Modeling the Infrastructure of Autonomous Logistic Control Systems

Bernd Scholz-Reiter, Steffen Sowade, and Daniel Rippel

Abstract**—**Autonomous control has been approved as a suitable concept to increase the flexibility and robustness of logistic systems by enabling decentralized decision making and execution at the system elements. Thereto, a control system requires additional infrastructure components. This paper introduces a qualitative model of terms and drivers being relevant to configure the infrastructure of autonomous logistic control systems in a specific scenario. It discusses the terms, logistic system, infrastructure, configuration, and autonomous control in context of control systems for production logistics.

Keywords**—Autonomous Control System Design, Control System Infrastructure, System Architecture**.

I. Introduction

INDUSTRIAL production employs several logistic processes to produce goods for customers. Each process determines the efficiency of the value added. For this reason, companies use powerful planning and control systems to manage the achievement of their logistic objectives, e.g. lead time, produced amount, and capacity utilization. Although centralized control approaches are used widely today, they lack flexibility and robustness to reach the logistic objectives in case of unexpected events, like machine breakdowns or rush jobs. In this context of highly fluctuating supply and demand of manufacturing capacity, researchers analyze the paradigm of autonomous control in logistics. Flexibility and robustness shall be increased by use of decentralized decision making and execution with specific decision methods by the logistic objects (orders, resources, and commodities) themselves [1].

A. Research Question

Researchers have already defined and characterized the term autonomous control and its principles [2] and have proposed a notation and a procedure model to specify autonomously controlled adaptive business processes [3]. Additionally, simulation tools are required in order to evaluate the functionality, correctness, and accurateness of modeled logistic scenarios. Methods to configure the infrastructure of autonomous control systems and cost-benefit-models are required as well.

This research article aims to present a qualitative model of terms and drivers which influence the configuration of a control system's infrastructure in autonomously controlled logistic systems. The basic terms are being defined in detail in order to provide a base for future research.

B. Outline

The first section introduces problems in production planning and control approaches and presents the research question. Section two employs a literature survey to deepen the understanding of the terms logistic system, infrastructure, configuration, and autonomous control. The third section presents a qualitative model of terms and drivers influencing the configuration of the infrastructure of autonomous logistic systems. The final section gives an outlook on subsequent research.

II. Understanding Basic Terms

A. Logistic System and Logistic Element

Mikus states spatial-temporal transfers as core function of logistic systems [4]. Objects being involved into the spatial-temporal transfer are named logistic system elements. These are material and immaterial resources which are necessary to produce the logistic outcome. Further, commodities and half finished products are logistic system elements. Chains of logistic transfer activities are called logistic processes. Spatial-temporal transfers are relations between different logistic objects. The logistic system elements and their relations form a network of nodes and edges. Nodes work as buffers and are used for the selection of the next edge, while edges describe the change of object's states. Indeed, Delfmann uses a broader systemic view on logistic systems and understands them as a unit of functional, instrumental, and institutional design elements [5]. Interdependencies between the system at a glance and specific details are addressed at the same time. He comprehends the spatial-temporal transfer of objects as logistics and the elements of a logistic system as starting and ending point of transfer processes. The transfer specific characteristics of a logistic system structure and the logistic processes specify the flows within logistic networks. How-

Manuscript received October 29, 2010. This research is funded by the German Research Foundation (DFG) as part of the Subproject B2 of the Collaborative Research Center 637 "Autonomous Cooperation Logistic Processes – A Paradigm Shift and Its Limitations" (CRC 637).

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ever, the transfer approach of both authors neglects qualitative transformations of system elements. Thus, our understanding of logistic systems explicitly includes qualitative transformations, like wear, maturity, and production processes, besides spatial-temporal transfers, like storage and transportation. Additionally, Delfmann names controlling and management as supplementary functions. In production logistics, system elements are resources, like machines and workers, as well as commodities, like raw materials or ready-made parts.

Logistic systems can be structured by conceptual layers, by different viewpoints, or by the type of the logistic performance [4], [5]. Each layer in the conceptual layer model aims to achieve a steady sequence of activities and processes. The lowest layer provides the spatial-temporal transfer of logistic objects as basic logistic function. The middle layer contains required coordination functions which are needed to maximize the logistic outcome. It takes care of planning, realization, monitoring, and control of the logistic system. Finally, management and strategic issues are handled as logistics philosophy in the upper layer. The layer considers inter-functional and inter-organizational interdependencies of the logistic system's processes. Further, logistic systems can be structured by the type of integrated institutions, commodity flows, processes, or transfer objects [4]. The structuring of logistic systems will help for the infrastructure discussion in successive sections.

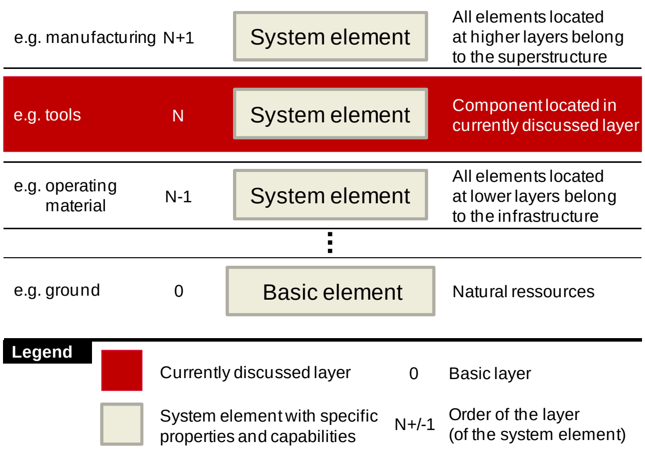

Fig. 1 Infrastructure Layer Model

B. *Infrastructure*

The historic outline of the term infrastructure shows an ongoing adaption of the term from a strict technical meaning to a military and economic use and towards its application in politics and informatics. The origin of "infrastructure" is located as a technical term of the French railway and denotes durable facilities which are connected to the ground, like tracks, tunnels, or stations. Its public character leads to the German phrase "public works". However, public works are used for any object being accessible and useable by the public, or being erected in public. Since 1950 stationary equipment of a military organization is named infrastructure as well. Later infrastructure has been adapted to economics [6]. For instance, governmental deregulation politics have used the term infrastructure often for transport-service-oriented basic works in telecommunication, electricity, gas, and water supply in Europe since the 1990s. Instead, informatics names hardware and software equipment as infrastructure for services in information technology (IT). An IT infrastructure provides a set of services to IT system users.

Besides these application area specific explanations, the Duden dictionary defines infrastructure based on its historical use as economical-organizational foundation for an economy and in the military sense mentioned above. Klaus states this understanding as too vague and comparably too tight from his juristic-methodological viewpoint. Thus, he defines infrastructure as: "the elementary human-made facilities, which are a precondition for a high developed economy and may change over time. Its main characteristics are its base-character, artificiality, indispensability for proper functionality, and changeability." [6].

However, neither these definition approaches converge to a unique general understanding, nor do they include logistic specifics. For this reason, this article defines infrastructure in a more abstract, system-theoretic view:

Infrastructure includes all system elements which are placed artificially into a given system, called native system. These system elements must be essential to enable specific higher order services within the system by use of capabilities supplied by native system elements and by artificially inserted system elements.

Neither the capabilities of a native system nor new system elements themselves can operate the demanded activities. Thus, artificially inserted elements are a precondition in order to execute specific functions or, respectively, to carry out higher order tasks in a spatial delimited logistic system, for instance. Further, a hierarchy of required elements is addressed in this definition and can be used to derive a generic infrastructure layer model (Fig. 1). This model bases on distinct layers containing system elements which provide specific functional services to higher layer elements. For instance, all system elements located in layer N-1 are infrastructure from layer N view. At the bottom, the model shows the elements of the native system.

Table 1 Infrastructure Classification [6]

Characteristic	Value	
Dedication	Public	Private
Usage	Productive	Consumptive
Materiality	Material	Immaterial
Network Orientation	Network-based	Non-network-based
Level Type	Primary	Secondary

The main characteristics of infrastructure remain and are its base-character, artificially integrated elements, indispensability for proper functionality, and changeability [6]. The establishment of infrastructure requires resources, i.e. usually space, and leads economically to sunk costs. The socio-technological development determines its social impact.

Contrary to Klaus, the artificiality refers to the process to add another element, but not to the type of element itself [6].

Several authors classify infrastructure with a background of deregulation politics [6], [7]. They distinguish infrastructure by its dedication, usage, materiality, network orientation, and level type (Table 1). The last three rows are partly counterintuitive and need further explanation. Contrary to [6], [7], the term immaterial is used instead of institutional/ personal. Both describe an immaterial regulation framework and the capabilities of a population, respectively. However, this classification is incomplete and imprecise from an engineering science viewpoint, because it neglects technical norms and standards. Thus, the term immaterial is employed. Further, an infrastructure is network-based, if its elements form a network which enables the system's functionality. Such networks are characterized by the presence of knots being interconnected via links. The links usually transport data, energy, or physical goods from one knot to another. Finally, secondary infrastructure requires subordinated infrastructure; primary infrastructure does not. System elements located in layer 0+1 are primary infrastructure, while higher layer system elements are secondary infrastructure.

C. Configuration

In general, configuration means the arrangement or combination of prime objects, which are used together in one context for a specific purpose [8]. A configuration is a result of such an arrangement, i.e. objects or system elements are combined to a higher order structure. The type of possible configurations depends on the logical design and on the characteristics of the objects used. For example, a molecule structure describes the spatial alignment of atom groups. A software configuration determines the type of present software elements and how they behave in the system or how the system itself behaves.

A basic configuration is a recurring or frequent arrangement of objects. It is used as a starting point for further modifications in order to ensure inclusion of all necessary or desired objects [9]. Basic configurations are an important method to reduce the efforts on configuring systems. Applied reference models are an example of basic configurations. Additionally, configurations can be used in order to classify and standardize possible and useful arrangements of objects.

D. Autonomous Control in Logistics

Autonomous control is seen as one option to handle the increasing complexity and dynamics of logistic systems. Hülsmann and Windt have adopted its principles and define autonomous control as "processes of decentralized decision-making in heterarchical structures. It presumes interacting elements in non-deterministic systems, which possess the capability and possibility to render decisions independently. The objective of Autonomous Control is the achievement of increased robustness and positive emergence of the total system due to distributed and flexible coping with dynamics and complexity." [1]. In addition, the Collaborative Research Centre 637 has introduced the term intelligent logistic object for elements of the logistic system which are characterized "by the ability … to process information, to render and to execute decisions on their own." [1]. Hence, presence of decision alternatives is the most important precondition in order to allow local decision making by logistic objects themselves [10]. Further, intelligent logistic objects require decision competence in form of knowledge about methods and algorithms, as well as about environment and object specific data. Thus, either system designers implement this knowledge normative or logistic objects have to explore it with self learning strategies.

System layer	Criteria	Properities			
Decision system	Time behaviour of objective system	static	mostly static	mostly dynamic	dynamic
	Location of objective system	global	mostly global	mostly local	local
	Organisational structure	hierarchical	mostly hierarchical	mostly heterarchical	heterarchical
	Quantity of alternative decisions	none	some	many	infinite
	Type of decision making	static	rule-based		learning
	Location of decision making	system layer	subsystem layer		system-elements layer
	System behaviour	elements and system deterministic	elements non-/ system deterministic	system non-/ elements deterministic	elements and system non-deterministic
Information system	Data storage	central	mostly central	mostly decentral	decentral
	Data processing	central	mostly central	mostly decentral	decentral
	Interaction ability	none	data allocation	communication	coordination
Execution system	Flexibility	inflexible	less flexible	flexible	highly flexible
	Identification ability	no elements identifiable	some elements identifiable	many elements identifiable	all elements identifiable
	Measuring ability	none	others	self	self and others

increasing level of autonomous control →

Fig. 2 Catalogue of Criteria of Autonomous Control [11]

Böse and Windt developed a catalogue of criteria in order to characterize autonomous systems by their level of autonomous control. The catalogue assigns several criteria to the three system layers: decision system, information system, and execution system. Each criterion expresses the single grade of autonomy for this criterion (Fig. 2). The grey shaded properties in Fig. 2 demonstrate one possible system specification. The relative importance of each criterion to each other is weighted by a pair-wise comparison. A discussion of each criterion is given in [11]. The definition of the properties describes the maximum level of autonomous control of a system. However, specific applications may have a lower level [1].

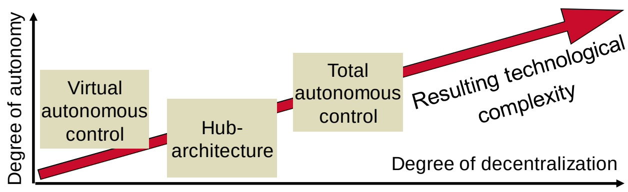

Fig. 3 Architecture types of autonomously controlled systems [12]

In addition, Scholz-Reiter et al. characterize three different architecture types of autonomous controlled systems (Fig. 3) and position them between the axes: degree of autonomy, degree of decentralization, and degree of resulting technologically complexity [12]. In case of total autonomous control architectures, every logistic object (resource, order, or commodity) is an autonomous object and renders and executes decisions of its own. Although the complexity at each logistic object is low, this architecture type leads to a high level of complexity at system level. In virtual autonomous control architectures, the whole logistic system is mapped into a central, real-time operating computer where software agents represent every single physical object. The logistic object's task is reduced to collect and forward information and to execute commands being provided by the virtual autonomous control system. The system's complexity concentrates in a central computer. Contrary, hub-architectures locate this complexity at specific resources or commodity objects which perform given abilities as services for other objects. In this context, resource centric and commodity centric approaches can be distinguished. The abilities are inhomogeneous distributed in hub-architecture.

III. Model of Terms and Drivers

The previous section presented basic terms as a starting point for the discussion of terms and drivers of the autonomous logistic infrastructure. Now, these terms are used in order to clarify the logistic infrastructure in production logistics and to distinguish the infrastructure for enabling autonomous control. The first subsection reflects elements of production logistic systems on the infrastructure of autonomous logistic systems. The second subsection introduces systemic characteristics of autonomous control. The third subsection derives main components of an autonomous control system infrastructure. The last subsection puts all pieces together and presents a qualitative model of relevant terms and drivers for the infrastructure configuration.

A. Production Logistics and Logistic Infrastructure

The previous section introduced logistic systems by their ability to transfer and transform properties of logistic objects, like commodities, in a spatial, temporal, and qualitative way. Indeed, this transfer and transformation approach forms the first layer of a logistic system, followed by a layer for coordination functions and a third layer describing the logistic philosophy. For each purpose, logistic systems require components, called infrastructure, in order to perform tasks, like storage, transportation, and manufacturing, as well as to organize manufacturing processes economically.

Autonomous control serves in the logistic philosophy as a management statement. However, its main purpose is in the coordination function where it shifts control functionality from the coordination layer to the transfer and transformation layer and couples both layers tight. Resources, commodities, and orders perform control tasks in the lowest layer. Hence, the first and the second layer of a manufacturing system are of interest in order to discuss infrastructure components. For this purpose, the logistic system can be investigated with a specific view on the system or with specific elements in mind. This paper assumes the application area of production logistics exemplarily. System elements are resources and transformable objects, which include physical objects and corresponding data objects. Resources include machines, work places, and transport devices, as well as its underlying infrastructure, like routes, power grids etc. Transformable objects are raw materials, half-finished goods, ready-made commodities, and orders. Although orders consist of data, they belong to the group of transformable objects, because their properties (e.g. the degree of completion) change during manufacturing. Contrary, static data objects (e.g. product structure diagrams) are non-transformable objects.

Work systems and transport devices alternately process commodities in a production system until they comply with the demanded specifications. Insofar, production is structured as a network that organizes resources in order to transform and to transfer commodities. The linked-up resources form the physical infrastructure of a production system, which is required for transportation and transformation processes. Physical commodities use this infrastructure to become processed. Rules determine how the commodities use the resources.

Günther and Tempelmeier state logistic infrastructure as an important part of production systems, because it directly influences the system's economic efficiency [13]. For instance, selection and configuration of the infrastructure determine the interdependencies between production, logistic, and auxiliary processes. Two types of infrastructure are distinguished. All physical objects are perceived as hardware, e.g. manufacturing facilities and equipment to store and handle material flows. Contrary, organizational rules are summed up as software, e.g. the type of material flow control and its integration in production planning and control systems. Günther and Tempelmeier comprehend the configuration of infrastructure as spatial alignment of logistic infrastructure elements and their temporal usage. However, both authors neglect transport facilities.

In contrast, infrastructure as proposed by Klaus suits only limited to the subject area of production logistics and autonomous control. It leaves out the specifics of the infrastructure of production and control systems and omits a classification of infrastructure elements [6]. Nevertheless, his classification approach can be employed to outline its basic characteristics. Thus, infrastructure in production logistics is stated as private (provided by and on purpose for the private sector), network-based (bases on interconnected system elements), and secondary (requires lower layer infrastructure to operate). The infrastructure is productive, because it is used to create value in the future, instead of serving consumptive demands now.

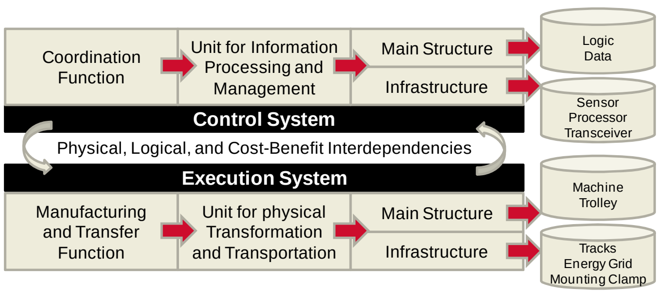

Fig. 4 Infrastructure in Manufacturing Systems

Figure 4 presents a basic model of the first two levels of a manufacturing system. Functions of the execution system require functional units in order to provide demanded tasks. The functional units decompose into components of the main structure, e.g. machines and trolleys, and of the infrastructure, e.g. tracks, energy grid, and mounting clamps. Accordingly, the control system requires functional units in order to process and manage data for manufacturing control. These contain control algorithms and technical components for information processing and propagation. Thus, the functional units subdivide into main structure, e.g. processing logic and data, and required infrastructure, e.g. sensors, processors, and transceivers. In short, the infrastructure of the production control system comprehends all components, which are necessary to enable coordination functions.

System layer	Criteria	Properties		
Systemic aspects	Control representation	virtual object	mixed	real object
	Extent of ability transfer	none	some	every
	Place of abilities	centralized	mixed	decentralized
		Increasing level of autonomous control →		

Fig. 5 Systemic Characteristics

B. *Systemic Characteristic of Autonomous Control*

While the catalogue of criteria introduced by Böse and Windt shows well defined sets of criteria for the three system layers, it neglects aspects of the system at a glance [11]. Thus, this paper proposes a fourth criteria category to amend the criteria catalogue with systemic aspects, e.g. to reflect the kind of control system architecture. The amount of autonomously controlled system elements is the underlying parameter for all three systemic aspects (Fig. 5). First, the place of the abilities is the most important aspect. The abilities for information processing, decision making, and decision execution can be placed at different locations, either centralized or rather decentralized. There is one special case worth to mention. If there are only a few autonomous logistic objects in a system, the spatial distribution of the abilities is centered at these logistic objects. They can provide their abilities as services to or for other objects. This case is stated as hub-architecture, where the system remains autonomously controlled, but specific system elements are controlled by hub objects [12]. Second, the extent of the ability transfer might apply to none, some, or every ability. This means that some abilities do not have to be transferred at all. In case of a centralized control approach, no ability is transferred from the central control system to its elements. Contrary, more abilities need to be transferred to the system elements if the degree of autonomous control increases. Third, the control methods are implemented either by virtual objects, such as a computer representation of the real system, or rather by the real objects themselves. In between, both concepts might be used in a mixed mode as well. Contrary to [12], there is no statement given about which objects manage the control method. These can be either native system elements or, additional system elements are required to take care of a multi-agent system. The amendments of the catalogue of criteria are important to characterize different control system architectures, the logistic objects, and their infrastructure components.

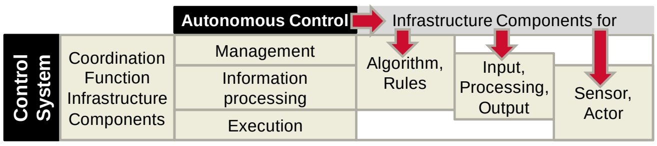

Fig. 6 Infrastructure in Manufacturing Systems

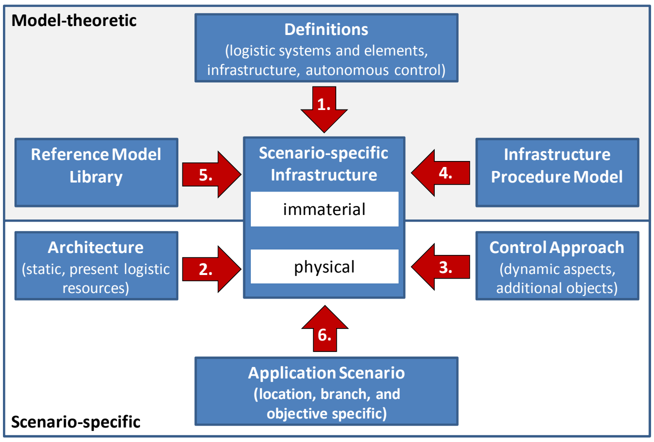

Fig. 7 Terms and Drivers of Infrastructure Configuration

C. *Infrastructure for Autonomous Control Systems*

Section II A introduced a model that helps to identify infrastructure components in manufacturing systems. However, as these components miss integration into the system layers of autonomous control, it is difficult to position them in an autonomously controlled system and even more to do so in the corresponding autonomous control system.

Hence, Fig. 6 presents a model showing the layers of autonomous control systems and their corresponding infrastructure components. The required infrastructure components are derived from the coordination function of the control system and are arranged to one of the three system layers of autonomous control. This classification of the infrastructure components reduces the complexity for the discussion of specific infrastructure components. Each system layer implies specific coordination functions and thus requires a different set of infrastructure components. The components address primary one system layer, however they also loom into neighbor layers.

Algorithms and rules belong to the management layer. The specific infrastructure components selected here affect the information-processing layer as well. The infrastructure components of the information-processing layer focus on components to gather, process, and distribute information that is required for local decision-making and execution. This layer's components affect both surrounding layers. Especially, the execution layer is directly affected by decisions made in the middle layer. Furthermore, components, like sensors and actors, are infrastructure components in the execution layer. They enable logistic objects to interact with their environment. Although they operate primary in the execution layer, they take effect in the information-processing layer as well.

D. Terms and Drivers of Control Systems Infrastructure

Several scenario-specific and model-theoretic terms and drivers influence the configuration of a control system's infrastructure. Figure 7 summarizes the elements of both groups and shows them in single block diagram model. The numbers on the arrows indicate the order of each object's investigation. Although, this research paper focuses on the first component by introducing a system-theoretic understanding of the term infrastructure in the subject area of production logistics, the other elements will be described in short as follows.

The term's definitions constitute one of three components of the model-theoretic terms and drivers, which influence the infrastructure of a logistic control system.

The understanding of the basic terms is crucial in order to determine the relevant elements of autonomous logistic control systems. As the term infrastructure is very important here, most effort has been spent in order to define this term and to derive a generic infrastructure layer model. Thus, we recapitulate that *"Infrastructure includes all system elements which are placed artificially into a given system, called native system. These system elements must be essential to enable specific higher order services within the system by use of capabilities supplied by native system elements and by artificially inserted system elements."*

Besides the definitions, a method is required to ensure that all important infrastructure design aspects are considered during the development process of autonomous logistic systems. A procedure model for the configuration of the control system's infrastructure is able to fulfill this purpose. Further, reference models may limit the applicability of infrastructure components by proposing obligatory elements in specific situations. For instance, selection of a control method may decrease the number of adequate infrastructure components.

Scenario-specifics, like an applied system architecture type or an adequate control system, determine the infrastructure as well. The selection of a system architecture type directly influences obligatory infrastructure components, e.g. for purpose of communication and energy supply. Moreover, the architecture type determines the locations where functional infrastructure components have to be present and affects the required interfaces between autonomous logistic objects, too.

In contrast, the decision for a specific control approach dimensions the capabilities of compatible infrastructure components. Hence, the behavior of a system under dynamic influences will be determined. Moreover, the selection of a control approach allows the identification of control-method specific infrastructure components.

IV. Conclusion and Future Work

In this paper, we investigated the basic terms, which have to be understood in order to configure the infrastructure of logistic control systems. We discussed the term infrastructure in detail and defined it in a system-theoretic way. Furthermore, we introduced a generic infrastructure layer model being able to characterize any infrastructure component of a technical system. In addition, we applied the terms investigated earlier in this paper in production logistics and derived generic components of the infrastructure of a manufacturing system's execution and control system. The research results are a precondition for our future work on the configuration of a control system's infrastructure.

The authors plan future research in order to determine and classify the infrastructure of autonomous control systems in more detail. This research will include an identification of basic characteristics of infrastructure components, which are important for the selection and configuration of specific infrastructural elements in a given logistic scenario. Further, the authors aim to develop a procedure model for the configuration of the infrastructure of autonomous logistic control systems. Furthermore, we plan to analysis the influence of specific control strategies on the required infrastructure.

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