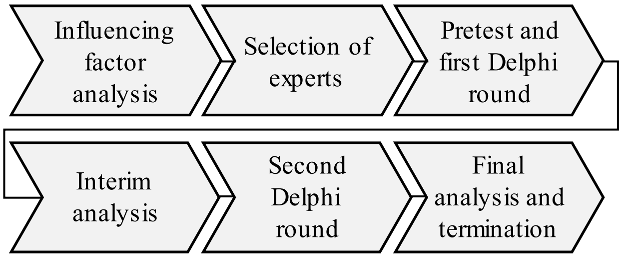

Figure 1. Delphi procedure (based on [21])

2.2 QUESTIONNAIRE STRUCTURE AND DEVELOPMENT

The questionnaire is based on a previously conducted Systematic Literature Review (SLR) as well as an analysis of a reference process that identifies factors and aspects relevant to this Delphi study [31] (see Table A in the appendix). In case of the following categories *reason for AMR/AGV introduction, AMR/AGV operations, AMR/AGV introduction barriers* and *cloud,* the questions were developed directly from this analysis. To complete the framework of influencing factors, an additional section called *general factors* is added to provide a thematic introduction to the research area. Figure 2 shows what questions were asked in which categories. Based on the core elements of the Delphi method, the questionnaire presented in this paper was divided into Part A and Part B which build on the two-part research question and is explained in more detail below.

Part	Category	Question
A	**General factos**	• What do you understand by the terms "autonomous mobile robot" (AMR) and "automated guided vehicle" (AGV)? • How do you estimate the share of AMR/AGV in intralogistics transport processes in the next 10 years? • How do you predict the number of AMR/AGV providers will develop over the next 10 years? • Which processes are suitable for implementation with currently available AMR/AGV? • How do you rate the degree of standardization of AMR/AGV applications in intralogistics transport processes? • How do you rate the efficiency (process execution in the planned time, quality and costs) of current AMR/AGV systems compared to manually operated industrial trucks?
	Reason for AMR/AGV introduction	• How important is the factor for introducing AMR/AGV?
	AMR/AGV operations : Project / overall system; Function / process; Hardware:; Software; Radio technology; Costs	• How important will this factor be for successfuland efficient use of AMR/AGV in the next ten years?
	AMR/AGV operations : Autonomy	• How important will autonomy functions in AMR/AGV become in future? • Can autonomy functions open up new areas of application? • Which autonomy functions are most important?
	AMR/AGV introduction barriers	• How big do you rate this factor as an introduction barrier?
B	**Cloud**	• How can the use of AMR/AGV be made more efficient with cloud solutions? • What will be the main application of cloud solutions in AMR/AGV in 2035? • Which outsourcing options for computing power do you find advantageous? • What will be the target control architecture of AMR/AGV systems in 2035? • What advantages and disadvantages do you see in combining AMR/AGV with cloud solutions?

Figure 2. Questionnaire development from influencing factor framework [31]

Part A addresses the question of which factors influence the use of AMR/AGV and their importance. Based on questions that define the current and future environment of AMRs/AGVs and market development, the most important decision criteria for the introduction of AMRs/AGVs are examined. This is followed by a section that highlights the importance of the key influencing factors that play a role in the use of AMR/AGV. To measure the importance of a factor, a Likert scale was used, ranging from (1) very unimportant to (5) very important [32]. In contrast to higher-level scales, the use of a five-point scale offers the particular advantage that the values can also be distinguished and differentiated linguistically. Part A concludes with questions about barriers to automation in order to identify knock-out criteria for the use of AMR/AGV. In Part A, only closed questions were used to evaluate the research area, which has already been well researched by previous work. Comment fields give the participants in the Delphi survey the opportunity to make additions and explain their assessments.

Part B asks how AMR/AGV can be combined with a cloud and thus covers the second research question. The questions in Part B range from the demand for increased efficiency of AMR/AGV using a cloud, to future main applications, outsourcing options for computing power and their purpose, the target architecture of such systems, and the general advantages and disadvantages of cloud-based operation of AMR/AGV. Except for the target architecture aspect, all questions are open-ended. The use of open questions makes sense at this point because the combination of AMRs/AGVs with a cloud represents a new way of operating transport robots, and only open questions provide a path to truly new information [33]. Closed questions would limit the solution space of cloud-based AMR/AGV solutions by prescribing answers. The answers to the questions are given in free text fields. To avoid misunderstandings and to create a basic common understanding of the questions, examples are also provided. In Part B, participants are also given the opportunity to explain their statements in the form of comment fields.

2.3 SELECTION OF EXPERTS

The selection of experts is of increased relevance in the Delphi method. The correct selection plays an important role in the validity and reliability of the results [34], [35]. There is no general rule of thumb for the selection of experts [36]. Rather, the group of experts must be individually adapted to the specific problem and topic of the Delphi survey in terms of heterogeneity, appropriate expertise and group size [37]. To obtain a meaningful result from the survey and to interview the right experts, it should be clarified for the specific study what an expert is, which experts from which area should be included, and how many experts are necessary for good results. Finally, it must also be ensured that the requirements set are fulfilled by the participants [19].

To determine what constitutes an expert, experience and level of expertise can be used as evaluation parameters. Accordingly, a participant is considered an expert if he or she has sufficient experience in the research area and a high level of expertise [38]. In addition, the areas (e.g. industry, research, politics) from which the experts should come must be defined for each research question and the overall objective of a Delphi survey [39]. It is important to avoid biasing the results by affiliation to a particular field [38]. Most Delphi studies have a number of participants between 11 and 50 experts [38]. More important than the number of participants, however, is that the right experts are interviewed for the specific problem. The significance of the results of a Delphi survey is determined by the expertise and the questioning of the right participants, not by the number of participants.

To provide targeted answers to the research questions of this Delphi study, experts from academia on the one hand and logistics and IT experts from industry on the other hand were interviewed. The interdisciplinary nature of the combination of AMR/AGV and a cloud is reflected in the experts' fields. When selecting the experts from academia, the focus was on their work and years of experience in the field of technical logistics. This requirement was met by professors and long-time academic staff. By interviewing logistics and IT experts from industry, the practical perspective is strengthened and the application perspective is included in addition to the theoretical and planning-oriented perspective. AMR/AGV manufacturers were not interviewed due to their potential conflict of interest. The main reason for this is the risk of one-sided influence on the results of the manufacturers in part B of the survey. If the experts of a manufacturer consider the combination of AMRs/AGVs with a cloud to be disadvantageous and inappropriate and prefer their own software solutions (e.g., guidance control system), a neutral and objective assessment of the potential is not guaranteed. Since AMRs/AGVs are distributed exclusively in the form of projects (high level of expertise also on the part of the user as a participant in the projects) and the Delphi study primarily focuses on the application and use of AMRs/AGVs, the extensive product expertise of the manufacturers in the development of these robots is not decisive. A minimum of five years' professional experience in the field of AMR/AGV and automation of intralogistics processes was required and, in addition, the necessary specialist knowledge was verified by asking about expertise in round one of the survey [25], [28].

2.4 DELPHI-METHOD PROCEDURE

The Delphi method was carried out in the form of an online survey. To validate the content of the questionnaire [21], to ensure the questions being comprehensible and to prove their functionality, a pretest was conducted with three representative members of the target groups. The participants of the pretest were not intended to take part in the Delphi survey and did not participate as experts.

The questionnaire for the first round was sent to the identified group of experts by e-mail in May. In addition to the questionnaire as such, participants also received a short briefing in the form of an information sheet. This provided information on the background and objectives of the Delphi survey and provided guidance on how to complete the questionnaire correctly ensuring a consistent understanding. After the first round, a quantitative and qualitative interim evaluation of the results was conducted in July. All closed questions were analyzed quantitatively using descriptive statistics. The mostly open questions in Part B were analyzed qualitatively. The free text answers of the experts were summarized and clustered thematically. In the second round, the experts were informed of the results of the first round in the form of histograms and the median, and were given the opportunity to reconsider and, if necessary, change their answers, taking into account the answers of the other experts. Based on the feedback from the experts in round one, the area of autonomy and wireless technology was adjusted. In contrast to round one, no individual evaluation of autonomous functions should be carried out in round two, but the importance of autonomous functions for AMR should be emphasized in the form of selected "TOP functions". In Part B, the open-ended questions, participants had the opportunity to actively and justifiably disagree with the answers of other experts. At this point, no restriction in the form of "TOP functions" has been deliberately chosen to open a solution space as wide as possible. This solution space will be examined and further restricted in subsequent research.

The second round of the Delphi survey was completed at the end of September 2023. A central and critical point of a Delphi survey, for which there is no single solution, is the definition of a termination criterion. One possible criterion is the overarching goal of Delphi surveys, the pursuit of consensus or dissent [40]. Another possible stopping criterion is the stability of the result [41]. If experts make no or very few changes in their assessment from round to round, the added value of follow-up rounds is questionable. Furthermore, there are studies on the loss of participants from round to round, so that the duration of Delphi surveys is also a limiting factor [42].

One measure of consensus and dissent is the interquartile range (IQR). The IQR is the measure of dispersion that includes the middle 50% of the experts' ratings. To determine whether consensus has been reached, a maximum threshold for the IQR must be defined. If the mean 50% of the submitted ratings vary by less than the threshold value, consensus is considered to have been reached [43]. In comparison with previous Delphi surveys using a five-point Likert scale, consensus is reached when the IQR ratio (threshold value) is a maximum of one [44]. The stability of responses was determined using the coefficient of variation (CV). The CV is the ratio of the standard deviation of an expert opinion on a given factor to the corresponding mean [45]. To measure stability, the absolute change in CV for each factor was calculated by subtracting the CV results of the first round from those of the second round. A maximum threshold of 0.1 provides sufficient evidence of achieved stability [46].

A further round of questions would not have been useful for several reasons. In Part A, a high degree of consensus was achieved in the area of influencing factors. In addition, the very low value of the CV change shows that there is a high degree of stability in the results and that the experts have changed their opinion only minimally against the background of knowing all the answers. Against this background, the added value of a further round of questions is not given. The numerous impulses in Part B of the Delphi method are sufficient to draw conclusions and identify future research areas for the combination of AMR/AGV with a cloud. On this basis, we have therefore decided not to conduct a further round of questions.

3 Results and Discussion

This chapter describes the results of the Delphi survey and places them in their overall context. The presentation of the results follows the structure of the questionnaire. General information about the study participants is followed by the results of Part A of the Delphi study with the categories general factors, reason for AMR/AGV introduction, influencing factors of AMR/AGV operations with further subcategories, and finally implementation barriers. The results of linking AMR/AGV to a cloud, which were surveyed in Part B, conclude the presentation of results.

3.1 Delphi Expert Panel

Based on the criteria described for selecting experts for the Delphi survey, 25 experts were identified and contacted by e-mail. Of these, 13 experts participated in the survey. This corresponds to a participation rate of 52%. All experts from the first round of questions also answered the questions in the second round, so the drop-out rate was zero. Drop-out rates of 18% or more between rounds are common [47].This is an indication of the participants' satisfaction with the study and the questionnaire design and shows their interest in the topic. The experts include three logistics experts from industry (users), two IT experts from industry, and eight experts from academia with a focus on technical logistics (see Figure 16 in the appendix). The professional experience of the participants ranges from seven to 40 years in the field of intralogistics and AMR/AGV, which is decisive for the Delphi method, with an average of 20 years. Since experience in the field is not the only determinant of the validity of the results, the experts were also asked to self-assess their expertise: "How would you rate your expertise in the area of AMR/AGV?" The self-assessment had to be made on a five-point Likert scale [26]. Eight participants (62%) rated their expertise in AMR/AGV as (5) very high, four participants (31%) as (4) high and (1) one participant (7%) as medium. The high level of expertise strengthens the validity of the Delphi survey results.

3.2 Part A: Influencing factors and their relevance to AMR/AGV use

The results of the experts' ratings of the influencing factors using the Likert scale are shown in Table 1. It also serves as an orientation and data basis for the further graphical evaluations in the following sections. The evaluation of the other questions, which were not evaluated by means of the Likert scale, are shown in separate diagrams.

Table 1: Influencing factors and their relevance to AMR/AGV use

	Factor	Round 1 (n = 13)				Round 2 (n = 13)				CV change[b]	Consensus	Stability
		IQR	CV	Med.	Mean	IQR[a]	CV	Med.	Mean			
1	Cost savings	1,00	0,10	5,00	4,69	0,00	0,09	5,00	4,77	0,01	Yes	Yes
2	Skills shortage	1,00	0,18	5,00	4,38	1,00	0,18	5,00	4,38	0,00	Yes	Yes
3	Quality	1,00	0,27	3,00	3,62	1,00	0,27	3,00	3,62	0,00	Yes	Yes
4	Industrial safety	2,00	0,30	4,00	3,69	2,00	0,23	4,00	3,85	0,07	No	Yes
5	Process stability	1,00	0,20	4,00	4,23	1,00	0,15	4,00	4,38	0,05	Yes	Yes
6	Efficiency (productivity)	1,00	0,17	4,00	4,31	1,00	0,17	4,00	4,23	0,00	Yes	Yes
7	Simplicity of implementation	1,00	0,22	4,00	4,23	1,00	0,20	4,00	4,31	0,02	Yes	Yes
8	Scalability	2,00	0,20	4,00	4,00	1,00	0,17	4,00	4,15	0,04	Yes	Yes
9	Robustness	1,00	0,14	5,00	4,62	0,00	0,13	5,00	4,69	0,01	Yes	Yes
10	Flexibility	1,00	0,19	4,00	4,08	1,00	0,14	4,00	4,23	0,04	Yes	Yes
11	(Project-)Planning	1,00	0,23	3,00	3,38	1,00	0,19	3,00	3,46	0,04	Yes	Yes
12	(Project-)Commissioning / Realization	1,00	0,19	3,00	3,31	1,00	0,15	3,00	3,38	0,04	Yes	Yes
13	Navigation	1,00	0,17	4,00	4,31	1,00	0,15	4,00	4,38	0,03	Yes	Yes
14	Route planning	0,00	0,18	4,00	4,00	0,00	0,16	4,00	3,92	0,01	Yes	Yes
15	Localization	1,00	0,17	5,00	4,46	1,00	0,15	5,00	4,54	0,03	Yes	Yes
16	Object detection	1,00	0,31	3,00	3,31	1,00	0,28	3,00	3,38	0,03	Yes	Yes
17	Order management	1,00	0,23	4,00	3,85	0,00	0,16	4,00	3,92	0,07	Yes	Yes
18	Fleet management	1,00	0,24	4,00	3,62	1,00	0,20	4,00	3,69	0,04	Yes	Yes
19	Traffic control / deadlock prevention	1,00	0,17	5,00	4,46	1,00	0,17	5,00	4,46	0,00	Yes	Yes
20	Battery- runtime	1,00	0,24	4,00	3,62	1,00	0,24	4,00	3,62	0,00	Yes	Yes
21	Computing power (onboard)	1,00	0,28	3,00	3,38	1,00	0,27	3,00	3,54	0,01	Yes	Yes
22	Sensors	2,00	0,24	4,00	3,92	1,00	0,19	4,00	4,08	0,06	Yes	Yes
23	Mechanics	1,00	0,28	4,00	3,69	1,00	0,23	4,00	3,69	0,05	Yes	Yes
24	Artificial intelligence (e.g. machine learning)	1,00	0,37	3,00	2,77	0,00	0,27	3,00	3,00	0,09	Yes	Yes
25	SLAM	2,00	0,27	4,00	3,77	2,00	0,27	4,00	3,77	0,00	No	Yes
26	Sensor fusion	1,00	0,22	4,00	3,77	0,00	0,16	4,00	3,92	0,06	Yes	Yes
27	Latency	1,00	0,35	3,00	3,46	1,00	0,27	3,00	3,62	0,08	Yes	Yes
28	Datathroughput	1,00	0,20	4,00	3,69	1,00	0,19	3,00	3,54	0,02	Yes	Yes
29	Reliability	1,00	0,20	5,00	4,38	1,00	0,17	5,00	4,46	0,02	Yes	Yes
30	WLAN	2,00	0,24	5,00	4,15	2,00	0,23	4,00	4,08	0,00	No	Yes
31	LTE, 4G	1,00	0,35	3,00	2,69	1,00	0,35	3,00	2,69	0,00	Yes	Yes
32	5G	1,00	0,33	3,00	2,77	1,00	0,30	3,00	3,00	0,03	Yes	Yes
33	Purchase price	0,00	0,09	5,00	4,77	0,00	0,09	5,00	4,77	0,00	Yes	Yes
34	Planning / commissioning costs	1,00	0,20	4,00	4,23	1,00	0,20	4,00	4,23	0,00	Yes	Yes
35	Operating costs- energy costs	1,00	0,35	3,00	3,38	1,00	0,35	3,00	3,38	0,00	Yes	Yes
36	Operating costs- Maintenance costs	1,00	0,17	4,00	4,31	1,00	0,17	4,00	4,31	0,00	Yes	Yes
37	Operating costs- repair costs (spare parts)	1,00	0,12	4,00	4,46	1,00	0,12	4,00	4,46	0,00	Yes	Yes
38	Costs computer hardware	1,00	0,26	3,00	3,23	1,00	0,26	3,00	3,23	0,00	Yes	Yes
39	Flexibility	1,00	0,35	3,00	3,46	1,00	0,32	3,00	3,54	0,03	Yes	Yes
40	Cycle time	1,00	0,35	3,00	3,38	1,00	0,27	3,00	3,54	0,08	Yes	Yes
41	Speed due to safety	0,00	0,38	3,00	2,92	0,00	0,35	3,00	2,85	0,03	Yes	Yes
42	Mixed operation	2,00	0,40	3,00	3,31	1,00	0,35	3,00	3,46	0,05	Yes	Yes
43	Load pickup / load transfer	1,00	0,26	3,00	3,38	1,00	0,22	4,00	3,54	0,04	Yes	Yes
44	Availability	2,00	0,42	4,00	3,23	2,00	0,41	4,00	3,15	0,02	No	Yes
45	Variant variety container	1,00	0,31	3,00	3,38	1,00	0,26	3,00	3,23	0,05	Yes	Yes
46	Costs	1,00	0,17	4,00	4,31	1,00	0,17	4,00	4,31	0,00	Yes	Yes
47	Application area outdoor	1,00	0,25	3,00	3,54	1,00	0,19	3,00	3,54	0,06	Yes	Yes
48	Manufacturer-independent control system	1,00	0,46	3,00	2,69	1,00	0,46	3,00	2,69	0,00	Yes	Yes
49	Lack of knowhow, knowledge, competence	1,00	0,41	4,00	3,38	1,00	0,34	4,00	3,54	0,07	Yes	Yes
50	Lack of guidelines, regulation, standardization	2,00	0,42	3,00	2,77	2,00	0,42	3,00	2,77	0,00	No	Yes
51	Target architecture	1,00	0,36	3,00	2,46	0,00	0,35	3,00	2,54	0,01	Yes	Yes

[a] Consensus reached if interquartile range (IQR) of maximum 1.00
[b] Stability reached if absolute coefficient of variation (CV) difference between round 1 and round 2 of maximum 0.1

DOI: 10.2195/lj_edrev_morgenstern_en_202409_01

3.2.1 General factors

Technological advances in navigation and developments such as object and image recognition have led to the term AMR being increasingly used in the context of automated transport processes, alongside the classic term AGV. The use and interpretation of the two terms ranges from their use as synonyms to the view that AMR is a marketing term used by manufacturers to improve sales [7], [48–50]. However, experts clearly and unanimously agree on the definition that the distinction between the terms AMR and AGV must be evaluated in different gradations for processes and functions (e.g., navigation) [7]. For example, a predefined track on a map is not an autonomous function. For this specific aspect, AMRs only have a predefined driving area in which they independently plan a route to complete their transport order. Another example function of an AMR, unlike an AGV, is obstacle avoidance.

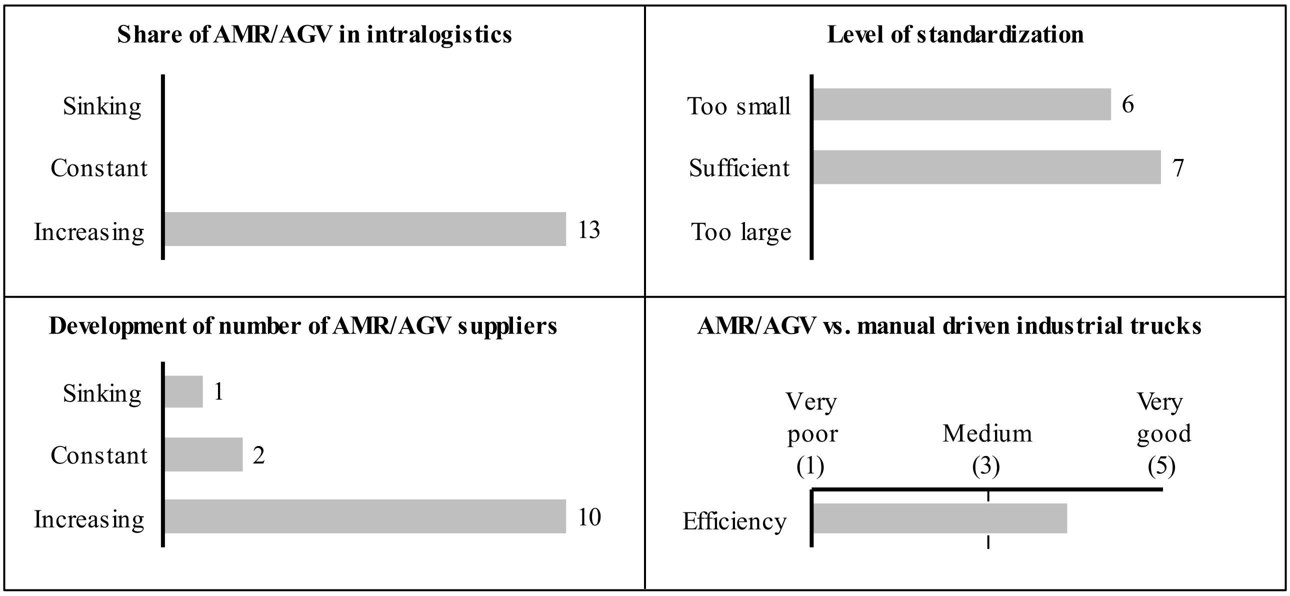

Figure 3. Results of general factors

The future development and forecasts for the AMR/AGV market are considered positive [6]. To verify the forecasts, the share of AMR/AGVs in intralogistics transport processes and the development of the number of AMR/AGV suppliers were assessed. The answers to these two questions underline the forecasts and statements that the AMR/AGV market is growing. According to the experts, the share of AMR/AGV in intralogistics transport processes is increasing (100%) and the most experts (77%) predict that the number of providers in the market will continue to increase, while two experts (15%) predict that the number of AMR/AGV providers will remain the same and one participant (8%) predicts that the number will decrease.

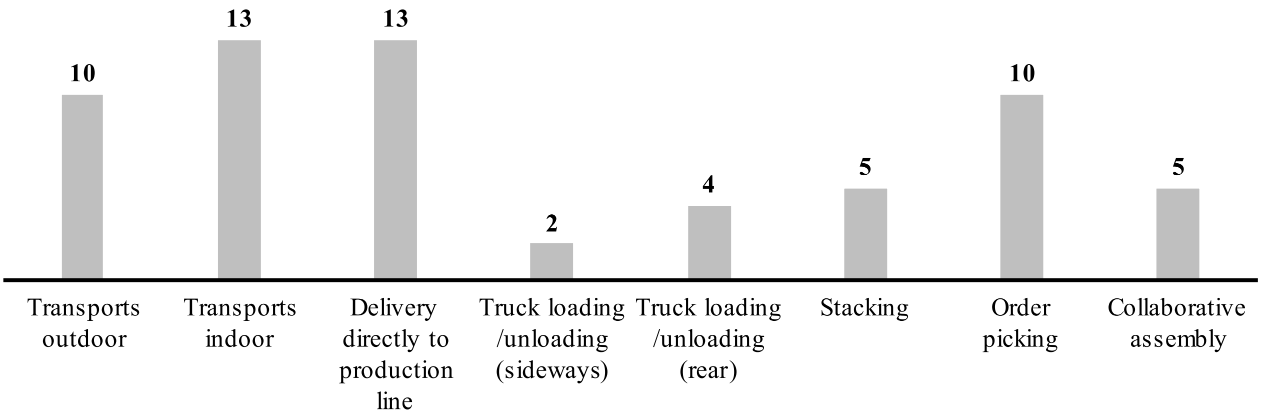

Figure 4. Suitability of the use case for AMR/AGV implementation

Indoor transport processes, transportation within halls and provisioning processes to production lines are the most suitable for execution with AMR/AGV. It is noteworthy that transport processes outside the halls (outdoor) are more suitable than in the study by Clauer [14] in 2019 on the use of autonomous transport systems on the factory premises. This shows that technological developments in the field of AMR/AGV components can gradually open new applications and that the systems are becoming increasingly robust. The experts also see a high degree of suitability for order picking processes. Processes with many degrees of freedom and influencing variables are considered less suitable: Collaborative assembly, stacking processes, side loading and unloading of trucks, and rear unloading of trucks. In summary, the focus of AMR/AGV applications is on transportation processes and certain applications cannot be realized with currently available AMR/AGV solutions. This means that there is untapped automation potential, especially in the field forklift processes. It has also been found that new technologies require new processes and that current intralogistics processes need to be adapted to AMR/AGV requirements to realize the full automation potential and the full performance potential of AMR/AGV in the future. Particularly in forklift processes, the approach of automating a human-oriented process is reaching its limits.

In order to derive the future need for action and research, the degree of standardization and the efficiency of AMR/AGV compared to manually operated industrial trucks were evaluated. Efficiency is defined here as the execution of the process within the planned time, quality and costs. The degree of standardization is considered sufficient (53%) to too low (47%). The efficiency of AMR/AGV compared to manually operated industrial trucks is rated as good (3.92). The main reasons given for this efficiency rating are that several AMR/AGVs can replace a human-operated process with positive economic efficiency or, in contrast to humans, work continuously and reliably in terms of quality.

3.2.2 Reason for AMR/AGV introduction

Various economic, environmental and social factors play a role in the decision to use AMR/AGV. As the decision to implement AMR/AGV in intralogistics transport processes is basically the starting point of any project and therefore also important for the combination of AMR/AGV with a cloud, various reasons for implementation were evaluated. The most important reasons for implementation are cost savings (4.77), lack of skilled labor (4.38), and achieving improved process stability (4.38). As it becomes increasingly difficult for companies to find qualified personnel for their processes, process automation offers a way to counteract this trend, in addition to the still most important factor of reducing personnel costs. Especially process stability is seen as the benefit of predictable, reliable and therefore traceable processes. AMR/AGV therefore take on other functions in addition to the execution of the process, such as an organizational tool in the intralogistics system. The factors of increased efficiency, occupational safety and damage prevention are considered less relevant. However, there is disagreement among the experts about the importance of occupational safety, as evidenced by the spread of the ratings and the IQR (2.00). The disagreement applies to both the academic experts and the logistics and IT experts from industry. Experts who gave a low rating to the importance of occupational safety state that safe working conditions are already established in the intralogistics environment and that safety can be increased through other measures such as training or impact protection. A high rating for occupational safety represents the view that the introduction of AMR/AGV will result in the implementation of tested, intrinsically safe systems that reduce the risk of injury to people.

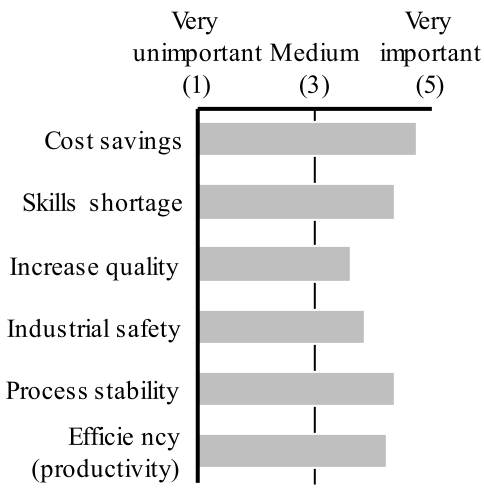

Figure 5. Importance - Reason for AMR/AGV introduction

3.2.3 Factors influencing the successful use of AMR/AGV

For better clarity and traceability, the influencing factors for successful AMR/AGV use category is divided into subcategories. These are as follows:

- Project / overall system
- Function / process / technology
- Hardware
- Software
- Radio technology
- Costs
- Autonomy

The factors were rated on a standardized five-point Likert scale. The overarching question to the experts for all subcategories is: "How important will this factor be for the successful and efficient use of AMR/AGV in the next ten years?” with possible answers ranging from very unimportant (1) to very important (5). Based on expert feedback from the first round of questions, the areas of wireless technology and autonomy were expanded and detailed questions were added.

Project / overall system

The Project / overall System subcategory includes influencing factors which relate to the cycle of an entire AMR/AGV project and factors that describe the characteristics of the overall AMR/AGV system. Within the subcategory, robustness (reliability) (4.69), ease of implementation (4.31), flexibility (adaptability) (4.23), and scalability (4.15) are considered most important. The high rating of these factors goes hand in hand with expecting high availability of a production machine in general. According to the experts, it is important that AMR/AGV works as smoothly as possible and can be used in the company's own processes and structures without a costly project. It should also be as easy as possible to adapt to new processes and to increase the number of AMR/AGV units. The factors relating to the various planning phases, (project) planning (3.42), (project) commissioning / implementation (3.42), were rated as less important by the experts. One argument for this assessment is that planning and commissioning will become less important in the future if AMR/AGV are easy to implement. All influencing factors in this subcategory are consistent and stable.

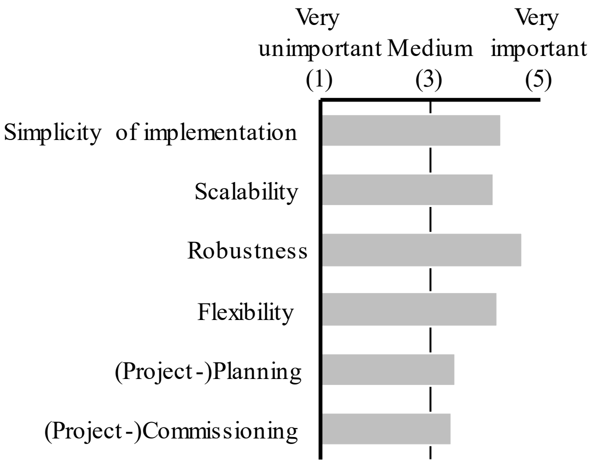

Figure 6. Importance - Project / overall system

Function / process / technology

The subcategory "Function/Process/Technology" summarizes influencing factors that are of great importance for the operation of AMR/AGV. These are presented on a very aggregated level. The experts' assessment of the different functions in terms of their relevance for the successful and efficient use of AMR/AGV can be divided into three groups. According to the participants, traffic control/congestion avoidance (4.46) and navigation (4.38) are the most important ones. The high relevance of these functions underlines the view that AMR/AGV can be broken down into a production machine that must work. In concrete terms, this means that AMR/AGVs must be integrated into the logistics traffic without disruptions or bottlenecks and must always be able to determine their own position in their environment and follow their transport route. The second group consists of the functions Route Planning (3.92), Order Management (3.92), and Fleet Management (vehicle status monitoring) (3.69). In addition to traffic control, the functions of order management and fleet management are assigned to the control system in the conventional AGV architecture. The least important function in this context is Object Recognition & Image Processing (3.38). However, it should be noted that the experts stated in their comments that this function will become more important in the future. It can therefore be assumed that, in contrast to the future-oriented question, this is more of a status quo assessment. Well-functioning object recognition and processing can also generate information that has a direct impact on improving other functions, such as traffic control and route planning. By recognizing and classifying other road users, such as other forklifts or people, actions such as overtaking or not overtaking can be derived. The spread of the expert ratings in this subcategory is not conspicuous and the results are also stable over the two rounds of questions.

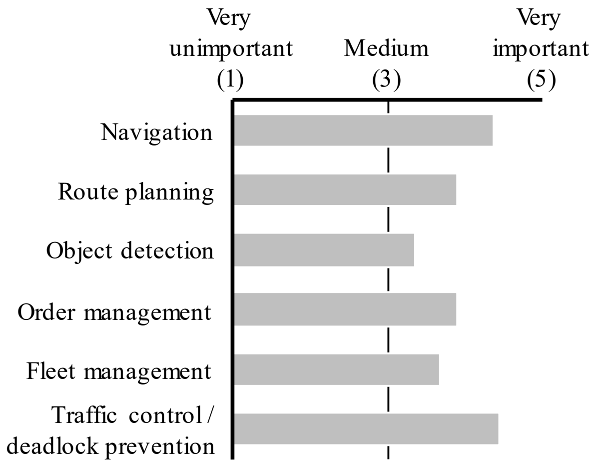

Figure 7. Importance - Function / process / technology

Hardware

In the Hardware subcategory, again when compared directly to the Software subcategory, it is noticeable that the influencing factors are considered highly relevant on average. However, it is particularly striking that the sensor technology factor (4.08) is rated the highest in terms of its importance for the successful and efficient use of AMR/AGV. The experts identify sensor technology as the critical factor for the overall performance of AMR/AGV in the future. The mechanical motion component factor (3.69) forms the basis for the functioning of the AMR/AGV. The design of the overall battery concept (3.62) can influence the overall economy of the AMR/AGV. The number of AMR/AGVs required for a process depends on their runtime and therefore on the battery type and the charging concept. Poor design of these parameters can result in the need for more AMR/AGVs to ensure uninterrupted operation. The computing power (on board) factor (3.54) was rated as the least relevant in the subcategory. However, the fact that sensor technology will become more important in the future and that sensor data will need to be processed may increase the importance of computing power in the future.

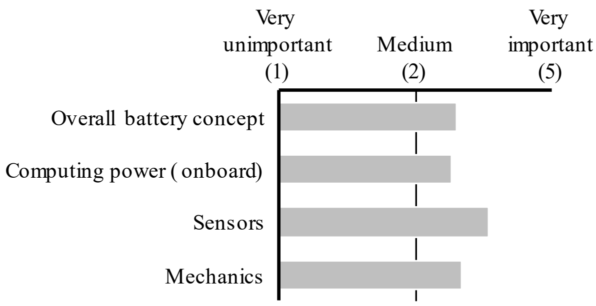

Figure 8. Importance - Hardware

Software

The evaluation of the sensor fusion factor (3.92) extends the importance of sensor technology. It is not only the sensor technology as such that is critical, but also the merging and combining of different sensor signals into an overall picture. For example, adding infrastructure and combining the sensors of multiple AMR/AGVs in process-critical areas such as intersections can improve AMR/AGV deployment. Without sensor fusion, the perception range of the AMR/AGV is only as large as the environment detected by the vehicle's own sensors. In line with the high relevance of navigation, the associated algorithm SLAM (Simultaneous Localization and Mapping) (3.77) is also rated as important. However, the experts' opinions differ, so that the IQR is above the threshold. The delta of the CV between the two rounds of questions is zero, which means that this disagreement is also stable. Artificial intelligence (e.g., machine learning) (3.00) was rated as the least important factor. One reason given for the average rating is that the overall trend needs to be related to specific applications for a clearer rating of important or unimportant.

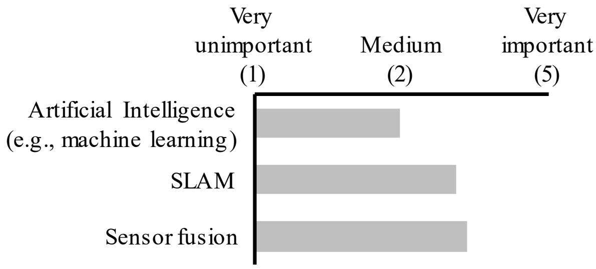

Figure 9. Importance - Software

Radio technology

The Radio Technology subcategory includes various wireless technologies and characteristics that describe wireless technologies. In the area of radio technologies, WIFI (4.08) was clearly rated as the most important radio technology compared to 5G mobile communications (3.00) and LTE, 4G mobile communications (2.69). This result should be seen in conjunction with the responses to the question of which processes are suitable for implementation with currently available AMR/AGV. In particular, indoor transport was rated as highly suitable. The high importance of WIFI as an economical and easy-to-implement wireless technology in production halls is therefore plausible. Although WIFI was rated highest on average, the Delphi participants disagree between medium and very important relevance (IQR>1). In the area of outdoor applications, the result is reversed and more than two thirds of the experts see 5G (69%) as the most suitable wireless technology. This is due to the fact that the cellular network has better availability and coverage in outdoor areas compared to WIFI.

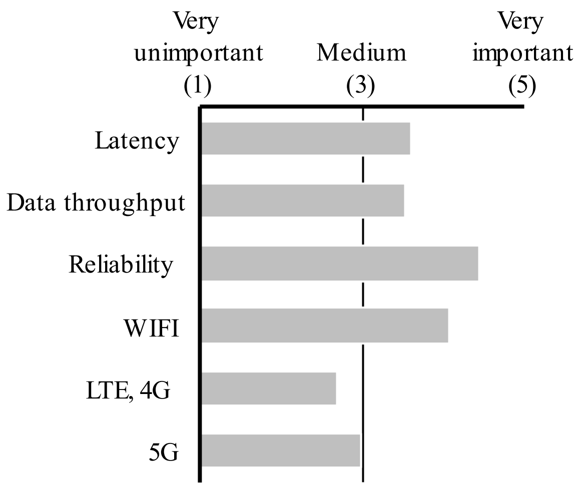

Figure 10. Importance - Radio technology

Reliability (4.46) of the wireless technology was identified as the most important feature. In a worst-case scenario, the loss of connectivity to the AMR/AGV fleet can lead to a standstill of the devices, thus threatening the continuation of production in the area of production supply.

For example, in the assembly of an automobile plant, a shutdown of production facilities or assembly lines results in enormous costs [51]. Latency (3.62) and data throughput (3.54) were rated as less important but are becoming more relevant as functions are outsourced to a cloud environment.

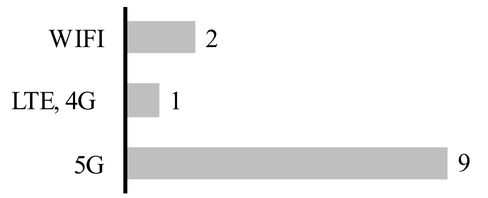

Figure 11. Outdoor suitability radio technology

Costs

In the area of costs, it is noticeable that all factors included in this category are considered important on average. The most important factor is the purchase price (4.77). Repair costs (cost of spare parts) (4.46), maintenance costs (4.34) and planning and commissioning costs (4.23) were also rated as very important by the Delphi experts. According to the experts, energy costs (3.38) and computer hardware costs (3.23) are less important. AMR/AGV are introduced in the form of projects where the net present value method and the payback period are often used to assess the profitability [52]. One-time and recurring costs are considered and compared with the savings achieved through the use of AMR/AGV. As an initial one-time expense, the purchase price is of greater importance in this analysis. The shorter the required payback period, the greater the importance of the purchase price of the AMR/AGV. In addition to the purchase of AMR/AGV, it is increasingly possible to rent the transport systems in a comparable way to a car. This can reduce the initial one-off costs and make the technology accessible to financially weaker companies.

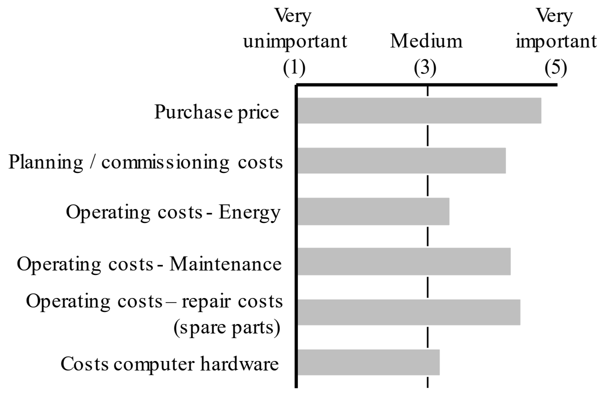

Figure 12. Importance - Costs

Autonomy

The need for and necessity of autonomy functions in transport robots is a controversial topic in current debates on AMR/AGV in science and practice [50].One extreme position is characterized by the view that autonomy functions are not necessary for the automation of transport processes. Instead of many degrees of freedom and driving on cleared areas, this position considers, for example, following a lane to be the most expedient navigation. On the other hand, there is the camp of those who see the autonomy function as absolutely necessary to optimize current use cases and open up new ones. These two positions are also reflected in the dispersion (IQR>1) of the importance of autonomy (4.00). Twelve experts (92%) answered "yes" and one expert (8%) answered "no" to the question of whether autonomy functions can open up new applications for AMR/AGV. Examples of new applications include mixed traffic and AMR/AGV applications in the public sector. The experts were also asked to create a "TOP 3" ranking of currently known autonomy features. The evaluation of the ranking resulted in the following order:

- Actions based on object recognition and classification
- Driving in approved areas instead of designated lanes
- Obstacle avoidance

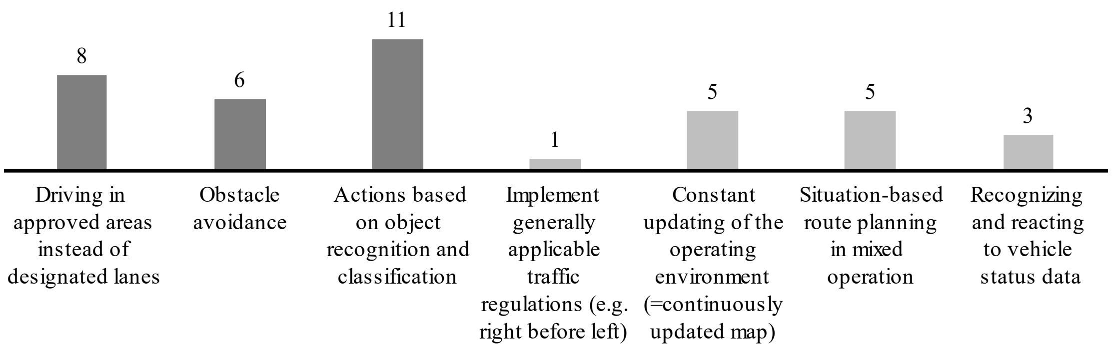

Figure 13. Evaluation of the importance of autonomy functions

One expert considered it necessary to drive on cleared areas instead of predefined lanes and to drive around obstacles in order to achieve appropriate system robustness in mixed operations and in interaction with passenger traffic.

3.2.4 AMR/AGV INTRODUCTION BARRIERS

The barriers to implementation fall into three groups. The experts rate costs as the biggest obstacle (4.31). This means that costs play a key role both as a reason for adoption in the form of expected savings, during operation in the form of acquisition and operating costs, and as an obstacle in the form of excessive costs of AMR/AGV.

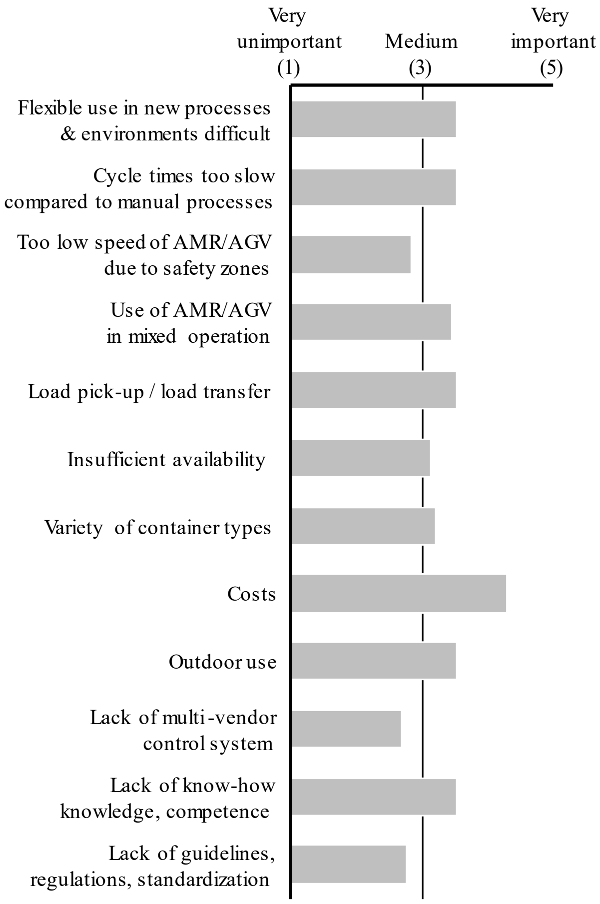

Figure 14. Importance - Introduction barriers

The second group consists of the following barriers:

- Lack of know-how, knowledge, competence (3.54)
- Flexible use in new processes & environments difficult (3.54)
- Cycle times too slow compared to manual processes (3.54)
- Outdoor use (3.54)
- Load pick-up / load transfer (3.54)
- Use of AMR/AGV in mixed operation (3.46)
- Variety of container types (3.23)
- Insufficient availability (3.15)

The factors that present the fewest obstacles are

- Too low speed of AMR/AGV due to safety zones (2.85)
- Lack of guidelines, regulations, standardization (2.77)
- Lack of multi-vendor control system (2.69)

Ideally, the identified barriers to adoption can be overcome by combining AMR/AGV with a cloud. One possible alternative solution to reduce the main barrier to AMR/AGV adoption identified by the experts is, for example, on-demand cloud-based services ("x-as-a-service"). The combination of sub-areas is highlighted in Part B of the Delphi survey.

3.3 PART B: HOW CAN AMR/AGV BE COMBINED WITH A CLOUD?

Part B of the Delphi survey examines the combination of AMR/AGV with a cloud solution. The main questions are how the current operation of AMR/AGV can be made more efficient with a cloud, in which architecture a possible implementation can be carried out, and what general advantages and disadvantages result from the combination of the two sub-areas. In this way, a solution space is created from which further in-depth research requirements can be derived. In order not to limit the solution space from the outset, open-ended questions were used in Part B. It is important to note that these are the summarized views of the experts in the Delphi survey and therefore not already proven research results. For a clearer presentation of the results, the answers with the most mentions are highlighted and discussed in the following subchapters. All expert responses are considered and help to classify and explain the results.

Figure 15 shows an interpretation of the expert responses to Part B, which are discussed in detail in the following sections. The basic interaction between the AMR/AGV and a cloud works in a hybrid system in that the master control functions and also functions that traditionally run on board the AMR/AGV are provided in the cloud. There are also functions that run locally on the AMR/AGV. The advantages of the cloud are the provision of high computing power combined with better scalability and flexibility. Implementing future AMR/AGV innovations on the AMR/AGV itself increasingly requires high computing power, which leads to high costs if each device has to be equipped accordingly.

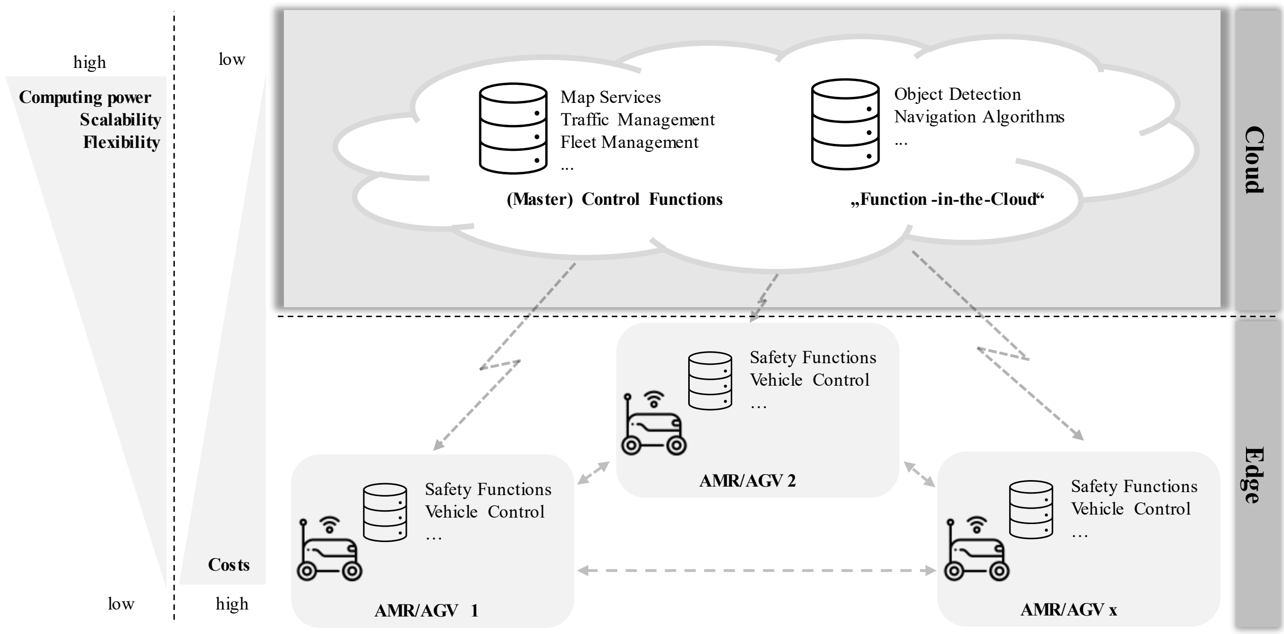

Figure 15. Summary of the results of the AMR/AGV and cloud combination

3.3.1 AREAS OF APPLICATION AND IMPLEMENTATION ARCHITECTURE

Based on the implementation barriers and the cloud applications identified in the SLR, the Delphi method is used to explore possible application areas and an implementation architecture for AMR/AGV and a cloud with the following questions:

- How can the use of AMR/AGV be made more efficient with cloud solutions?
- What are the advantages of outsourcing computing power?
- What will be the target control architecture of AMR/AGV systems in 2035?

The fact that no expert answered "no" to the question of whether AMR/AGV deployment can be made more efficient with cloud solutions, coupled with the large number of different efficiency-enhancing design measures, emphasizes the potential of an AMR/AGV cloud combination. The three most commonly cited are:

- Control functions in the cloud - a multi-vendor control system
- Cloud as global coordinator
- “Function-in-the-cloud” without real-time capability (e.g., object detection)

The most frequently mentioned aspect is control functions in the cloud (multi-vendor control system). This answer should be seen in the context of the classic AMR/AGV business. Typically, a user not only buys a robot from a manufacturer, but also requires a proprietary control system to control and monitor the devices. In the case of large-scale applications, such as automotive manufacturing, multiple AMR/AGV vendors need to be coordinated and interfaced with planning systems. This adds a level of complexity that can be avoided with a multi-vendor AMR/AGV control system. According to experts, cloud-based control systems can achieve global traffic control and, in conjunction with this, holistic task and route optimization. Another result of a multi-vendor AMR/AGV control system is ultimately cost savings, which are even greater when many different AMR/AGV vendors are implemented in a user's intralogistics processes.

The second point, the cloud as a global coordinator, covers several aspects. First and foremost, it is about enriching the AMR/AGV's own recorded states (via sensors) with contextual knowledge and enabling sensor fusion. Compared to the current status quo, this means that an AMR/AGV can record and combine more states than it can record with its own sensors. This makes it possible to integrate infrastructure (e.g., gate controls, traffic lights) and monitor process-critical areas such as intersections with sensors. A cloud-based global coordinator acts as an overarching information control center, providing centralized information and ensuring that decisions are made in favor of the overall system without prohibiting decentralized decisions. The example of a navigation system can be used to illustrate this. If traffic delays occur on the planned route, alternative routes are suggested to the driver, and it is up to the driver to decide whether to take the alternative route or stay on the original route.

Providing complete functions in the cloud is another way to increase efficiency, experts say. Due to latencies and bandwidth requirements, an initial sweet spot is found in functions that do not require real-time capability and at the same time are associated with high costs for an onboard AMR/AGV implementation. A frequently cited example is image and object recognition. The current state of the art excludes safety-related functions due to their real-time requirements.

Outsourcing functions to the cloud can lead to cost savings by reducing the computing power required on board the AMR/AGV. In this context, experts see the following options for outsourcing computing power to the cloud as advantageous:

- Cost reduction
- Evaluation of computationally intensive functions (e.g., image data evaluation)
- Reducing energy consumption

The cost effect is linked to the use of cheaper processors on board the vehicles, which is only possible if the functions are computed in the cloud and can therefore be accessed as a service by the AMR/AGVs. Finally, outsourcing resource-intensive computing operations also results in reduced energy consumption and extended uptime for the AMR/AGV [53].

In principle, there are three options for implementing the control technology: centralized, decentralized, or hybrid control architecture [54]. Control systems are described as centralized if the decisions of the entire system are made exclusively by a master controller. The opposite is decentralized control, where control processes are distributed among different components or participants in the system. When a control system has both centralized and decentralized characteristics, it is considered hybrid. A hybrid control system is therefore a mixture of centralized and decentralized control. The experts in the Delphi survey largely rate the target architecture for controlling AMR/AGVs in 2035 as a hybrid control system (10). Three experts predict centralized control (3) and no experts selected decentralized control (0) as the target architecture. According to the experts, both decentralized decisions will be made at the AMR/AGV and centralized decisions will be made by the master controller. This is particularly interesting in view of the discussions in the context of Industry 4.0, which largely predict an increasing trend towards decentralization [55].

3.3.2 Advantages, Disadvantages and Measures to Overcome Disadvantages

In addition to simply naming the efficiency measures resulting from combining AMR/AGV with a cloud, the Delphi survey asked experts to group these measures into major applications. The top applications in 2035 for cloud solutions for AMR/AGV are:

- (Master) control functions
- Cloud as global coordinator
- Computing power
- Administration
- Cloud as digital twin

The application (control) management functions, cloud as global coordinator and computing power have already been described in detail in section 3.3.1. Several sub-applications are grouped under the main administration application. For one, this includes the management of the software and thus also the updates for the software. By connecting an entire AMR/AGV fleet to a cloud, a software update can be performed directly for all vehicles in the fleet. In addition, each vehicle's data (e.g., vehicle status data, battery status, job data, faults) can be centralized in a data room in the cloud. A common data room instead of many separate data lakes is the basic prerequisite for the value-adding use of data, which creates further potential [56]. A further expansion stage in the aggregation of all data and system properties is the use of the cloud as a digital twin. The digital twin creates transparency about the implemented AMR/AGV system and is also useful for planning and simulating new systems. Production and logistics buildings can be planned and material flow simulations can be performed in the realistic digital simulation environment. Finally, the logistics system can be planned as a whole and different AMR/AGV configurations can be realistically tested and optimized without disrupting the real processes.

The explicit benefits of combining AMR/AGVs with a cloud, as identified by the experts' responses, are:

- Cost reduction (outsourcing, easier implementation of new applications)
- Ease of integration
- Control system in the cloud = universal interfaces for communication between vehicle, control system and all other systems (including infrastructure)
- Management, scalability, flexibility of heterogeneous AMR/AGV fleet
- Combination of AMR/AGV does not preclude general cloud benefits
- Ability to implement functions that cannot be calculated on AMR/AGV

In addition to the efficiency-enhancing measures and benefits of the combination, the experts also identified disadvantages and weaknesses of cloud-based AMR/AGV.

On the one hand, these are driven by the current perspective and assume that the cloud AMR/AGV combination lacks technological maturity, an overall concept and, ultimately, the expertise to implement the new approach, which requires a high level of knowledge in the areas of technical logistics and IT. One expert elaborates on the lack of an overall concept, saying that individual applications are currently being considered in isolation, and that the real benefits and great potential can only be realized by taking a holistic view of the big picture. There are also risks in the areas of IT security and data protection. The wireless connection to the cloud provides an additional gateway for external attacks. In addition to the benefit of cost savings by outsourcing intelligence to the cloud and the associated installation of less expensive components in the AMR/AGV, the operating costs and energy consumption of the cloud must also be considered ("ecological footprint"). The downside of simplifying the operation of an entire AMR/AGV fleet via the cloud is the increased complexity of the overall system and the associated increased synchronization effort. The most cited disadvantage is the radio bottleneck and single point of failure associated with a cloud. There are two points to consider here. On the one hand, the connection to the cloud can come to a standstill if the wireless technology is interrupted, and on the other hand, cloud downtime can also occur. In both cases, a potential consequence is the shutdown of the entire AMR/AGV fleet. The disadvantages of cloud-based AMR/AGV applications can be summarized as follows:

- Lack of competence
- Lack of overall concept
- Isolated consideration of individual applications without evaluation of the overall picture
- Lack of technological maturity, suitability for production only in the future
- Wireless technology bottleneck: transmission, latency, availability
- Single point of failure →radio, cloud
- Increased complexity of the overall system, increased synchronization effort
- IT security, privacy
- Operating costs, energy consumption, carbon footprint Cloud

In connection with the naming of disadvantages, the experts were also asked about measures to minimize risks and disadvantages. The most mentioned measures to mitigate single points of failure and increase reliability are redundancy and caching. Specific methods include geo-redundancy and zone-redundancy in the cloud and the active-active or active-passive cloud pattern [57–59]. For example, hot backup is used for intermediate storage. Caching allows transport requests and routes to be buffered so that a disruption does not bring the AMR/AGV system to a stop. Another safeguard is that safety-related functions that require real-time capability are not outsourced over a wireless technology. Although the 5G wireless standard promises latencies down to 1 ms, there is no real-time capability. It is also argued that despite centralization and the associated dependence on the cloud, decentralized decisions should still be possible and the AMR/AGV should have sufficient independence. Finally, a large number of experts rely on interdisciplinary development in the network and research. Only through further research into combining AMR/AGV with a cloud, robust hybrid systems can be developed that can deliver the benefits and efficiencies described above.

4 CONCLUSION

The automation of transport processes using AMR/AGV is a continuing trend in intralogistics. Automation will play a key role in the coming years to ensure competitiveness in high-wage locations such as Germany and in the face of a growing shortage of skilled workers. Lowering the barriers to adoption and continuously improving the efficiency of the use of AMR/AGV are essential to enable companies with little know-how to access these automation options. For this reason, this scientific paper uses a Delphi method to determine the importance of the key influencing factors for the use of AMR/AGV and, in a next step, develops measures to increase efficiency based on the combination of AMR/AGV with a cloud with the help of experts.

Based on a preliminary study in which the factors that play a role in the use of this automation in intralogistic transport processes were determined by means of an SLR and the analysis of an AMR/AGV reference process, a Delphi questionnaire was developed to evaluate the importance of the factors (Part A). The experts' answers confirm the trend of a growing market for AMR/AGV solutions. Furthermore, they believe that a distinction between the terms AMR and AGV needs to be evaluated in different gradations of processes and functions (e.g., navigation). The experts see the main applications of AMR/AGV in transport processes. Here, the suitability of indoor transport processes is much greater than that of outdoor processes. Furthermore, use cases have been identified that cannot be realized with the AMR/AGV solutions that are technically available today. This results in a high untapped automation potential, e.g. in forklift processes. The main reasons for adopting AMR/AGV are the expected cost savings and the shortage of skilled workers. In addition, the desire for increased predictability and process stability is also cited as a very important reason for the decision to implement AMR/AGV. AMR/AGV are seen by the experts as production machines, which underlines the very high rating of the robustness factor. Flexibility and scalability are also very important. The planning phases of

AMR/AGV projects and the importance of commissioning will become less relevant in the future due to the simpler operability of the devices. The most important functions of AMR/AGV are navigation and, in the context of a fleet, traffic control. Another key differentiator in the future will be the sensor technology used, while the mechanical system will be the basic framework. Experts believe that sensor fusion, i.e. the algorithmic combination of multiple sensor information, will be essential in the future to achieve stable and robust operation of AMR/AGV, even in dynamic operating environments. The reliability of the wireless connection is the most important feature for connecting AMR/AGV to a cloud. Despite the continuous development of cellular technology, intralogistics experts consider WIFI to be the best wireless solution. For outdoor applications on the factory premises, the use of 5G is recommended. According to the experts, new applications for AMR/AGV can be developed with the help of autonomy features. These will mainly be based on object recognition and classification. Driving on approved areas instead of predefined lanes and avoiding obstacles will also contribute to the development of new applications. The most important factor for the experts is cost. In particular, the purchase price is the deciding factor for or against the use of AMR/AGV for commercial companies. This is confirmed by the fact that the experts see high costs as the biggest obstacle to implementation. In addition, there is a perceived need for further knowledge and skill development to implement more AMR/AGV projects.

The second part (Part B) of the Delphi survey explored how to combine the use of AMR/AGV with a cloud. Here, the experts provided a variety of assessments of the efficiency-enhancing measures, advantages, and disadvantages associated with such a combination. Most of the the experts' opinions on efficiency gains can be summarized in two points: "Control functions in the cloud" and "Cloud as global coordinator". In this way, heterogeneous AMR/AGV fleets can be orchestrated and optimally operated by a single user. Experts see a hybrid solution as the target control architecture. In a hybrid system, the cloud can be seen as a coordinator that can perform and enable both centralized and decentralized system interventions. In this way, information can be provided centrally while decision authority remains decentralized. In later stages of cloud-based AMR/AGV systems, experts believe that it is also possible to provide entire functions in the cloud. In this way, computing power and intelligence can be taken from the individual AMR/AGV and made available once in the cloud. This outsourcing option is particularly advantageous for functions that have a very short runtime compared to the total operating time of the AMR/AGV and require a lot of computing power. This can lower the costs of an AMR/AGV fleet and reduce the energy consumption of the devices. In addition to the cost benefits, experts say that connecting to a cloud offers the advantages of improved scalability, flexibility and management of heterogeneous AMR/AGV fleets. The main disadvantage is the dependence on the cloud connection. Here, the wireless connection represents a bottleneck and increased risk to the overall system, which has become more complex because of the cloud. There is a lack of expertise and overall concepts that describe such a combination of the AMR/AGV and cloud sub-areas.

AMR/AGV implementations are application specific projects. The results of the Delphi survey therefore provide a very good delimitation and also a basic distinction of the importance of the influencing factors, but ultimately the specific application determines the importance of a factor. The importance of the influencing factors can therefore vary from case to case. To reflect this diversity, it is conceivable not only to limit the field to intralogistics processes, but also to provide the experts with a specific use case. By specifying and compiling several reference use cases, an overall picture could be generated. However, due to the time-consuming nature of such a study design, there is a risk of high dropout rates, which would require a much larger study, the implementation of which could reach the limits of practicability.

The Delphi study creates a high degree of transparency about the factors that play a role in the use of AMR/AGV. In addition, the current and, above all, the future importance of the factors is presented. By creating transparency, users without prior knowledge will be able to identify potential critical factors that need to be considered when implementing an AMR/AGV in their company. By answering open questions, a comprehensive solution space for possible combinations between AMR/AGV and a cloud was also developed, which should make the overall deployment more efficient. Despite the widespread use of AMR/AGV, not all applications are currently cost-effective, and some applications, such as forklift processes, are not yet fully developed. By combining this with a cloud, a path has been identified that has the potential to unlock new efficiencies and implement applications.

In addition to the results of this study, one aspect that could lead to the development of greater potential in the future when combining cloud and AMR/AGV is the adaptation of processes. If the intralogistics transport processes that are currently carried out manually and are already conventionally automated are taken as given and these are then simply automated on a cloud basis with an AMR/AGV, this does not lead to the full performance of the approach being achieved. The full potential can only be realized if the processes are tailored to cloud-based AMR/AGV automation. To do this, the processes must be reviewed in their sequence and it must be examined where in the intralogistics system which functions must be performed by which participant (e.g., AMR/AGV vs. cloud).

A final stage in the development of cloud-based AMR/AGV systems will be to create plug-and-play systems that can be implemented by users with little process experience. Implementation and operation will be based on modules and functions that can be easily accessed via the cloud and paid for on a pay-per-use basis. In this way, high initial investments can be avoided and SMEs in particular can gain easier access to the necessary automation solutions for intralogistics transport processes. To reach this final stage of expansion, the developed solution space must be deepened and further investigated in further research work. The next step in this project is to derive the potential for outsourcing AMR/AGV processes and functions to the cloud, which will provide precise information on the technical and economic impact of outsourcing options.

1 References

[1] I. Altintac, "Digitalisierung und Industrie 4.0," in *Produktion und Logistik in der digitalen Transformation*, K.-J. Meier and M. Pfeffer, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2022, pp. 3–24.

[2] M. Xu, J. M. David, and S. H. Kim, "The Fourth Industrial Revolution: Opportunities and Challenges," *IJFR*, vol. 9, no. 2, p. 90, 2018, doi: 10.5430/ijfr.v9n2p90.

[3] M. Kleinemeier, "Von der Automatisierungspyramide zu Unternehmenssteuerungs-Netzwerken," in *Handbuch Industrie 4.0 Bd.1*, B. Vogel-Heuser, T. Bauernhansl, and M. ten Hompel, Eds., Berlin, Heidelberg: Springer Berlin Heidelberg, 2017, pp. 219–226.

[4] C. Muchna, H. Brandenburg, J. Fottner, and J. Gutermuth, "Elemente technischer Logistiksysteme," in *Grundlagen der Logistik*, C. Muchna, H. Brandenburg, J. Fottner, and J. Gutermuth, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2021, pp. 163–206.

[5] G. Ullrich and T. Albrecht, "Geschichte der Fahrerlosen Transportsysteme," in *Fahrerlose Transportsysteme*, G. Ullrich and T. Albrecht, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2019, pp. 1–28.

[6] A.-K. Kohl and F. Pfretzschner, *Logistikmonitor 2018: Ergebnisse einer Expertenbefragung von Statista und der Bundesvereinigung Logistik (BVL) e.V.* [Online]. Available: https://www.bvl.de/files/1951/1988/2128/Logistikmonitor_2018_-_Der_Wirtschaftszweig_in_Zahlen.pdf (accessed: Nov. 9 2021).

[7] J. Fottner *et al.,* "Autonomous Systems in Intralogistics – State of the Art and Future Research Challenges," *Logist. Res.*, vol. 14, no. 1, 2021.

[8] B. Belzile and D. St-Onge, "Safety First: On the Safe Deployment of Robotic Systems," in *Foundations of Robotics*, D. Herath and D. St-Onge, Eds., Singapore: Springer Nature Singapore, 2022, pp. 415–439.

[9] G. Ullrich and T. Albrecht, "Die Welt des FTS," in *Fahrerlose Transportsysteme*, G. Ullrich and T. Albrecht, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2023, pp. 1–32.

[10] T. Hänisch and S. Rogge, "IT-Sicherheit in der Industrie 4.0," in *Industrie 4.0: Wie cyber-physische Systeme die Arbeitswelt verändern*, V. P. Andelfinger and T. Hänisch, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2017, pp. 91–98.

[11] W. Günthner and M. ten Hompel, *Internet der Dinge in der Intralogistik*. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg, 2010. [Online]. Available: http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10362093

[12] T. Barton, Ed., *E-Business mit Cloud Computing*. Wiesbaden: Springer Fachmedien Wiesbaden, 2014.

[13] R. Hentschel and C. Leyh, "Cloud Computing: Status quo, aktuelle Entwicklungen und Herausforderungen," in *Edition HMD, Cloud Computing*, S. Reinheimer, Ed., Wiesbaden: Springer Fachmedien Wiesbaden, 2018, pp. 3–20.

[14] D. Clauer and J. Fottner, *Einsatz von autonomen Transportsystemen auf dem Werksgelände: Aktueller Umsetzungsstand und Handlungsbedarf.* Garching b. München: Lehrstuhl für Fördertechnik Materialfluß Logistik (fml) TU München, 2019.

[15] U. Kubach, "Device Clouds: Cloud-Plattformen schlagen die Brücke zwischen Industrie 4.0 und dem Internet der Dinge," in *Springer Reference Technik, Handbuch Industrie 4.0: Bd. 3: Logistik*, B. Vogel-Heuser, T. Bauernhansl, and M. ten Hompel, Eds., 2nd ed., Berlin: Springer Vieweg, 2017, pp. 181–200.

[16] M. Schenk and M. Schumann, "Einleitung – Herausforderungen für die Produktion mit Zukunft," in *VDI-Buch, Produktion und Logistik mit Zukunft: Digital Engineering and Operation*, M. Schenk, Ed., Berlin, Heidelberg: Springer Vieweg, 2015, pp. 1–48.

[17] BMWi, "Leitfaden 5G-Campusnetze – Orientierungshilfe für kleine und mittelständische Unternehmen: Konzepte, Begriffe, Betreibermodelle und Auswahlkriterien für Produktion und Logistik mit Übertragbarkeit auf weitere Domänen wie Medizin-Campus/Krankenhäuser, Häfen, Bergbau, Baustellen und Landwirtschaft," 2020.

[18] N. Dalkey and O. Helmer, "An Experimental Application of the DELPHI Method to the Use of Experts," *Management Science*, vol. 9, no. 3, pp. 458–467, 1963, doi: 10.1287/mnsc.9.3.458.

[19] K. Cuhls, "Die Delphi-Methode – eine Einführung," in *Delphi-Verfahren in den Sozial- und Gesundheitswissenschaften*, M. Niederberger and O. Renn, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2019, pp. 3–31.

[20] M. Häder and S. Häder, "Die Delphi-Methode als Gegenstand methodischer Forschungen," in *ZUMA-*

Publikationen, Die Delphi-Technik in den Sozialwissenschaften: Methodische Forschungen und innovative Anwendungen, M. Häder and S. Häder, Eds., Wiesbaden: Westdt. Verl., 2000, pp. 11–31.
[21] H. A. von der Gracht and I.-L. Darkow, "Scenarios for the logistics services industry: A Delphi-based analysis for 2025," *International journal of production economics*, vol. 127, no. 1, pp. 46–59, 2010, doi: 10.1016/j.ijpe.2010.04.013.
[22] H. A. von der Gracht and I.-L. Darkow, "Energy-constrained and low-carbon scenarios for the transportation and logistics industry," *The International Journal of Logistics Management*, vol. 27, no. 1, pp. 142–166, 2016, doi: 10.1108/IJLM-12-2013-0150.
[23] S. Escherle, E. Darlagiannis, and A. Sprung, "Automated Trucks and the Future of Logistics – A Delphi-Based Scenario Study," *Logist. Res.*, 2023.
[24] D. Beiderbeck, N. Frevel, H. A. von der Gracht, S. L. Schmidt, and V. M. Schweitzer, "Preparing, conducting, and analyzing Delphi surveys: Cross-disciplinary practices, new directions, and advancements," *MethodsX*, vol. 8, p. 101401, 2021, doi: 10.1016/j.mex.2021.101401.
[25] U. Kluge, J. Ringbeck, and S. Spinler, "Door-to-door travel in 2035 – A Delphi study," *Technological Forecasting and Social Change*, vol. 157, p. 120096, 2020, doi: 10.1016/j.techfore.2020.120096.
[26] B. Anderhofstadt and S. Spinler, "Factors affecting the purchasing decision and operation of alternative fuel-powered heavy-duty trucks in Germany – A Delphi study," *Transportation Research Part D: Transport and Environment*, vol. 73, pp. 87–107, 2019, doi: 10.1016/j.trd.2019.06.003.
[27] J. E. Gary and H. A. von der Gracht, "The future of foresight professionals: Results from a global Delphi study," *Futures*, vol. 71, pp. 132–145, 2015, doi: 10.1016/j.futures.2015.03.005.
[28] C. Fritschy and S. Spinler, "The impact of autonomous trucks on business models in the automotive and logistics industry–a Delphi-based scenario study," *Technological Forecasting and Social Change*, vol. 148, p. 119736, 2019, doi: 10.1016/j.techfore.2019.119736.
[29] M. Häder, "Begriffsbestimmungen," in *Delphi-Befragungen*, M. Häder, Ed., Wiesbaden: Springer Fachmedien Wiesbaden, 2014, pp. 19–37.
[30] M. Häder, "2800 Jahre Delphi: Ein historischer Überblick," in *Delphi-Befragungen*, M. Häder, Ed., Wiesbaden: Springer Fachmedien Wiesbaden, 2014, pp. 13–17.
[31] J. Morgenstern and H. Zadek, "AMR : influencing factors and potentials of cloud-robotics," 2023.
[32] S. Y. Y. Chyung, K. Roberts, I. Swanson, and A. Hankinson, "Evidence-Based Survey Design: The Use of a Midpoint on the Likert Scale," *Perf. Improv.*, vol. 56, no. 10, pp. 15–23, 2017, doi: 10.1002/pfi.21727.
[33] A. Patrzek, "Fragearten," in *essentials, Systemisches Fragen*, A. Patrzek, Ed., Wiesbaden: Springer Fachmedien Wiesbaden, 2021, pp. 15–39.
[34] J. Landeta, "Current validity of the Delphi method in social sciences," *Technological Forecasting and Social Change*, vol. 73, no. 5, pp. 467–482, 2006, doi: 10.1016/j.techfore.2005.09.002.
[35] A. Spickermann, M. Zimmermann, and H. A. von der Gracht, "Surface- and deep-level diversity in panel selection — Exploring diversity effects on response behaviour in foresight," *Technological Forecasting and Social Change*, vol. 85, pp. 105–120, 2014, doi: 10.1016/j.techfore.2013.04.009.
[36] L. C. Giunipero, R. E. Hooker, and D. Denslow, "Purchasing and supply management sustainability: Drivers and barriers," *Journal of Purchasing and Supply Management*, vol. 18, no. 4, pp. 258–269, 2012, doi: 10.1016/j.pursup.2012.06.003.
[37] G. Rowe and G. Wright, "Expert Opinions in Forecasting: The Role of the Delphi Technique," in *International Series in Operations Research & Management Science, Principles of Forecasting*, F. S. Hillier and J. S. Armstrong, Eds., Boston, MA: Springer US, 2001, pp. 125–144.
[38] K. Steinmüller, "Das „klassische“ Delphi. Praktische Herausforderungen aus Sicht der Zukunftsforschung," in *Delphi-Verfahren in den Sozial- und Gesundheitswissenschaften*, M. Niederberger and O. Renn, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2019, pp. 33–54.
[39] S. W. Schuckmann, T. Gnatzy, I.-L. Darkow, and H. A. von der Gracht, "Analysis of factors influencing the development of transport infrastructure until the year 2030 — A Delphi based scenario study," *Technological Forecasting and Social Change*, vol. 79, no. 8, pp. 1373–1387, 2012, doi: 10.1016/j.techfore.2012.05.008.
[40] H. A. von der Gracht, "Consensus measurement in Delphi studies," *Technological Forecasting and Social Change*, vol. 79, no. 8, pp. 1525–1536, 2012, doi: 10.1016/j.techfore.2012.04.013.
[41] J. S. Dajani, M. Z. Sincoff, and W. K. Talley, "Stability and agreement criteria for the termination of Delphi studies," *Technological Forecasting and Social Change*, vol. 13, no. 1, pp. 83–90, 1979, doi: 10.1016/0040-1625(79)90007-6.
[42] T. Webler, D. Levine, H. Rakel, and O. Renn, "A novel approach to reducing uncertainty: The group Delphi," *Technological Forecasting and Social Change*, vol. 39, no. 3, pp. 253–263, 1991, doi: 10.1016/0040-1625(91)90040-M.
[43] X. Wan, W. Wang, J. Liu, and T. Tong, "Estimating the sample mean and standard deviation from the sample size, median, range and/or interquartile range," *BMC medical research methodology*, vol. 14, p. 135, 2014, doi: 10.1186/1471-2288-14-135.
[44] M. S. Raskin, "The Delphi Study in Field Instruction Revisited: Expert Consensus on Issues and Research

Priorities," *Journal of Social Work Education*, vol. 30, no. 1, pp. 75–89, 1994, doi: 10.1080/10437797.1994.10672215.
[45] C. E. Brown, "Coefficient of Variation," in *Applied Multivariate Statistics in Geohydrology and Related Sciences*, C. E. Brown, Ed., Berlin, Heidelberg: Springer Berlin Heidelberg, 1998, pp. 155–157.
[46] K. P. Kwiatkowski and P. S. Chinowsky, "Climate change adaptation as an organizational system in transportation infrastructure organizations: Identifying processes and institutional elements," *Transport Policy*, vol. 60, pp. 47–53, 2017, doi: 10.1016/j.tranpol.2017.08.006.
[47] M. Nowack, J. Endrikat, and E. Guenther, "Review of Delphi-based scenario studies: Quality and design considerations," *Technological Forecasting and Social Change*, vol. 78, no. 9, pp. 1603–1615, 2011, doi: 10.1016/j.techfore.2011.03.006.
[48] G. Fragapane, D. Ivanov, M. Peron, F. Sgarbossa, and J. O. Strandhagen, "Increasing flexibility and productivity in Industry 4.0 production networks with autonomous mobile robots and smart intralogistics," *Ann Oper Res*, vol. 308, 1-2, pp. 125–143, 2022, doi: 10.1007/s10479-020-03526-7.
[49] T. Albrecht, J. Luz, W. Osterhoff, K. Pfeiffer, K. Rapp, and G. Ullrich, *FTS-Leitfaden - Autonomie für mobile Roboter*, 2021.
[50] G. Ullrich and T. Albrecht, "Die Zukunft des FTS," in *Fahrerlose Transportsysteme*, G. Ullrich and T. Albrecht, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2019, pp. 217–239.
[51] L. Wildraut, U. Stache, and T. Mauksch, "Planung von Produktions-versorgungssystemen," *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, vol. 114, no. 4, pp. 167–172, 2019, doi: 10.3139/104.112074.
[52] *Analyse der Wirtschaftlichkeit Fahrerloser Transportsysteme (FTS)*, VDI2710 - Blatt 4, Verein Deutscher Ingenieure e.V., Jul. 2011.
[53] J. Lambrecht and E. Funk, "Edge-Enabled Autonomous Navigation and Computer Vision as a Service: A Study on Mobile Robot's Onboard Energy Consumption and Computing Requirements," in *Advances in Intelligent Systems and Computing, Robot 2019: Fourth Iberian Robotics Conference*, M. F. Silva, J. Luís Lima, L. P. Reis, A. Sanfeliu, and D. Tardioli, Eds., Cham: Springer International Publishing, 2020, pp. 291–302.
[54] D. Arnold and K. Furmans, "Informationsflüsse in Logistiksystemen," in *Materialfluss in Logistiksystemen*, D. Arnold and K. Furmans, Eds., Berlin, Heidelberg: Springer Berlin Heidelberg, 2019, pp. 349–405.
[55] F. Almada-Lobo, "The Industry 4.0 revolution and the future of Manufacturing Execution Systems (MES)," *jim*, vol. 3, no. 4, pp. 16–21, 2016, doi: 10.24840/2183-0606_003.004_0003.
[56] B. Otto, M. ten Hompel, and S. Wrobel, "Industrial Data Space," in *Digitalisierung*, R. Neugebauer, Ed., Berlin, Heidelberg: Springer Berlin Heidelberg, 2018, pp. 113–133.
[57] Y. Liu, X. Li, Y. Lin, R. Kang, and L. Xiao, "A colored generalized stochastic Petri net simulation model for service reliability evaluation of active-active cloud data center based on IT infrastructure," in *2017 2nd International Conference on System Reliability and Safety (ICSRS)*, Milan, 122017, pp. 51–56.
[58] M. A. AlZain, B. Soh, and E. Pardede, "A New approach using redundancy technique to improve security in cloud computing," in *Proceedings Title: 2012 International Conference on Cyber Security, Cyber Warfare and Digital Forensic (CyberSec)*, Kuala Lumpur, Malaysia, 062012, pp. 230–235.
[59] Y. A. Younis, K. Kifayat, and M. Merabti, "An access control model for cloud computing," *Journal of Information Security and Applications*, vol. 19, no. 1, pp. 45–60, 2014, doi: 10.1016/j.jisa.2014.04.003.
[60] G. Fragapane, R. de Koster, F. Sgarbossa, and J. O. Strandhagen, "Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda," *European Journal of Operational Research*, vol. 294, no. 2, pp. 405–426, 2021, doi: 10.1016/j.ejor.2021.01.019.
[61] G. Ullrich and T. Albrecht, "Technologische Standards," in *Fahrerlose Transportsysteme*, G. Ullrich and T. Albrecht, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2019, pp. 29–118.
[62] M. Sauer, A. Dachsberger, L. Giglhuber, and L. Zalewski, "Decentralized Deadlock Prevention for Self-Organizing Industrial Mobile Robot Fleets," in *2022 IEEE International Conference on Omni-layer Intelligent Systems (COINS)*, Barcelona, Spain, 812022, pp. 1–6.
[63] D. Hrušecká, R. Lopes, and E. Juřičková, "Challenges in the introduction of AGVS in production lines: Case studies in the automotive industry," *Serb J Management*, vol. 14, no. 1, pp. 233–247, 2019, doi: 10.5937/sjm14-18064.
[64] J. Sinnemann, M. Boshoff, R. Dyrska, S. Leonow, M. Mönnigmann, and B. Kuhlenkötter, "Systematic literature review of applications and usage potentials for the combination of unmanned aerial vehicles and mobile robot manipulators in production systems," *Prod. Eng. Res. Devel.*, vol. 16, no. 5, pp. 579–596, 2022, doi: 10.1007/s11740-022-01109-y.
[65] M. B. Alatise and G. P. Hancke, "A Review on Challenges of Autonomous Mobile Robot and Sensor Fusion Methods," *IEEE Access*, vol. 8, pp. 39830–39846, 2020, doi: 10.1109/ACCESS.2020.2975643.
[66] A. Pandey, "Mobile Robot Navigation and Obstacle Avoidance Techniques: A Review," *IRATJ*, vol. 2, no. 3, 2017, doi: 10.15406/iratj.2017.02.00023.
[67] F. Rubio, F. Valero, and C. Llopis-Albert, "A review of mobile robots: Concepts, methods, theoretical framework, and applications," *International Journal of Advanced Robotic Systems*, vol. 16, no. 2,

172988141983959, 2019, doi: 10.1177/1729881419839596.

[68] M. de Ryck, M. Versteyhe, and F. Debrouwere, "Automated guided vehicle systems, state-of-the-art control algorithms and techniques," *Journal of Manufacturing Systems*, vol. 54, pp. 152–173, 2020, doi: 10.1016/j.jmsy.2019.12.002.

[69] E. A. Oyekanlu *et al.,* "A Review of Recent Advances in Automated Guided Vehicle Technologies: Integration Challenges and Research Areas for 5G-Based Smart Manufacturing Applications," *IEEE Access*, vol. 8, pp. 202312–202353, 2020, doi: 10.1109/ACCESS.2020.3035729.

[70] M. Sereinig, W. Werth, and L.-M. Faller, "A review of the challenges in mobile manipulation: systems design and RoboCup challenges," *Elektrotech. Inftech.*, vol. 137, no. 6, pp. 297–308, 2020, doi: 10.1007/s00502-020-00823-8.

[71] P.-E. Dossou, P. Torregrossa, and T. Martinez, "Industry 4.0 concepts and lean manufacturing implementation for optimizing a company logistics flows," *Procedia Computer Science*, vol. 200, pp. 358–367, 2022, doi: 10.1016/j.procs.2022.01.234.

[72] G. Ullrich and T. Albrecht, "Die ganzheitliche FTS-Planung," in *Fahrerlose Transportsysteme*, G. Ullrich and T. Albrecht, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2019, pp. 241–284.

[73] Y. Yang and W. Pan, "Automated guided vehicles in modular integrated construction: potentials and future directions," *CI*, vol. 21, no. 1, pp. 85–104, 2021, doi: 10.1108/CI-07-2019-0073.

[74] G. Ullrich and T. Albrecht, "Anwendungsgebiete," in *Fahrerlose Transportsysteme*, G. Ullrich and T. Albrecht, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2019, pp. 119–216.

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DOI: 10.2195/lj_edrev_morgenstern_en_202409_01

APPENDIX

Table A: Overview about AGV/AMR influencing factors and potentials of cloud-robotics

Part	Category	Subcategory	Nr	Factor	Source	Literature
A	**Reason for AGV/AMR introduction**		1	Cost savings	SLR	[14], [60]
			2	Skills shortage	SLR	[14]
			3	Quality	SLR	[14]
			4	Industrial safety	SLR	[14], [61]
			5	Process stability	SLR	[14]
			6	Efficiency (productivity)	SLR	[62]
	AGV/AMR operations	**Project / overall system**	7	Simplicity of implementation	Reference process	[60], [63]
			8	Scalability	SLR	[62]
			9	Robustness	SLR	[60], [62]
			10	Flexibility	SLR	[60], [62], [64]
			11	(Project-)Planning	Reference process	[63]
			12	(Project-)Commissioning / Realization	Reference process	[63]
		Function / process	13	Navigation	SLR	[61], [65–67]
			14	Route planning	SLR	[65], [68]
			15	Localization	SLR	[62], [65], [67]
			16	Object detection	SLR	[65]
			17	Route optimization	SLR	[67]
			18	Order management	SLR	[61]
			19	Fleet management	SLR	[62]
			20	Traffic control / deadlock prevention	SLR	[69]
			21	Guidance control system	SLR	[61]
			22	Vehicle control	SLR	[61]
		Hardware	23	Battery	SLR	[69]
			24	Computing power (onboard)	SLR	[60]

			25	Sensors	SLR	[61], [67]
			26	Mechanics	SLR	[61], [67]
		Software	27	Artificial intelligence (e.g., machine learning)	SLR	[60], [70], [71]
			28	SLAM	SLR	[60]
			29	Sensor fusion	SLR	[65]
		Autonomy	30	Dynamic modeling of environment	SLR, reference process	[49]
			31	Driving on released areas	SLR, reference process	[49]
			32	Driving around obstacles	SLR, reference process	[49]
			33	Acting on object recognition and classification	SLR, reference process	[49]
			34	Dynamic route planning in mixed operation	SLR, reference process	[49]
			35	Detect and respond to vehicle condition data	SLR, reference process	[49]
			36	Guidance control functions in the vehicles	SLR, reference process	[49]
		Radio technology	37	Latency	SLR	[53], [69]
			38	Reliability	SLR	[53], [69]
			39	Data throughput	SLR	[69]
			40	WLAN	SLR	[61]
			41	LTE, 4G, 5G	SLR	[53], [61], [69]
		Costs	42	Purchase price	Reference process	[72]
			43	Planning / commissioning costs	Reference process	[72]
			44	Operating costs - energy costs	Reference process	[63]
			45	Operating costs - Maintenance costs	Reference process	[63]
			46	Operating costs - repair costs (spare parts)	Reference process	[63]
			47	Costs computer hardware	Reference process	[53]
	AGV/AMR barriers		48	Flexibility	SLR	[60], [64], [73]
			49	Cycle time	SLR	[60], [64]
			50	Speed due to safety	SLR	[63]
			51	Mixed operation	SLR	[61]

		52	Load pickup / load transfer	SLR	[61]
		53	Availability	SLR	[74]
		54	Variant variety container	SLR	[72]
		55	Costs	SLR	[73]
		56	Application area outdoor	SLR	[14], [73]
		57	Manufacturer-independent control system	SLR	[50]
		58	lack of know-how, knowledge, competence	SLR	[73]
		59	Lack of guidelines, regulation, standardization	SLR	[73]
Part	**Category**	**Nr**	**Factor**	**Source**	**Literature**
B	**Cloud**	60	Efficiency increase	SLR	[53]
		61	Main application	SLR	[53]
		62	Outsourcing options	SLR	[69]
		63	Target architecture	SLR	[60]
		64	Single Point of Failure	SLR	[69]
		65	Incentives / Advantages	SLR	[53]
		66	Obstacles / Disadvantages	SLR	[53]

Expert group	Position	Industry experience (years)
Logistics (Industry)	Project Lead Logistics and Innovations	14
Logistics (Science)	Head of AMR/AGV Research & Consulting	40
Logistics (Science)	Research Assistant AMR/AGV	7
Logistics (Industry)	Project Lead AMR/AGV Projects	10
IT (Industry)	Department Lead Cloud Solutions	10
Logistics (Science)	Department Lead AMR/AGV Research	33
Logistics (Industry)	CEO	25
Logistics (Science)	Professor Technical Logistics	26
IT (Industry)	Project Lead Cloud Solutions	23
Logistics (Science)	Professor Technical Logistics	17
Logistics (Science)	Professor Technical Logistics	16
Logistics (Science)	Research Assistant AMR/AGV	6
Logistics (Science)	Professor Technical Logistics	29

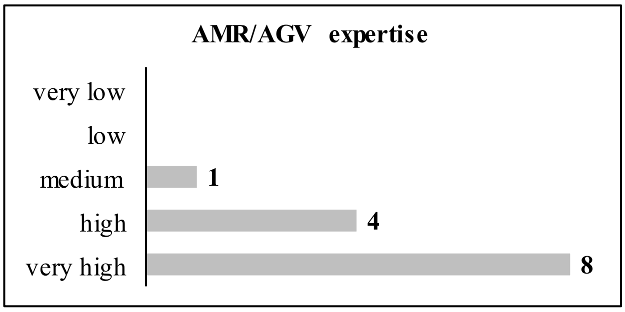

Figure 16. Delphi expert panel