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Usage of Autonomous Mobile Robots Outdoors – an Axiomatic Design Approach

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Abstract

Industry 4.0, growing material supply chains, and changing logistics structures require flexible material flow solutions. As a result of this development, the usage of autonomous mobile robots (AMRs) is increasing significantly. Although there has been much research undertaken on the design of indoor AMRs, there is a lack of research regarding outdoor systems. Weather and road conditions are still challenging for sensors and actuators. Furthermore, requirements regarding the system, which must be known and met beforehand to guarantee industrial applicability, are yet to be sufficiently determined. This paper aims to close this gap and identify functional requirements through Axiomatic Design, which is used to develop design guidelines for practitioners. Starting with a systematic literature review and semi-structured interviews, the authors gather basic customer requirements. These customer requirements will then be analyzed to define functional requirements. Through a mapping and top-down decomposition process, the research team deduces design solutions for using outdoor AMRs. These requirements and solutions will be transformed into guidelines, which help system designers to improve the implementation of AMRs on the factory premises.

Keywords: industry 4.0; logistics; material handling; autonomous mobile robots; axiomatic design

1. Introduction

The increase in robotics and automated guided vehicle (AGV) applications within the field of logistics during the last ten years has been significant. The International Federation of Robotics predicted an annual sales growth of 20-30 % [1]. Currently, most of these applications can be attributed to indoor applications. Moreover, many AGVs are automated, but not autonomous. This means they do not exhibit characteristics of autonomous systems, e.g. independent interaction with the environment [2]. Thus, flexible and more intelligent outdoor AGVs, which are also known as autonomous mobile robots [3, 4] can sustainably improve both transport efficiency and transport capacity in the outdoor environment. The increasing flexibility of material supply chains requires adaptable, comprehensive and intelligent solutions [5,6]. This does not only apply to indoor but also to outdoor environments within the factory premises. The reasons for the lower frequency of implementation of outdoor AMRs are numerous. For example, there is a lack of expertise in the technical, procedural and environmental requirements for implementing outdoor AMRs. These requirements include safety and navigation sensors, traffic, weather, and road conditions. Due to a lack of experience, approaches, and methods, feasible solutions have not yet been found. Guidelines already exist for implementing AGVs, e.g. the VDI guideline 2710 [7], but this guideline is more aimed at automated than autonomous mobile robots, and does not consider the outdoor environment. The authors are not aware of any other corresponding guidelines in this field. Therefore, this paper aims to present a design approach using Axiomatic Design [8], to develop and propose an implementation guideline for outdoor AMRs. Based on the inputs of a systematic literature review (SLR), combined with semi-structured interviews, the design approach provides a systematic identification of functional requirements and, subsequently, of appropriate design parameters to finally derive a comprehensive guideline for the design and implementation of outdoor AMRs.

2. Related Work

2.1. Systematic Literature Review

The goal of this SLR is to identify the requirements needed when implementing outdoor AMRs. The search process was a manual search of specific articles (ar) and conference papers (cp) in Elsevier's electronic database Scopus. This database aims to be the leading peer-review database in the field of engineering sciences. Keywords divided on three different levels characterize this search. The keywords refer to the title, abstract and keyword of the respective publication. The first level represents the delimitation through automation. The second level limits the intersection set to its application in an industrial logistics environment and the third level reduces the set of works to be investigated to the ones that contain the key "criteria". Boolean commands link these respective levels. The search is limited to the publication period from 2015 to 2020, to guarantee the novelty of the work. The subject area is limited to (i) materials science, (ii) decision science, (iii) management, business and accounting. Moreover, we considered only English language publications. Fig. 1. illustrates this selection procedure.

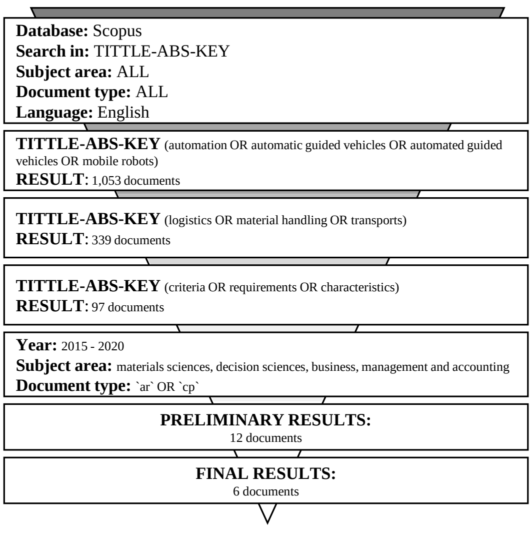

Fig. 1. Selection procedure by using inclusion and exclusion criteria.

The screening process of identified papers was carried out in two steps. First, we screened the abstracts with a preliminary result of 12 relevant works, and second, we made the judgment after reading the entire document. After this final validation process, we extracted six documents as being highly relevant. The coding scheme in the screening process was as follows: works that have been coded as being of "high relevance"; works that provide a general description of AMRs were coded as being of "low relevance"; and works which have no direct relation to the subject under investigation were coded as being of "no relevance". Table 1 shows the preliminary results including their relevance.

Table 1. Preliminary results of the SLR.

Author	High relevance	Low relevance	No relevance
Zi L, Gao B [9]			x
Blaga FS et al. [10]		x	
Reith K-B et al. [11]	x		
Dang Q-V et al. [12]			x
Lee CKM et al. [13]	x		
Capák T et al. [14]	x		
Watfa MK, Karmadi KA [15]	x		
Fedorko G et al. [16]	x		
Lyu X et al. [17]			x
Zhang F, Li J [18]			x
Heger J, Voss T [19]			x
Bostelman R, Messina E [20]	x		

For the further study we used only the six papers of high relevance and, in addition, reviewed the works of low relevance to gain a better understanding of the subject area. In the following sections we summarize the six highly relevant works.

Reith et al. [11] identify general system characteristics and different layout topologies for the vehicle implementation. Four essential aspects must be considered when planning an AGV: specifying the load size, guide path design, number and type of vehicles as well as the design of the control system. Further criteria are layout topology, vehicle speed, delivery reliability, waiting time, idle time, number of transports, transport distances, battery level and handling time. According to Lee et al. [13], particular attention must be paid to four aspects: layout setting, AGV motion setting, charging stations and workstation setting. Furthermore, sensor, zone and deadlock control play a major role. Capák et al. [14] describe the optimization of a traction unit for a developed AGV. They present basic requirements for designing an AGV, e.g. maximum AGV height, maximum load capacity, maximum speed, and power supply. Moreover, they give a deeper insight into omnidirectional wheels and their advantages and disadvantages, as the technology's turning radius of zero meters leads to more flexibility on the factory premises. Watfa and Karmadi [15] study non-fixed paths that can increase transportation efficiency, but will increase traffic complexity and create new controlling problems. They identify three criteria that should be taken into account when introducing AGVs: discharge time, average operation time and resource utilization. Fedorko et al. [16] focus on efficient and safe navigation. Obstacle sensors play an important role in the proper autonomy of AGVs. In order to achieve autonomy, state-of-the-art guidance systems in the form of laser sensors and GPS are used. Some advantages of these technologies in comparison with fixed paths are the diminished costs when a new route is to be created or updated, and the avoidance of maintenance costs. Autonomous guided vehicles are able to move freely and around obstacles. Furthermore, the integration of autonomous guided vehicles is easier and simpler in comparison to traditional, fixed paths for AGVs. Bostelman and Messina [20] proposes criteria for the performance level: vehicle classes, application-specific performance criteria, and other possible areas. The vehicle classes include loading, type, guidance, teach modes and autonomy level. Application-specific performance criteria cover docking, palletizing, obstacle detection, human detection, interaction with manual equipment and operations, environments, synchronization among vehicles, capacities, x/y movement, open source, intelligence, mean time between failures and mean time between charging. The last criteria, i.e. other possible areas, consists of human interaction burden and the use of external enablers for AGV capabilities.

In summary, the results of the SLR show several criteria for designing, programming and introducing AGVs. However, most of the publications focus on AGVs rather than AMRs. In addition, the international research community mainly addresses indoor applications. If they do cover outdoor topics, then this is primarily on a technical level, e.g. navigation and localization. Nevertheless, the introduction of AMRs is not only limited to technical aspects, but also relates to processual, control-related and organizational aspects.

2.2. Semi-Structured Interviews

The second input type of data is semi-structured interviews. Semi-structured interviews provide a great opportunity to gain a deep level of information from practitioners and experts in a specific field. In this case, experts in the field of innovation, automation and especially AMRs within logistics were invited. The target group was experts from the field of industrial truck and automation technologies, suppliers and logistics service providers, management consultancies, e-commerce and automotive manufacturers. The interviews took place from November 2018 to January 2019. In total, 24 experts were interviewed. One part of the guide used in the interviews covers requirements to implement AMRs. Since the survey addresses a topic with a deep information content in the field of AMRs, that only a few people have, we used semi-structured interviews as a suitable method for data collection [21]. The requirements that we derived from the semi-structured interviews can be divided in five main groups [22], (i) localization and navigation, (ii) perception, (iii) safety (iv) efficiency and (v) process control.

In terms of localization and navigation, it is required that the vehicle moves without any physical guidelines. Moreover, it should be able to localize and navigate in a complex indoor as well as an outdoor environment. The main challenge in terms of localization and navigation is the outdoor and transit area. Technical and mechanical components, e.g. actuators or sensors of an AMR, must be weather-resistant and robust. As well as guidance-free navigation which can be achieved using lidar, radar, ultrasonic, camera or GNSS. It is important for the AMR to be able to interact with other traffic participants, for instance, truck drivers, tugger trains, forklifts and pedestrians. Within the second relevant group ("perception"), the experts indicated three requirements. First of all, the AMR must understand its complex environment. On that basis, it makes decisions and derives actions. Therefore, cognitive skills must be available. Safety is of the highest importance, from the perspective of the experts [22]. Sensors used to detect humans and obstacles must be robust enough for indoor and outdoor applications. In several industrial use cases, sensors for human safety have to be certificated. In addition, these sensors are designed to detect ground and weather conditions, and derive necessary braking performance. Current outdoor sensors do not perform with 100 % availability, but 95 % to 98 % is required. Therefore, multidimensional safety scanners with more than one layer and a better angular resolution are needed. To make this possible, it is important to process information in real-time. Obstacle avoidance and positioning accuracy are not yet fully matured. The development of new sensors and better algorithms, especially for the outdoor area, is necessary. AMRs must be cost-efficient. This refers to all components of the mobile robot, e.g. actuators, sensors, battery and drives. Outdoor sensors in particular are very cost-intensive. Competition should develop. The consideration of alternative and sustainable motors is an essential aspect. Additionally, running costs should not exceed the costs of a hand-operated vehicle. The costs of adjustments in infrastructure must also be low. With regard to process efficiency, AMRs must be flexible in terms of short-term changes. The adaptability to new processes is a significant requirement from the experts' point of view. Furthermore, AMRs need to communicate with their environment, including infrastructure, other vehicles (hand-operated, automated or autonomous) and humans. The last group of requirements focuses on control. Control systems of AMRs must be uniform and manufacture-independent. Thus, standard norms and guidelines are needed. According to the experts [22], comprehensive automation needs a uniform control system.

3. Methodology

3.1. Fundamentals of Axiomatic Design

Axiomatic Design is a systematic method for designing complex systems. Suh developed this method in the late 1970s at the Massachusetts Institute of Technology. According to Suh, Axiomatic Design is based on four domains, which are also shown in Fig. 2 [8]:

- Customer attributes domain (CA): describes the needs and wishes of the customer with regard to material, product, process or system.
- Functional domain: translates customer attributes into functional requirements (FR).
- Physical domain: contains design solutions, also called design parameters (DP), to meet the previously defined functional requirements.
- Process domain: transforms design parameters into real process variables (PV).

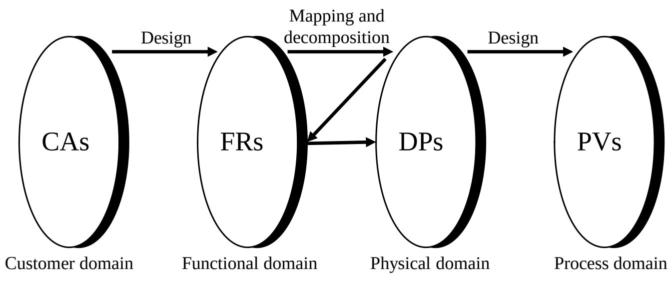

Fig. 2. The four domains of Axiomatic Design [8].

Axiomatic Design receives its name from two axioms that must be respected. The first is the independence axiom. It states that all defined FRs must be fulfilled without affecting other FRs, e.g. avoiding dependencies between DPs and other FRs. The second axiom is the information axiom. It minimizes information to the essential. As a result, the DP with the lowest information content and the highest probability of successful fulfillment of the FRs should be selected [23]. The necessary parts of the application of these axioms arrange the design structure of the lateral decomposition into design domains, and the vertical decomposition into hierarchies. Suh also introduced the process of creating the hierarchy by mapping between the domains [8,23].

3.2. Identification of Customer Attributes and Definition of Top-Level Functional Requirements

Merging CAs of the SLR with CAs of the semi-structured interviews, we obtain the scientific base for executing Axiomatic Design. In the following table 2, we gather common CAs for the introduction of AMRs on the factory premises.

Table 2. Assignment of CAs and FRs.

CAs		FRs	
CA_1	Drive outdoors on the factory premises, mastering different weather and road conditions	FR_1	Locate and navigate autonomously and robustly under outdoor conditions on the factory premises
CA_2	Guarantee the safety of humans and avoiding collisions	FR_2	Ensure human safety and collision avoidance
CA_3	Provide standards for implementing outdoor AMRs regarding design, functionalities, behavior, control, communication	FR_0	Integrate autonomous and robust mobile robots on the factory premises (outdoor)
CA_4	Be economically viable and having a positive business case	FR_5	Evaluate economic efficiency
CA_5	Have cognitive abilities and be able to multi-task	FR_3	Plan and control vehicle functions autonomously
CA_6	Provide accurate localization and navigation data for outdoor use	FR_1	Locate and navigate autonomously and robustly under outdoor conditions on the factory premises
CA_7	Perceive the environment and all their static and dynamic obstacles	FR_2	Ensure human safety and collision avoidance
CA_8	Be flexible with regard to changes in the environment	FR_4	Optimize operational material flow on the factory premises

The definition of CAs allows for the decomposition of the highest functional requirement, which represents the core requirement. Table 1 shows the transformation of the eight CAs into top-level FRs. It is enunciated as FR_0, to implement and integrate autonomous and robust mobile robots on the factory premises (outdoor). The corresponding design parameter of this core requirement is DP_0, to develop appropriate design guidelines for the implementation of autonomous and robust mobile robots on the factory premises (outdoor). This rather vague top-level FR-DP pairs need to be decomposed into lower level FR-DPs. To derive more tangible lower-level FR-DP pairs in the subsequent decomposition and mapping process, we first need to identify and then define the top-level FRs based on the translation of CAs into FRs [24].

3.3. Mapping of Top-Level Design Parameters

For the mapping process, we linked the five top-level FRs described in table 2 to feasible solutions. Furthermore, we defined design fields (DFs) that represent the basis for presenting the decomposition and mapping process in a structured way. The corresponding solutions to meet these FRs are shown in Fig. 3.

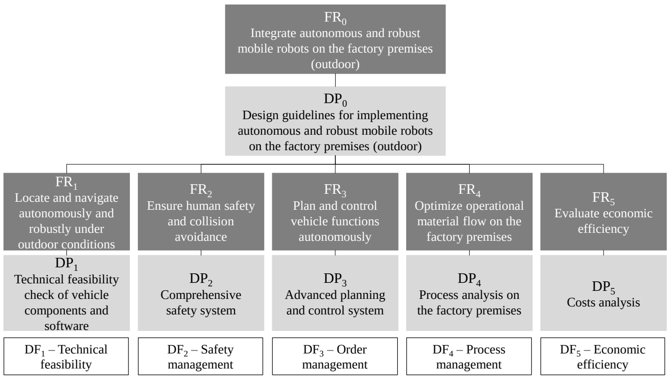

Fig. 3. Top-level decomposition FR-DP tree.

The design matrix at the top-level decomposition (eq. 1) shows the relation between DPs and FRs. The design represents a triangular matrix. In order to fulfil the first axiom (independence), the design matrix must be diagonal (uncoupled and thus a “good” design) or triangular (decoupled and thus an “acceptable” design). However, if a design matrix is neither diagonal nor triangular, it is a coupled design (“bad design”), which means the first axiom cannot be satisfied independently [25]. Equation 1 represents a decoupled design of the design matrix on the top-level.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ X & 0 & X & 0 & 0 \\ 0 & X & X & X & 0 \\ X & X & X & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{Bmatrix} \quad (1)$$

Aside from the coupling to FR_1, DP_1 has a relationship to FR_2, FR_3 and FR_5 since the design of the safety system, the autonomous planning and controlling of vehicle functions as well as the economic efficiency are directly related to the technical feasibility of the vehicle hardware and software components. A comprehensive safety system (DP_2) has no relationship in order to locate and navigate autonomously and robustly under outdoor conditions on the factory premises (FR_1). Nevertheless, it is related to FR_4 and FR_5. DP_2 plays an important role in optimizing the operational material flow and the economic efficiency. An advanced plan and control system (DP_3) has a relationship to FR_4 and FR_5 because a more advanced planning and controlling system can optimize the material flow as well as the cost situation.

The presented decoupled matrix (eq. 1) shows that DPs affect more than one FR. However, a closer investigation reveals that dependencies existing between FRs and DPs create manageable feedback loops if the DPs are implemented in the correct sequence from left to right. Hence, the decoupled design can be classified as an acceptable system design, provided the value of DP_1 is set before the value of DP_2 and the value of DP_2 before the value of DP_3 and so on [25,26].

3.4. Decomposition of Design Fields

Following the top-level decomposition and mapping of FRs and DPs, we perform the decomposition and mapping process for the lower level separately for each design field.

Table 3. Decomposition of DF_1 - Technical Feasibility

$FR_{1.1}$	Evaluate hardware components for outdoor use regarding their robustness	$DP_{1.1}$	Technical suitability test of hardware components for outdoor use
$FR_{1.2}$	Ensure robust and sustainable navigation software for the outdoor environment	$DP_{1.2}$	High-quality environment maps with robust and accurate localization
$FR_{1.3}$	Interact autonomously within a dynamic environment	$DP_{1.3}$	Environmental perception and understanding using sensor technology

Table 4. Decomposition of DF_2 – Safety Management

$FR_{2.1}$	Make sure that no danger emanates from the vehicle	$DP_{2.1}$	Systematic integration and networking of safety measures
$FR_{2.2}$	Provide documents to support a safe use of the vehicle	$DP_{2.2}$	Documentation (risk analysis, operating instructions, functional test of safety devices)
$FR_{2.3}$	Train relevant stakeholder before first implementation	$DP_{2.3}$	Trainings
$FR_{2.4}$	Ensure a comprehensive safety system under various weather, light and ground conditions	$DP_{2.4}$	Performance of test scenarios under extreme conditions

Table 5. Decomposition of DF_3 – Order Management

$FR_{3.1}$	Steer the vehicle automatically	$DP_{3.1}$	Control system of actuators and sensors
$FR_{3.2}$	Interact with the "outside world"	$DP_{3.2}$	I/O control
$FR_{3.3}$	Ensure and coordinate the right route for the vehicle	$DP_{3.3}$	Process control
$FR_{3.4}$	Control the operation of the vehicle in the short term	$DP_{3.4}$	Operations control (short-term planning)
$FR_{3.5}$	Plan the long-term operation of the vehicle	$DP_{3.5}$	Resource planning (long-term planning)

Table 6. Decomposition of DF_4 – Process Management

$FR_{4.1}$	Identify current transport processes outdoors	$DP_{4.1}$	State analysis
$FR_{4.2}$	Scan transport processes	$DP_{4.2}$	Process description
$FR_{4.3}$	Represent the transport process in its entirety	$DP_{4.3}$	Detail process description and visualization of transport processes
$FR_{4.4}$	Identify weak points and potential for improvement	$DP_{4.4}$	SWOT analysis
$FR_{4.5}$	Assess the process in terms of "autonomization"	$DP_{4.5}$	Process FMEA

Table 7. Decomposition of DF_5 – Economic Efficiency

$FR_{5.1}$	Gather expenses of the autonomous mobile robot	$DP_{5.1}$	Cost breakdown for the autonomous mobile robot
$FR_{5.2}$	Gather expenses of the manual reference process	$DP_{5.2}$	Cost breakdown for the manual reference process
$FR_{5.3}$	Assess the expenses for the autonomous mobile robot	$DP_{5.3}$	Dynamic capital expenditure budgeting tool

4. Design Guidelines

Based on the mapping and decomposition process of the top and lower level within the five design fields, we can now derive the design guidelines for implementing outdoor AMRs (Fig. 4).

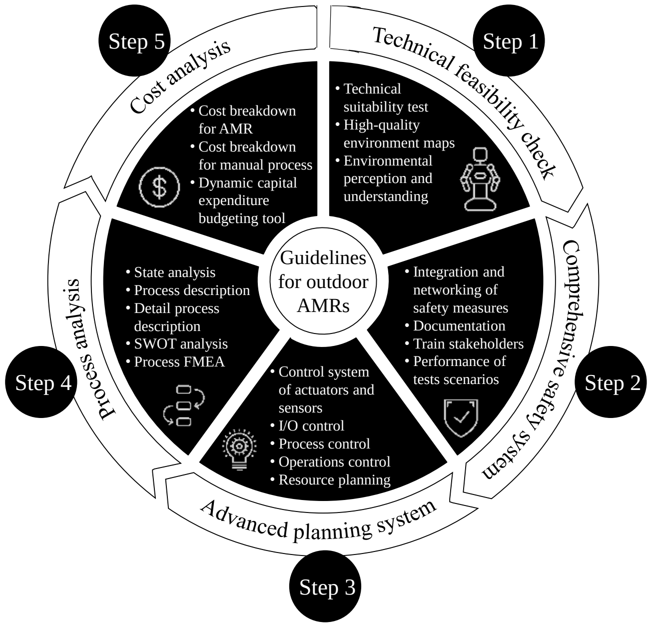

Fig. 4. Design guidelines for implementing outdoor AMRs.

The first step that needs to be considered for the implementation of outdoor AMRs is the technical feasibility check. For instance, road and weather conditions require robust and suitable mechatronic components of the vehicle. Therefore, technical suitability tests of hardware components for outdoor usage should be implemented. High-quality environment maps with robust and accurate localization allow a stable outdoor usage. An AMR interacts autonomously with the environment; thus it is mandatory to use sensor technology for perceiving and understanding the environment, including all actions within the latter. Interacting autonomously also depends on the two previously mentioned points: technical suitability tests and high-quality environment maps. After checking the vehicle itself, a comprehensive safety system must be developed. We have found that the systematic integration and networking of safety measures avoids danger, which emanates from the vehicle. It also influences the documentation and the overall comprehensive safety system. Moreover, it is essential to provide all relevant documents regarding the vehicle and its functions. The documentation must include a risk analysis, operating instructions as well as records of functional tests of safety devices. These documents have a relationship to stakeholder training and the comprehensive safety system. Training of stakeholders who are directly or indirectly involved with the AMR, e.g. employees, safety department, fire department, maintenance department, works council or process owners, should take place before the AMR arrives to the factory premises. Finally, various test scenarios must be performed under extreme outdoor conditions. The third step of the guideline contains the planning and control system. The lowest level of control includes the control of the actuators and sensors of the vehicle. The following includes the I/O control system, which transfers data between the main memory and peripheral devices. It makes the AMR capable of interacting with the "outside world". To ensure and coordinate the right route for the vehicle, and to control the operations in the short term, process control and operations control is required. Another part of an advanced planning system is resource planning. This can be done in a centralized or decentralized manner, depending on the overall environment. If the AMR interacts in a completely autonomous environment, centralized decision-making is more efficient than decentralized decision-making. If the environment contains manual, automated and autonomous objects, then decentralized decision-making would be more appropriate. The fourth step starts with a state analysis. This, in turn, involves a process as well as detail process description. After capturing the current process including all its information, it is recommended to perform a SWOT analysis in order to determine the strengths, weaknesses, opportunities and threats around implementing an AMR. Once a process has been identified, a Failure Mode and Effects Analysis (FEMA) should be performed to verify its quality. The final step of the guidelines applies to the costs of implementation. An extended cost analysis, which highlights the cost breakdown for the AMR and the manual process, creates transparency and supports the decision for implementation. Furthermore, a dynamic capital expenditure budgeting tool enables the assessment of the expenses for AMR implementation. The economic efficiency is a key aspect for a decision regarding implementation. Thus, it should be performed very precisely.

5. Conclusion

This paper presents an Axiomatic Design-based approach in the form of guidelines for implementing outdoor AMRs. A systematic literature review and interviews were conducted to gather customer needs from a scientific and practical point of view. Subsequently, the research team derived FRs and DPs using Axiomatic Design decomposition and mapping. Finally, these requirements and solutions were transformed into the proposed design guidelines in Fig. 4. These design guidelines allow system designers to understand and execute a complex implementation process by splitting it into small implementation steps. The design guidelines also contribute to the procedure for implementing AMRs on the factory premises. However, further investigations can be carried into the depths of FRs and DPs (e.g. third, fourth, etc. level), and into the individual elements of the guidelines, in which the research team identified further need for research. In conclusion, this contribution provides a valuable step in the direction of implementing outdoor AMRs.

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