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Design of AGV systems in working environments shared with humans: a multi case study

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Abstract: To meet the challenges and needs of an ever-changing market and as part of the fourth industrial revolution, factories are transforming into increasingly automated environments. A widely used and well-established solution today is Automated Guided Vehicles (AGVs), which often work closely with humans in crowded environments. Thus, in addition to flexibility, another important criterion associated with automatic handling systems is safety. The purpose of this work is to show how the involvement of three different but equally important roles in the design of an AGV system can benefit the whole project. The advantage of considering three different perspectives is the possibility of obtaining a more complete vision from the earliest stages of implementation, avoiding, as far as possible, the need to make changes in the next stages, which would generate higher costs than necessary. The article is based on two case studies, each one set in a major European manufacturing company: the first one is an Italian automotive manufacturer and the second one is a Swedish manufacturer of mechanical components. Both case companies apply AGVs in their material handling processes and, accordingly, have experience of both implementing and operating AGV systems. The article applies semi-structured interviews to study the three key roles, highlighting the key points for each role and showing the common issues that emerged from the interviews.

Keywords: Automated Guided Vehicle, safety, regulations, decision process, robot-human interaction.

1. INTRODUCTION AND BACKGROUND

Automation is a fundamental part of the fourth industrial revolution and here, Automated Guided Vehicle (AGV) systems have an important role to play. However, with ever-changing layouts and requirements for high flexibility, AGV implementations are challenging. Moreover, industrial environments are often crowed and the AGVs must share floor space with other entities, including human operators, whose trajectories are unpredictable, thus increasing the risk of collision (Sabattini et al., 2017). As Raineri et al. (2019) claimed the barriers that divided the manual and the automatic world are increasingly disappearing in automated warehouses until getting an environment where operators interact directly with AGVs. Therefore, a series of new measures need to be adopted, from the designing of a suitable layout and safety systems required by law, to the training of operators to avoid injuries. Each workplace is unique and likely to present different hazards and risks. Design and redesign of a new system comprise phases that follow each other chronologically, covering long time horizons and determining the cost that changes can have. The further we move away from the design phase and closer to the implementation phase, which involves purchases and layout changes, the more the cost of the changes increases (See the Fig. 1). Therefore, it is appropriate to take note of all the possible problems that could require changes and result in additional costs and delays in implementation. A way to obtain this information is to consider different roles in decision-making that can contribute with different perspectives. Johansson (2007) finds that in a product development project, the design process of a materials handling system should be integrated with the overall project. Along the same lines, this paper proposes a new perspective in AGV system design in which safety, working conditions and performance need to be considered at once.

1.1 Academic Literature

According to Mehami et al. (2018), driver-less vehicles will be key players in the future of manufacturing companies. From an Industry 4.0 perspective, human-robot interaction is considered as the most effective approach to achieve industrial success (Theunissen et al., 2018). Existing literature, however, is rich in works that deal with AGVs but often focus on their technical characteristics and systems (i.e. guidance systems, routes, sensors, etc.) and less on important aspects such as operational (i.e.training hours, pedestrian flow, etc.). Human safety has often been studied from an ergonomic point of view,

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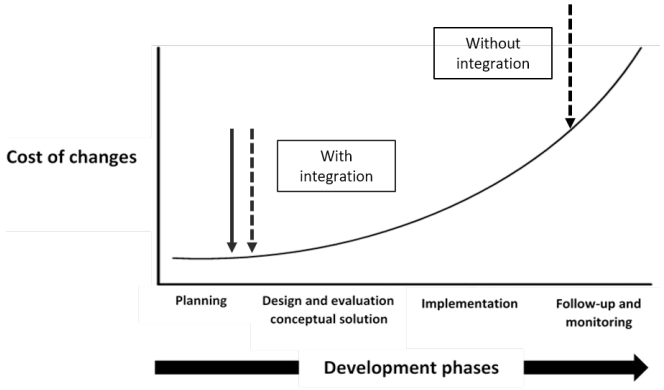

Fig. 1. Cost of changes (modified from: Folkestad and Johnson (2001))

measuring fatigue (energy expenditure) and recovery times of operators with the aim of balancing the load by managing the safety of operator (Finco et al., 2019a,b, 2020). By limiting the field of research to human-robot interaction, but excluding robotic design's point of view, the literature shows lack of documents that consider humans as a co-workers for the AGVs. The papers directly linked to the goal of this work are few and consider the presence of human in the same environment of AGVs from different perspectives. One noteworthy study, though a simulated approach, shows that humans are an interference for the movements of vehicles, forcing AGVs to slow down, or stop. As the number of people increases, the time needed to the vehicle to reach the fixed goal also increases, showing how the presence of men impairs the productivity of AGVs (Krkoška et al., 2017). This work, instead, focuses on Critical Decision Factors (CDFs) and critical issues involved in AGV systems design for situations where operators work closely with the AGVs in the same work spaces.

1.2 Regulation

When it comes to regulations, we often refer to two macro-committees: The Legislation Europe, the legislation valid within the European Union and the strictest in the world. (Ullrich, 2015); American ITSDF (Industrial Truck Standard Development Foundation) that manages the development of standards for lift trucks and the establishment of the safety requirements for design, operation and maintenance. The most important regulation to be adhered to for using of AGVs are the "ANSI/ITSDF B56.5-2012" document for the ITSDF committee and "EN ISO1525:1997"and "EN ISO 1526:1997-A1:2008". Among these most used are the "VDI 2510 Blatt 2:2013-12: Automated guided vehicle systems (AGVS) - Safety of AGVS", "VDI 2710:2010-04:Interdisciplinary design of automated guided vehicle systems (AGVS) and "VDI 4452:2004: acceptance specification for automated guided vehicle systems (AGVS)". However, these rules must be integrated with the laws in place in the countries where they are applied. For the countries of the European Community all machines that are produced and then installed must refer to the European Machinery Directive 2006/42/EC.

The issue of safety becomes of paramount importance when dealing with man in addition to AGVs, in particular the problem of the safety of the movement is widely discussed in the literature (Corrales et al., 2011; Meziane et al., 2017). As humans and machines increasingly share the same work environment additional safety issues can arise. As a result, regulations deemed relevant to the design of AGV systems were examined according to Ullrich (2015)to understand which of them consider the presence of humans. As can be seen in Table 1, nine out of seventeen regulations do so, but it is important to highlight which role that humans play. The human worker, often called "person" inside the rules, is mentioned in relation to the sensors and therefore considered as a physical obstacle for vehicles. Only in three rules (PAS 13:2007, EN1525 and EN ISO 14121), the person is considered as an entity present in the same working space as vehicles and therefore exposed to potential risks that need to be managed. There are, therefore, not many regulations that consider the issue of the co-presence of humans and self-driving vehicles to be centrally considered.

2. AIM OF THE STUDY

Within an environment occupied by humans, the implementation of an AGV system introduces new elements of risk. Therefore, safety must be managed in several phases of the system installation (Mortimer, 1991).The aim of this paper is to provide a foundation for a methodology by which issues of safety are considered as a fully integrated part of an AGV implementation project. To support the fulfilment of this purpose, two research questions have been formulated, which will subsequently be answered in subsections 5.1 and 5.2.

2.1 RQ1: Are there any critical decision factors (CDFs) for safety consideration in designing an AGVs system?

As mentioned before, the paper proposes that safety considerations should be considered as an integrated part of an AGV implementation process. In this process, there are critical decision factors that need to be considered.

2.2 RQ2: Are there any common challenges between the three roles (Designer, Safety Expert, Worker)?

It was possible to relate the CDFs that emerged from the interviews to three specific roles in an industrial company: *Designer, Safety Expert, Worker* [1]. Each role was found to emphasise some aspects while neglecting, or just not considering, others. The analysis identifies overlaps between the perspectives of the different roles. If an aspect was highlighted as important by more than one role, this is seen as an indication of a relatively higher relevance of that aspect.

3. METHOD

In addressing RQ1, which deals with critical design factors for safety consideration, the paper starts off with a model from the literature, on the overall process of designing internal logistics systems. The paper then identifies critical design factors (CDFs) from empirical data from two cases and links those to the different design process steps. To address RQ2, which seeks to identify common challenges between the three roles in focus, i.e. Designer, Safety

[1] Given the impossibility of interviewing each worker, give the large size of the companies, a representative of the workers, considered an expert, was interviewed to answer in a comprehensive way.

Table 1. AGV-relevant design regulations *(* identifies the norms that consider man only as an obstacle to sensory)*

Regulation	Main focus	Topics covered	Human presence is considered
EN 982	Safety technical aspects	Design, construction and modification of hydraulic systems	No
EN 983		Design, construction and modification of pneumatic systems	No
EN 1755		Design, construction and modification of handling devices in potentially explosive atmospheres	No
EN 954-1	Safety requirement	Process for the selection and design of safety measures	No
EN 1775 - 1		Electrical and related mechanical safety requirements	Yes*
EN 1775 -2		Electrical i requirements in internal combustion engine powered trucks	Yes*
EN 1775 -3		Design and construction of electrical power transmission systems of trucks with internal combustion engines	Yes*
EN 13849 -1		Design and integration of safety-related parts of control systems (SRP/CS), including the design of software	No
ISO 3691 - 4		Driverless vehicle Deals with all significant hazards, hazardous situations or hazardous events during all phases of the life of the truck	Yes*
PAS 13:2007		Guideline for the design of pedestrian and vehicle paths Resilience, dimensions and positions of safety barriers in the workplace Criteria for testing the impact resilience of a barrier.	Yes
ITSDF-B56-5		Unmanned industrial AGV General Safety practices Design and construction standards	Yes*
EN 1525	Hazard identification and risk assessment	Environmental requirements	Yes
EN ISO 10218		Inherent safe design, protective measures and information for use of industrial robots Requirements to eliminate, or adequately reduce, the risks associated with the hazards.	No
EN ISO 12100		Basic terminology, principles and a methodology for achieving safety in the design of machinery Procedures for identifying hazards Estimation and evaluation of risks during relevant phases of the machine life cycle	Yes
EN ISO 14121		Guidance on the making of decisions relating to the safety of machinery Guidance on the documentation required to verify the risk assessment carried out Exposure of persons to hazards	Yes
EN ISO 13849 - 2	Procedure and tests validation	Procedures and conditions to be followed for the validation of ISO 13849-1	No
ISO 15623		Performance requirements and test procedures for systems capable of warning the driver of a potential rear-end collision with other vehicles ahead of the subject Vehicle while it is operating at ordinary speed	No

Expert, and Worker, the paper focuses further on the empirical data, identifying from the interviews which factors were brought up by the representatives of the different roles. The findings indicate which factors are considered especially important in relation to each of the roles. The cases are from two industrial companies which will here be named Alpha and Beta to ensure confidentiality. Company Alpha, is an Italian firm among the world's largest and most well-known automotive companies. Only the area with human-robot interaction has been considered: the assembly line zone. Company Beta is one of the world's largest suppliers of products, solutions and services in the mechanical sector. The level of automation of this plant is high. These two cases were selected for their use of AGVs integrated with the presence of man in two different, but complementary, activities: assembly and material handling. The fact that the case studies were conducted in two different countries increases the likelihood that the paper's findings are not linked specifically to the culture or regulations within a specific country, which strengthens generalizability. Semi-structured interviews were chosen to allow flexibility, adapting the questions according to the answers given by the respondents (Williamson, 2002). In each company, interviews were held with representatives of each of the three roles of Designer, Safety Expert, and Worker in order to understand their perspectives and perceptions. The *Designer* was in effect managing the design and implementation of the system, including the identification of the most suitable technology, the definition of AGVs paths and the fleet sizing . The *Safety Expert* should see to the safety of the workers and ensure that rules and regulations are followed. Finally, the *Worker*

ensured that the work experience of the operators were considered. The questions were divided into 4 four categories: 1) information on the overall production system, e.g. production volumes, 2) information on the AGVs, mainly technical specifications regarding e.g. navigation and safety sensors, 3) safety regulations that were considered during the implementation and operation of the AGVs, and 4) safety measures taken to ensure safety in the plant. In both cases, several visits were made to the plants: a first time to directly observe the of the whole system; the subsequent ones, when necessary, to carry out the interviews. The interviews took place between March 2019 and July 2019. Detailed notes were taken during each interview. When necessary, supplementary questions were asked via Skype call or via email for more details. At the end, each respondent was able to read the notes and validate the data.

4. CASE STUDIES

In order to investigate the aforementioned research question, a multi-case study has been adopted. Alpha company is the Italian one, while Beta is the Swedish one.

4.1 Case study I: Alpha company

The Italian automotive company applies laser guided vehicles (LGVs), i.e. AGVs that use a guidance system based on the use of lasers and reflective materials to orient themselves in the environment. The Alpha company uses a fleet of thirty LGVs; half of which preserves the handling of the product on the assembly line, while the other half is intended for feeding operations, always on the assembly line. More precisely, there is no interaction at the level of activity, since they occur when the vehicle is stationary. The area in which the vehicle and the operator move overlap, giving rise to possible bilateral interference. These possible events are extra reason to take the best safety measures; indeed, all LGVs are equipped with safety scanners that detect obstacles while travelling in order to slow down or stop the vehicle avoiding collisions.

4.2 Case study II: Beta company

Also in *case study II*, at the Swedish company, LGVs are used but in for material handling activities. This phase is hybrid, i.e. there is the manual part composed of pedestrians and manned forklifts; and an automatic part consisting of a fleet of seventeen AGVs, some more recent than other. The vehicles move within the plant according to fixed routes that can be one-directional or bi-directional depending on the area of the plant in which we are located and sometimes also due to the presence of corridors for pedestrians (safety reasons). All LGVs are equipped with obstacle detection systems to reduce the speed to avoid collisions. The plant was rebuilt around the same time, The plant was rebuilt around the same time that the first AGVs were introduced. Company Beta chose to leave their previous setup, where production took place along production lines, and instead arrange their production in dispersed production cells, between which the materials then needed to be transported. While the two changes (the re-arrangement of the production setup and the introduction of AGVs) occurred more or less at the same time and were part of the same overall project, no considerations to the AGVs were made when the layout of the new assembly setup was decided. (Note that the production was rebuilt within the existing facilities.), Accordingly, it was not considered whether paths needed to be broader or narrower to accommodate AGVs, or any other similar concerns. Instead, the AGV introduction had to be planned into a layout that was already set.

5. DATA ANALYSIS AND DISCUSSION

The critical part of this qualitative method is the analysis of the data. The interviews collected were carefully read and analyzed, line by line, identifying, tagging and grouping data (Grosse et al., 2016).

5.1 Answer to RQ1

Tompkins et al. (2010) proposes a process model for automation development in internal logistics systems. The model includes several steps, of which the first ones precede the decision to apply automation. In relation to the focus of the current paper, where the decision to apply automation has already been made, these steps are not seen as relevant. The steps were also used in Fig. 1 to describe the stages of the development process; we start with the planning, then follow the design of the evaluations of the proposed solutions, the implementation of the latter and finally the monitoring. The aim is to consider the factors that influence the implementation process of the AGVs system the most. Based on the data collected, the critical design factors that emerged were categorised as: technical, operational or safety. It is in the phases preceding the implementation of the AGVs system that the evaluation of CDFs is most important. It is interesting to see how some CDFs are considered by multiple roles but with different meanings. For instance, "AGV and human path segregation" is a factor that affects all three roles, but it takes on a technical meaning for the designer, concerning e.g. layout, whereas the safety expert and the worker view it as a matter of safety. The safety expert is concerned with implementing all the safety measures regulated by law (i.e. horizontal and vertical signs) and the worker, who is the one most directly affected by the system design, uses the provided safety measures and respects the rules. Data collected from the interviews revealed some matches between factors considered important in the design process by the relevant roles: the training of people with the aim of learning and complying with the set of rules provided; the sensors to avoid collisions; the parameters of the plant and the changes on this; vehicle speed. Therefore, when considering the process of implementing an AGV system, the factors described above need to be carefully considered, particularly in the steps leading up to the implementation of the system (Hrušecká et al., 2019).

5.2 Answer to RQ2

The design of automatic guided vehicle systems presents common difficulties and can be difficult to predict without a complete analysis of the entire systems (Ali and Khan, 2010). In order to have a more complete knowledge of the system it was decided to approach it from three different perspectives. In a first phase of coding of collected data, the problems highlighted by each role were labelled. In response to the research question, the focus was on the

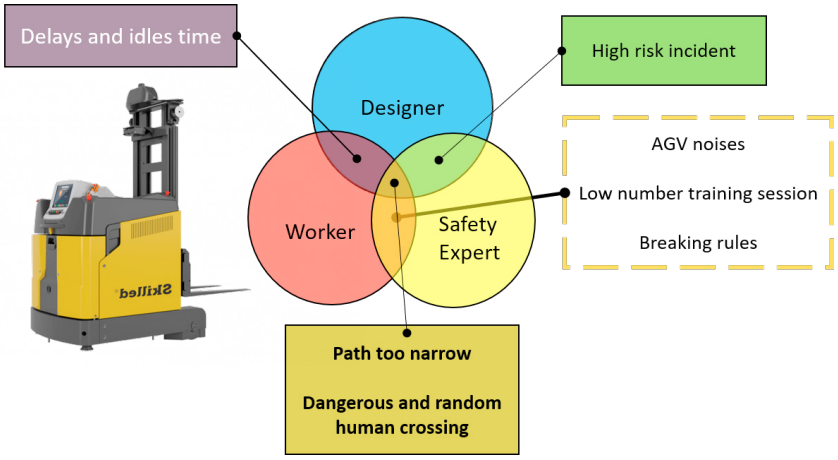

Fig. 2. Common issues emerged for the three roles

Table 2. Critical Design factors (CDFs) *(source: interviews)*

	Case 1			Case 2		
CDFs type	Designer	Safety Expert	Worker	Designer	Safety Expert	Worker
Technical	**1.** AGV and human paths segregation **6.** Speed ranges setting **10.** Sensors to prevent collision **13.** Optimized layout design	**2.** AGVs sensors to prevent collision **7.** Speed limitation **11.** Optimized layout design	**3.** AGV floor markers	**4.** Existing layout constrains **8.** AGVs sensors to prevent collision	**5.** Existing layout constrains **9.** Speed limitation **12.** AGVs sensors to prevent collision	
Operational		**1.** Training activities **4.** Procedure definition	**2.**Task re-scheduling **5.** Training activities **6.** AGV charging time		**3.** Training activities	
Safety		**1.** AGV and human paths segregation **5.** Number and location of pedestrian path crossing **9.** Safety signals **10.** Safety norms and standards **11.** Emergency exits	**2.** AGV and human paths segregation **6.** Training activities	**3.** Dimension of aisles	**4.** AGV and human paths segregation	**8.** Training activities

Table 3. Critical issues detected by each role *(source: interviews)*

	Case 1			Case 2		
Issues	Designer	Safety Expert	Worker	Designer	Safety Expert	Worker
Delays and idle time	x		x			
Breaking the rules		x	x		x	x
Paths too narrow	x	x	x	x	x	x
Job/task re-scheduling						x
Low level of humans precautions		x			x	
Low number training sessions		x	x		x	x
High incident risk	x	x		x	x	
AGVs noises		x	x			x
Dangerous and random human corssing	x	x	x	x	x	x

issues that were common to multiple roles. In fact, the more roles highlight the same challenge, the greater the attention that should be attributed because it puts several roles in difficulty at the same time. On the basis of this statement, the issues that were found to have the greatest impact are "Too narrow path" and "dangerous and random human crossing", since although for different reasons, they are critical for all roles. The former puts the designer in difficulty because the structure of the plant is already existing and immutable, which restricts the freedom of the design.But the most important consequence is that an insufficient distance between AGV routes and pedestrian paths increases the risk of injuries, a key point for the safety expert and for the worker who feels constantly at

risk. With regard to dangerous crossings, interviews have shown that these episodes are often caused by operators who do not sufficiently respect the rules. This happens because the operators rely on the system that slows down and stops the vehicle when it detects the presence of an obstacle in its path. This problem not only affects safety, but also productivity, as these crossings affect the performance of the vehicle, forcing it to slow down (and stop sometimes). This problem is often not taken into account when designing an AGV system, although system performance is one of the key aspects. An example of this is Battini et al. (2015) focused on designing an AGV system in part feeding assembly lines. The approach is performance oriented and does not consider aspects that can equally impact on the system performance but coming from multidisciplinary approaches. Other problems were identified by two of the three roles (see Figure 2); the designer and the worker complained about delays and down times which, especially for the Italian company, constitute an important inconvenience since chain delays are created. This problem is a direct consequence of unplanned crossings. Finally, there are three issues that the designer does not emphasize: "AGV noises", "less training hours" and "Breaking rules". As for the two cases, if there was no involvement of the safety expert and the worker from the earliest stages of design, these problems could be overshadowed and receive less attention than they should.

6. CONCLUSION

This paper develops a multi-case study analysis by semi-structured interviews with the three key roles in AGV fleet design: the designer, the worker and the safety expert. The final aim is to benefit from considering three different perspectives in the AGV system design and implementation phase in order to avoid need for future changes, safety risks and workers performance losses. In addition, the failure of other figures to be involved with the designer would result in the loss of relevant information. As the Fig. 2 shows, the critical issues in the dashed, bold rectangle were in this study brought up only by the safety expert and the worker and not by the designer. This work demonstrates the need to develop a multidisciplinary approach to AGV fleet design and lays the groundwork for future design procedures capable of proactively engaging the three roles (designer, worker and safety experts) from the very beginning of the AGV introduction phase.

REFERENCES

Ali, M. and Khan, W.U. (2010). Implementation issues of agvs in flexible manufacturing system: A review. *Global Journal of Flexible Systems Management*, 11(1-2), 55–61.

Battini, D., Gamberi, M., Persona, A., and Sgarbossa, F. (2015). Part-feeding with supermarket in assembly systems: transportation mode selection model and multi-scenario analysis. *Assembly Automation*, 35(1), 149.

Corrales, J., Candelas, F., and Torres, F. (2011). Safe human–robot interaction based on dynamic sphere-swept line bounding volumes. *Robotics and Computer-Integrated Manufacturing*, 27(1), 177–185.

Finco, S., Abdous, M.A., Battini, D., Calzavara, M., and Delorme, X. (2019a). Assembly line design with tools vibration. *IFAC-PapersOnLine*, 52(13), 247–252.

Finco, S., Battini, D., Delorme, X., Persona, A., and Sgarbossa, F. (2020). Workers' rest allowance and smoothing of the workload in assembly lines. *International Journal of Production Research*, 58(4), 1255–1270.

Finco, S., Zennaro, I., Battini, D., and Persona, A. (2019b). Workers' availability definition through the energy expenditure evaluation. *25th ISSAT International Conference on Reliability & Quality in Design*.

Folkestad, J.E. and Johnson, R.L. (2001). Resolving the conflict between design and manufacturing: integrated rapid prototyping and rapid tooling (irprt). *Journal of Industrial Technology*, 17(4), 1–7.

Grosse, E.H., Dixon, S.M., Neumann, W.P., and Glock, C.H. (2016). Using qualitative interviewing to examine human factors in warehouse order picking. *International Journal of Logistics Systems and Management*, 23(4), 499–518.

Hrušecká, D., Lopes, R.B., and Juřičková, E. (2019). Challenges in the introduction of agvs in production lines: Case studies in the automotive industry. *Serbian Journal of Management*, 14(1), 233–247.

Johansson, E. (2007). Towards a design process for materials supply systems. *International Journal of Operations & Production Management*, 27(4), 388–408.

Krkoška, L., Gregor, M., and Matuszek, J. (2017). Simulation of human effect to the adaptive logistics system used in public facilities. *Procedia engineering*, 192, 492–497.

Mehami, J., Nawi, M., and Zhong, R.Y. (2018). Smart automated guided vehicles for manufacturing in the context of industry 4.0. *Procedia Manufacturing*, 26, 1077–1086.

Meziane, R., Otis, M.J.D., and Ezzaidi, H. (2017). Human-robot collaboration while sharing production activities in dynamic environment: Spader system. *Robotics and Computer-Integrated Manufacturing*, 48, 243–253.

Mortimer, P. (1991). Safety aspects of autonomous guided vehicles in automated warehouses. In *IEE Colloquium on Autonomous Guided Vehicles*, 9–1. IET.

Raineri, M., Perri, S., and Bianco, C.G.L. (2019). Safety and efficiency management in lgv operated warehouses. *Robotics and Computer-Integrated Manufacturing*, 57, 73–85.

Sabattini, L., Aikio, M., Beinschob, P., Boehning, M., Cardarelli, E., Digani, V., Krengel, A., Magnani, M., Mandici, S., Oleari, F., et al. (2017). The pan-robots project: Advanced automated guided vehicle systems for industrial logistics. *IEEE Robotics & Automation Magazine*, 25(1), 55–64.

Theunissen, J., Xu, H., Zhong, R.Y., and Xu, X. (2018). Smart agv system for manufacturing shopfloor in the context of industry 4.0. In *2018 25th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, 1–6. IEEE.

Tompkins, J., White, J., Bozer, Y., and Tanchoco, J. (2010). *Facilities Planning*.

Ullrich, G. (2015). Technological standards. In *Automated Guided Vehicle Systems*, 97–163. Springer.

Williamson, K. (2002). *Research methods for students, academics and professionals: Information management and systems*. Elsevier.