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Levels Of Autonomy In Production Logistics: Terminology And Framework

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Abstract

The increasing demand of flexibility in production systems influences the organisation of production logistics and enhances the role of autonomous resources for logistic tasks. In the current state of the art, there exists neither a common definition of the term “autonomy” in the production logistics context nor a generalised approach regarding the classification of autonomous resources depending on their characteristics as well as their skills. Due to this lack, difficulties appear when intending to integrate autonomous resources - that are implemented for logistic tasks - in the superior production control processes which aim to meet the key performance indicators of the production system.

This paper analyses in a first step the current use of terminology regarding autonomy and related terms like automation and self-x approaches in production logistics. Based on these results, a definition of “autonomy” for production logistics and a universal framework for classifying autonomous resources regarding their level of autonomy can be proposed. This allows to specify afterwards the appropriate level of autonomy in production logistics for a specific production system.

Keywords

Autonomy; Autonomous Transport System; Autonomous Guided Vehicle; Production Logistics; Production Control

1. Introduction

Globalization forces production companies to deal with high market dynamics, shorter product life cycles, increased competition, and rising volatility. Therefore, production systems need to cope among other challenges more and more with the customer demand of getting individualized products. This expectation leads to rising complexity and dynamics in production environments as well as production processes due to the necessary flexibility [1,2].

The current developments in the context of industry 4.0 concerning data exchange and interconnectivity in production systems offer various possibilities to analyse workflows in a more detailed way [3]. It is now possible to understand processes and their interdependences on different levels based on collected data and to hereupon optimize diverse parameters and target values, e.g. throughput time and/or product output [4,5]. In addition, this also highlights the significance of non-value-adding processes in production like production logistics as well as their importance for reaching key performance indicators (KPI) and emphasizes the importance of integrating them in communication and exchange processes [6,1]. In the context of logistics,

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this development is called “logistics 4.0” [7] and underlines that it is not preferable to look at intralogistics processes in an isolated way due to its influence on meeting planned production schedules and due dates [8]. Challenges for planning and control in this context consist in finding a connection between central and decentral approaches [9] and in integrating autonomous and intelligent systems [10]. Especially choosing an appropriate autonomous system is difficult for decision-makers as there is a lack of term definition and classification of levels of autonomy within the scope of production logistics.

With increasing dynamics, flexibility, and complexity as detailed above, an increasing decentralized and autonomous based organization of production logistics systems is required [7]. An exclusively central approach in production logistics is not sufficient because of the unpredictable environment. Therefore, decentralized approaches have to be taken into account [4] and conventional planning and control methods for logistic processes are no longer sufficient [11]. That’s why this paper introduces an appropriate definition of the term “autonomy” for production logistics based on an analysis of the current use of the term in state of the art publications (cf. chapter 3). Afterwards, a universal framework for classifying autonomous systems regarding their level of autonomy is described (cf. chapter 4). The developed framework supports decision-makers in manufacturing companies to choose a proper autonomous transportation system with relevant characteristics referring to a corresponding application.

2. State of the art

In this section, basic principles of production logistics and applied resources are presented to frame the analysis as well as the developed definition and the framework explained afterwards in chapter 3 and 4. The whole topic has a non-neglectable connection to production planning and control processes. So, they are briefly introduced in the beginning.

2.1 Production logistics

Within a production organization, production logistics deal with the planning and control of material and information flow. In this context, production logistics are placed between procurement logistics and distribution logistics and comprise all activities to supply production and assembly processes with material (raw material, operation material, semi-finished goods or purchased goods) as well as the transportation of semi-finished or finished products to the next production step or the stock [12]. The main goal of production logistics is the on-time delivery of material on the one hand to avoid costs for downtimes due to delays and on the other hand to prevent high waiting times in case of too early deliveries [13,14]. So, there exists an important influence on throughput time [8]. Current challenges in production logistics are induced by the changes due to industry 4.0 approaches and comprise especially ensuring the logistic flow in uncertain and changing production environments as well as the integration in higher level control processes [6,15].

2.2 Production planning and control

The main tasks of production planning and control in manufacturing systems are generating a valid production program based on orders, task allocation and production supervision in order to reach logistic KPIs [16,17]. Planning and control is introduced here briefly because of the interaction and relation between the superior planning and control level and the executing logistic level: a transport system is not able to operate without respecting other processes in the manufacturing system and impacts overall KPIs. Basic logistic KPIs in production are for instance throughput time (time between order approval and order completion), inventories (amount of orders that are approved but not yet completed), utilization (ratio between average output and maximum output of a production resource or system) and delivery reliability (amount of orders that are completed within the planned delivery time) [19,18,23,20,22,21]. Logistic KPIs that are relevant in the context of production logistics are in general derived based on customer needs - here the requirements of value-adding manufacturing processes - and therefore include objectives as delivery time, delivery lateness, and delivery reliability [18,21]. For more detailed information on planning and control see for example [18,24,16,17].

2.3 Autonomous transport system

In this paper an autonomous transport system (ATS) is defined as a fleet of autonomous vehicles. The terms autonomous guided vehicle (AGV) and autonomous vehicle are used synonymously and describe vehicles without a driver that fulfil transport tasks in production logistics. Depending on the manufacturer and respectively the model, they can have differing skills and competences in order to complete transportation tasks. “Modern” shopfloor layouts and flexible organisation processes require intelligence on transport resource level to reach adaptability. More detailed information can be for instance found in [21,25,26].

3. Analysis regarding the use of the term “autonomy” in production logistics

The goal of this chapter is to derive a definition of the term “autonomy” in context of production logistics. Therefore, an analysis of the current use of terminology regarding autonomy and related topics is required.

3.1 Comparison autonomy – automation – self-x-approaches

Within a literature review, the main terminology differentiation between the terms autonomy, automation, and self-x is demonstrated in this subchapter. Subsequently, all central ideas are summarized and compared regarding abilities of considered system resources. Relevant literature is listed in Table 1 subdivided by their focus regarding differentiation of terminology.

Table 1: Classification of literature in context of production systems

Authors	Autonomy	Autonomy and automation	Autonomy and self-x
Windt et al., 2008 [27]	X		
Dumitrescu et al., 2018 [28]	X		
Gamer et al., 2019 [29]		X	
Müller et al., 2021 [30]		X	X
Stock et al., 2020 [31]			X
Scholz-Reiter and Höhns, 2006 [20]			X
Schuhmacher and Hummel, 2020 [22]			X

[27] describe the term autonomy in the context of autonomous control by processes with decentralized decision-making and the ability of system elements to make decisions independently. Furthermore, the authors characterize autonomous control in logistic systems “by the ability of logistics objects to process information, to render and to execute decisions on their own”. The superior goal of the autonomous control is the increase of system robustness of non-deterministic system behavior and positive emergence through objective achievement of every single logistics object. Accordingly, [28] generally describe autonomous systems as systems with the ability to process tasks on their own without human influence. Beside the independent task fulfilment, the high adaptability to changing environments is one major characteristic.

In contrast, [29] interpret autonomous systems from an industry perspective in the context of industrial automation systems as the highest level of automation. In this regard, the authors describe an automation system characterized by little to no human influence while system tasks are pre-defined using a predetermined rule-based decision-making in structured environments. Autonomous systems, on the other hand, are described by learning-based capabilities and the ability to adapt to changing system conditions while actions are not pre-programmed. Complementary, [30] describe autonomy in the context of industrial automation systems by four major characteristics commonly used in definitions: First, a systematic process execution is stated which is defined as the ability of a system to execute modeled processes. Second, the adaptability to changing environments for reaching its goals is mentioned. Furthermore, self-governance as the system's ability to manage its resources without human intervention through context-awareness and self-containedness of the system (defined goal and scope of the system) are stated. In the authors perspective, the autonomous system is an extension of the (intelligent) automation system by the above-mentioned further characteristics. Here, self-x capabilities are considered as characteristics of autonomous systems but as-well of automation systems depending on the specific self-x property.

An overview of essential self-x capabilities for cyber-physical systems (CPS) is given by [31]. In this respect, self-x is described as e.g. self-description, self-organization, self-control and self-configuration. All relevant self-x capabilities are ordered within a hierarchy while the authors allocate these capabilities to levels of autonomy. As a result, autonomy is described by these self-x capabilities which enable a certain level of autonomy while an increasing level of autonomy comes along with a decrease in human control. Nevertheless, in line with [30], non-autonomous systems as well can be characterized by certain self-x capabilities as for example self-description. Self-x capabilities are not solely part of autonomous systems but depend on the self-x characteristic and might also describe automation systems with less or no autonomy.

In contrast, the term self-organization on the one hand can be a representative of self-x and on the other hand can be regarded as a separated concept as in [20]. The authors define self-organizing systems as collection of processes of decentral decision-making in heterarchical structures that require the ability for autonomous decisions of interacting entities. In conclusion, the authors see autonomy as a part of the concept of self-organization. [22] acquire a differentiation between the term self-organization on the one hand and autonomous control on the other hand. Here, self-organized systems are regarded as the ability of a system to "design its processes und systematic structures in an autonomous manner" and is therefore more focused to an organizational level. Whereas autonomous control is considered according to [27] and is regarded on an execution level or single object level of the corresponding system. [31] in contrast, consider self-organization as one self-x capability of the highest level of autonomy.

In conclusion, the above-mentioned literature describes autonomy to a certain degree in a similar way, but some inconsistencies and differences can be identified especially in the differentiation with autonomy and automation as well as the terms autonomy and self-x. These are summarized within Figure 1.

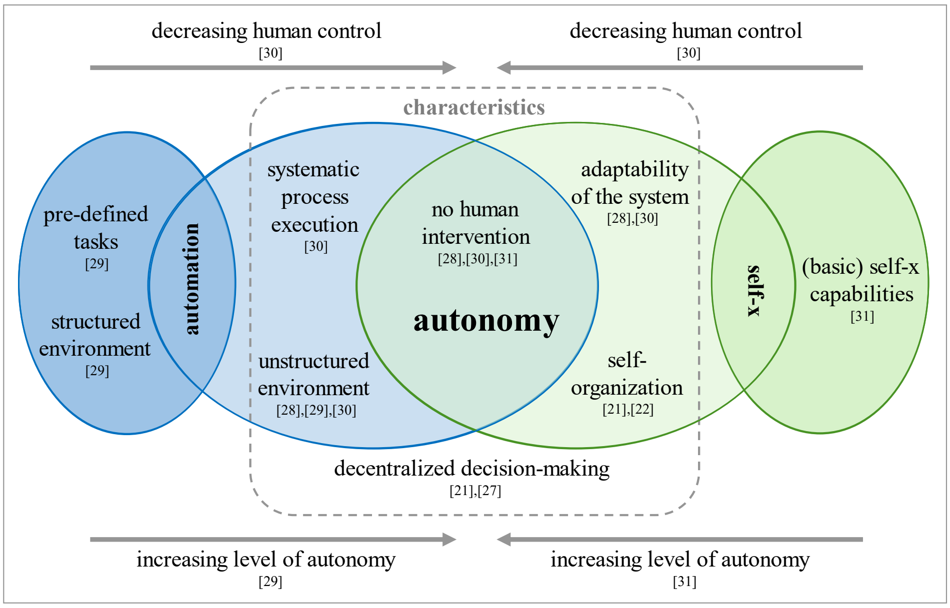

Figure 1: Summary of term differentiation in literature referring to system's characteristics

Furthermore, as most of the sources focus on production systems in general, a specific definition of the term autonomy in context of production logistics needs to be derived dissolving the described inconsistencies (cf. chapter 3.2).

3.2 Definition of autonomy in production logistics

Based on the section above, a definition for autonomy in production logistics can be derived. For a better understanding of the main definition elements, a more detailed explanation will follow below. In this paper, autonomy in production logistics is defined as follows:

> *"Autonomy is the ability of a system to make decentralized decisions* ***without human intervention*** *in order to reach pre-defined goals (transport tasks) and to cope with an* ***uncertain, unknown, and/or dynamically changing environment****. Therefore, the transport task fulfilment related to logistic-specific objectives is realized through an* ***internal intelligence*** *of cooperating autonomous resources."*

Within the mentioned decentralized decision-making, decision-problems are split into smaller problems and only local information depending on the systems environment is considered [20,27]. Therefore, information is generated and processed by the individual system's resources itself. This comes along with the absence of human intervention as the decision-process is realized without external trigger or control by humans [31]. Consequently, the system as well as all individual resources have the ability of self-organization and self-adaption. As part of the decision-making process the achievement of pre-defined system objectives i.e., specific key performance indicators, is pursued. In relation to that, resource tasks like route planning, collision avoidance or navigation in the context of production logistics need to be fulfilled in alignment with the overall system objectives (goal-orientation) while task allocation is again achieved without external control [30]. Especially the cooperation and interaction of individual autonomous resources is required to realize the above explained elements such as decision-making and task fulfilment. In this context, the required adaptability, and the ability to learn for optimized decision-making is realized by internal intelligence of these cooperating autonomous resources.

As in practical not all elements of the definition are fulfilled by every autonomous vehicle, the classification as "autonomous" is insufficient and does not help when comparing AGVs with varying characteristics. That's why different levels of autonomy need to be considered and are described in the next section.

4. Framework for levels of autonomy in production logistics

Based on the above definition of autonomy for production logistics (cf. chapter 3.2) it is possible to specify a description of a universal framework for classifying AGVs regarding their level of autonomy. This framework helps to create comparability and to simplify the choice of an appropriate AGV for a production system by linking skills (cf. chapter 4.1) and tasks (cf. chapter 4.2) in a standardized way. Because in production logistics, there is not necessarily a human worker involved in the task fulfilment the way of cooperation between human and system cannot present a valid classification criterion as it is done for autonomous vehicles in the automotive context (see definitions by National Highway Traffic Safety Administration and Society of Automotive Engineers). The framework presented hereinafter (cf. chapter 4.3) aims to answer the question how to classify the level of autonomy of an autonomous system implemented in a production system.

4.1 Skills of AGVs

The characteristics of AGVs define the skills they can offer to fulfil tasks and influence therefore their level of autonomy. The skills of an AGV depend on the hardware and software components the manufacturer has implemented. In production logistics, as explained above, we consider a technical view "without" implication of any human. An analysis of available publications showed that there exist various approaches to classify skills of autonomous vehicles. The framework is based on the work of [33,32,34] and the following five main skills defining autonomy in the context of production logistics are derived:

- Acquisition of information, i.e. collecting data via various channels/ways
- Information processing, i.e. generating knowledge out of the collected data
- Decision making, i.e. choosing what to do based on the derived knowledge
- Interaction, i.e. communicating with the environment for the execution of a task
- Control, i.e. checking and documenting the successful execution of a task

These five skills constitute the foundation for AGVs being able to fulfil tasks that occur when these AGVs are used in production logistics. The characteristics of AGVs allow to clearly delimit the scope as well as the content of each of these skills and therefore, they have been chosen for the framework presented in this paper. Summing up, the skills of the AGVs define which role an autonomous transport system can take in the production system, i.e. how responsibilities can be shared with an external system (cf. chapter 4.3).

4.2 Tasks of AGVs in production logistics

When analysing the role of logistics in production environments and comparing different approaches (cf. chapter 2.1), four central tasks of autonomous resources can be derived that AGVs have to complete and which are relevant for defining autonomy: navigation, task assignment, collision avoidance, and charging. In order to clarify the scope of each of these tasks as well as their meaning in this paper and hence for the presented framework the four tasks are described below:

- Navigation: This task comprises in particular registering the existing production layout, implementing strategies for how to reach a destination in the production layout using a given algorithm and documenting current routes as well as locations of moving vehicles [25].
- Task assignment: The basis of transporting materials, semi-finished products or finished products consists in deciding which transport resource fulfils which transport task considering defined rules. A production planning system collects all the tasks and disposes of supplementary information like work process, specific requirements, and due dates.
- Collision avoidance: While moving the autonomous vehicle has to consider and avoid collisions with either potentially moving objects, i.e. other vehicles or humans, or static objects, i.e. “things” standing around, that are not captured in the production layout. At crossings there need to be strategies on how to assign priorities in order to avoid dead locks. For more information on the classification of obstacles and the choice of a strategy in the case of collisions like waiting or taking alternative routes see [35].
- Charging: This approach does not focus on strategies for charging (cf. other publications), but on the influence of this procedure in logistics as it interrupts the workflow and is consequently relevant for planning and control. Here, only the supervision of battery charge is taken into account.

The developed framework (cf. chapter 4.3) is based on these task descriptions as it is fundamental for any kind of standardized approach to dispose of a clear definition of the applied basis. Their extent is consciously limited to the jobs that can be assigned to an autonomous transport system applied in production logistics of manufacturing companies.

4.3 Description of the framework

Based on the skills and tasks described in chapter 4.1 and 4.2, the framework proposed hereafter combines these aspects. There can be three ways of distributing the four tasks between the autonomous transport system and an external system (human and/or IT system) based on the five skills:

(1) No external control (except initial order registration), i.e. the autonomous system proposes all necessary skills
(2) Implication of external system, i.e. division of responsibilities and the external system is only responsible for the initial acquisition of information
(3) Control via external system, i.e. the autonomous system proposes only the "executing" skill of interaction

Table 2 specifies the three possible ways for distributing responsibilities between the autonomous transport system and an external system for the five skills (cf. chapter 4.1).

Table 2: Possibilities for distribution of responsibilities

	(1)	**(2)**	**(3)**
Acquisition of information	Autonomous transport system	External system	Autonomous transport system
Information processing		Autonomous transport system	External system
Decision making			
Interaction			Autonomous transport system
Control			External system

The work presented in chapter 4.1 and 4.2 is transferred into a framework by considering these three ways of distributing tasks. In theory, for each of the four tasks an AGV can take over each of the five skills either completely on its own, partly with an external system or transfer it to the external system, i.e. three possible levels per task as introduced above. In practice, not for every task every way of responsibility for the skills is reasonable, so the choices have to be reduced:

- Navigation: (1), (2), (3), i.e. all three ways of responsibility are possible
- Task assignment: (2), (3), i.e. an external system is always required
- Collision avoidance: (1), (3), i.e. the acquisition of information (concerning obstacles) and the interaction is completed by the autonomous transport system itself
- Charging: (1), (3), i.e. the acquisition of information (concerning charging level) is completed by the autonomous transport system itself

As mentioned, not all ways of responsibility are applicable for the four tasks when defining levels of autonomy. This results in three ways for the navigation task and two ways respectively for task assignment, collision avoidance and charging. When additionally considering dependences between the tasks especially between navigation and collision avoidance which are linked to the strategies implemented in AGVs for these tasks, eleven levels of autonomy can be distinguished. They arise from three possible combinations between navigation and collision avoidance, two ways for task assignment and two ways for charging:

$$11\ levels\ of\ autonomy = 3 \cdot 2 \cdot 2 - 1 \tag{1}$$

One possibility has to be subtracted for the combination when all tasks are executed by an external system except charging. This would not be reasonable.

Figure 2 summarizes the approach for the definition of eleven levels of autonomy in production logistics.

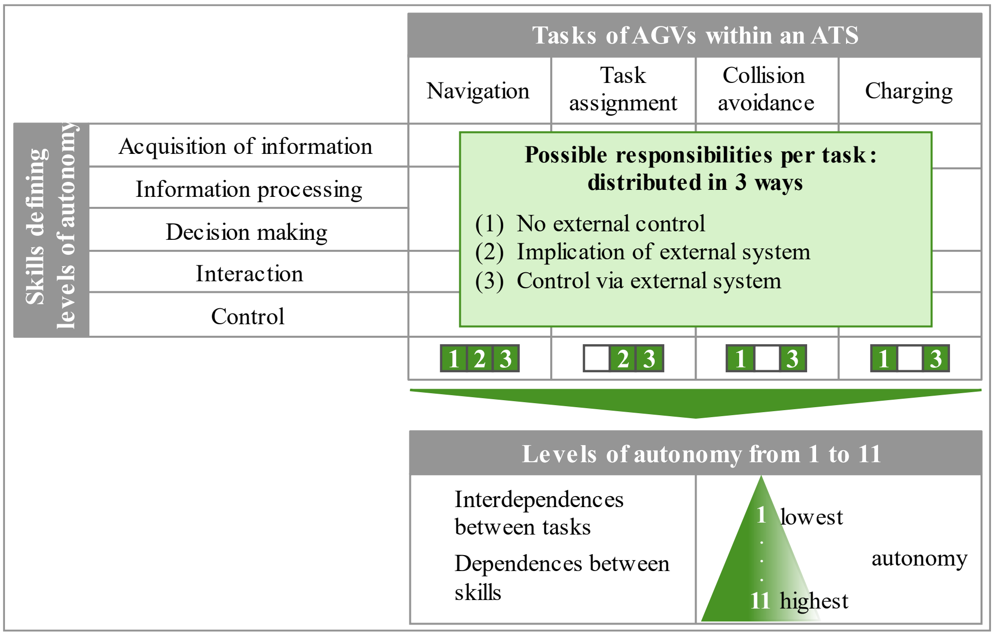

Figure 2: Framework for the classification of autonomy in the context of production logistics

For arranging the levels of autonomy, the rule applies “the less implication of an external system the more autonomy of a system” as proposed also e.g. by [32]. The order was determined by calculating the distance to the origin in a 3D coordinate system by using the number of implicated external systems for the skills acquisition of information, information processing, decision making, interaction, and control. The closer to the origin the more autonomous the autonomous system is. The numbering was inverted compared to the description in [32], so level 11 describes the highest and level 1 the lowest level of autonomy.

5. Conclusion

After shortly introducing the relevant state of the art regarding production logistics and autonomous transport systems, this paper presents an analysis of the current use of the terms autonomy, automation and self-x-approaches in production logistics. These are compared and differentiations in the terminology are summarized. As there exists no clear characterisation of autonomy for production logistics, a definition for this important term in the context of the rising use of AGVs in manufacturing environments is deduced. Afterwards, a framework for classifying AGVs based on their skills and the tasks they have to fulfil is explained. This approach differentiates between eleven levels of autonomy in production logistics.

The presented framework is necessary for decision-makers in manufacturing companies in order to choose in a next step an appropriate AGV for a production system and its specific characteristics. Therefore, the framework provides a basis and is part of a procedure for the organisational integration of an autonomous transport system in a production system. This aspect becomes more and more important due to the rising demand of flexibility in transportation systems and the request for the use of autonomous systems. Further research has to be done on the relation between vehicles classified with the proposed levels of autonomy and their appropriate use in different production organisations.

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Biography

Michaela Krä (*1990) has been working at the Chair of Digital Manufacturing, Faculty of Applied Computer Science at Augsburg University since 2016. In 2015, she completed her bilingual studies in “Production and Automation” in Munich and Paris. She acquired practical knowledge among others in internships at MINI (BMW Group, Great Britain), MTU Aero Engines (Germany) and Airbus (France).

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