Drivers for the Configuration of Autonomous Logistic Control Systems' Infrastructure

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***Abstract*—**Autonomous control is a suitable concept in order to increase the flexibility and the robustness of logistic processes by enabling decentralized decision making and execution at the elements of the logistic system . Thereto, the system's elements require additional components that provide the necessary functionality to them. Orders, resources, and commodities are the relevant system elements to be enhanced. They are denoted as logistic objects. The new components are embedded into the logistic objects. They form the necessary infrastructure of an autonomous logistic control system. This paper introduces a qualitative model of drivers being relevant in order to configure the infrastructure of autonomous logistic control systems in a specific scenario. It presents and discusses the basic terms: logistic system, infrastructure, configuration, and autonomous control in the context of control systems for production logistics. Further, the paper presents an ontology of an assortment of infrastructure components in functional, object-oriented, and technological manner.

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

I. Introduction

INDUSTRIAL production employs several logistic processes in order to produce goods for customers. Each process determines the efficiency of the value added. Thus, companies manage the achievement of their logistic objectives, e.g. lead time, produced amount, and capacity utilization, by use of powerful planning and control systems. Although centralized control approaches are used widely today, they lack flexibility and robustness in order to reach 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. The application of this concept shall increase the flexibility and robustness by the 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 for the configuration of the infrastructure of autonomous control systems and cost-benefit-models are required as well.

This research article aims to present a qualitative model of drivers which influence the configuration of a control system's infrastructure in autonomously controlled logistic systems. The basic drivers are defined in detail in order to provide a base for future research. Furthermore, all remaining drivers are presented briefly in order to introduce the complete model of drivers.

B. Outline

The first section introduces problems in existing production planning and control approaches and presents the research question. The remainder of the paper is structured as follows. 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 drivers influencing the configuration of the infrastructure of autonomous logistic systems. Hereby, infrastructure components are derived and classified as well as assigned to specific layers of autonomous control systems. Further, the components of the model are introduced briefly. 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-

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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 overall system 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. However, 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 constitutes 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.

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.

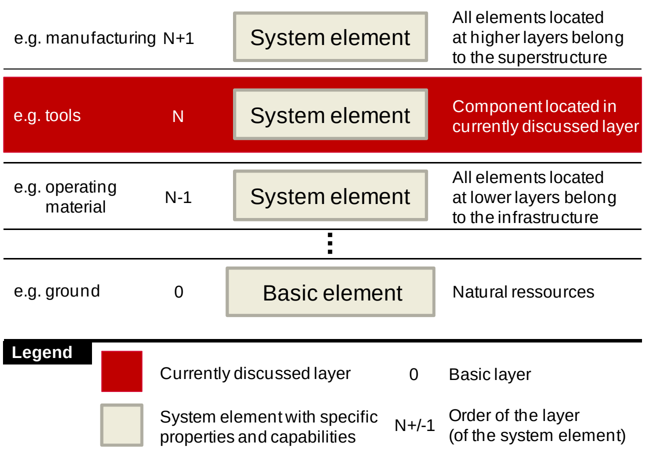

Fig. 1 Infrastructure Layer Model [7]

The main characteristics of infrastructure remain and are its base-character, artificially integrated elements, indispens-ability 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].

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

Several authors classify infrastructure with a background of deregulation politics [6], [8]. 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], [8], 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 nodes being interconnected via links. The links usually transport data, energy, or physical goods from one node 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 [9]. 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 [10]. 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 define autonomous control as "pro-cesses of decentralized decision-making in heterarchical struc-tures. 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 [11]. 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.

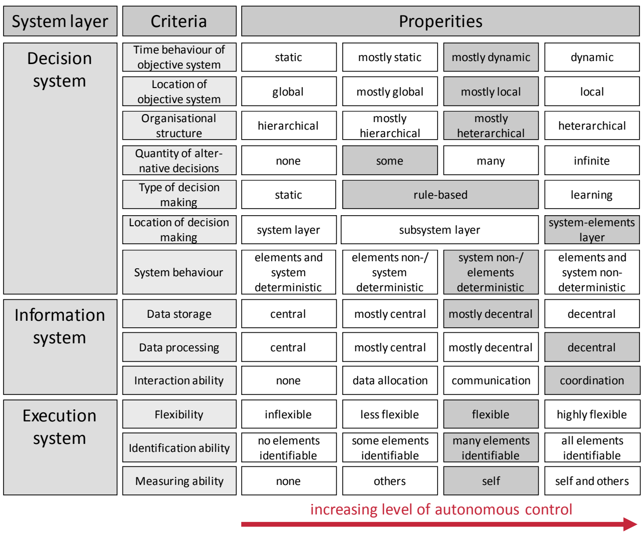

Fig. 2 Catalogue of Criteria of Autonomous Control [12]

Böse and Windt developed a catalogue of criteria in order to characterize autonomous systems by their level of auto-nomous control [12]. 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. The definition of the properties describes the maximum level of autonomous control of a system. However, specific applications may have a lower level [1].

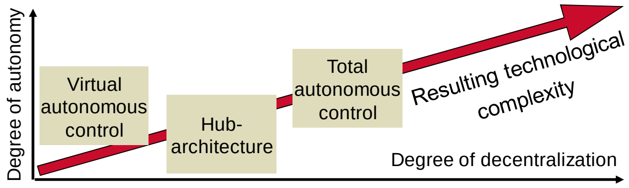

Fig. 3 Architecture types of autonomously controlled systems [13]

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 [13]. 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.

In order to enable modeling of autonomous logistic business processes, the Autonomous Logistics Engineering Methodology (ALEM) is developed by the Collaborative Research Centre (CRC) 637 [14], [3]. ALEM includes a notation, a structuring view concept, and a procedure model. Its design process bases on decisions about a system's architecture and on selection of infrastructure components being specific for a control system of autonomously controlled logistic processes. ALEM combines all methods into a software tool (ALEM-T) guiding logistic process experts through the process of model creation, simulation, and evaluation. Further, ALEM-T is able to transform ALEM-models into executable simulation models [15], [16]. The three step transformation concept employs a model driven approach and creates a multi-agent simulation which corresponds to the scenario modeled. ALEM's notation bases on the Unified Modeling Language (UML) and supplementary diagrams that are specific for the domain of autonomous logistic processes [3], [17]. A view concept is used and reduces the complexity of an overall model [11], [18], [19]. Five primary views divide models into distinct, semantic aspects, i.e. an ALEM model's structure, knowledge, abilities, processes, and communication. Further, views group model segments in static and dynamic aspects as well as in micro and macro aspects. Kolditz proposes the procedure model ALEM-P (procedure) in order to guide logistic process experts through the modeling process of autonomous logistic business processes [3]. ALEM-P consists of eight steps, each dealing with one specific aspect of autonomous logistic business processes. Although the procedure model's steps form a straight sequence, reordering of the steps is allowed and depends on whether a top-down approach or a bottom-up approach is used for modeling. Further, ALEM-P accepts feedback loops within the modeling process in order to include new aspects of a system when they appear while modeling. However, ALEM-P lacks to describe an exact procedure for the configuration of the infrastructure of autonomous logistic processes.

III. Model of Drivers

The previous section presented basic terms as a starting point for the discussion of 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's infrastructure and presents them in an object-, function-, and technology-centered manner. The last subsection puts all pieces together and presents a qualitative model of relevant 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 [20]. 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 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.

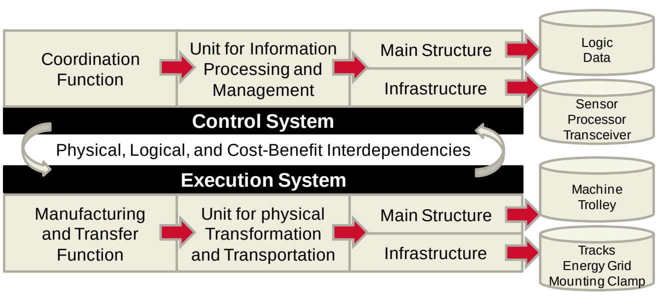

Fig. 4 Infrastructure in Manufacturing Systems [7]

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 [7]

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 overall system [12]. 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 [13]. 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 [13], 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.

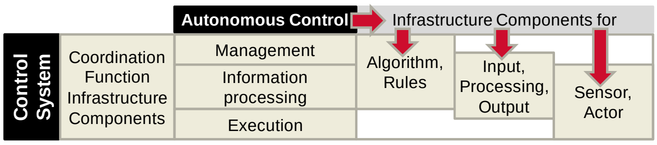

Fig. 6 Infrastructure in Manufacturing Control Systems [7]

C. *Infrastructure for Autonomous Control Systems*

Section II A introduced a basic understanding of logistic systems and their elements. It supports the identification of infrastructure components for control tasks 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 as well as in the corresponding autonomous control system.

For this reason, 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 infrastructure components reduces the complexity for the succeeding discussion of assorted 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.

The management layer includes algorithms and rules which are immaterial components indeed. Decision protocols and strategies belong to this layer. Infrastructure components selected here affect the information-processing layer as well, because they define how information has to be processed in the second layer.

The infrastructure components of the information-processing layer focus on devices for gathering, processing, and distribution of data and information that is required for local decision-making and execution. This layer's components loom into both surrounding layers. Especially, the middle layer's decision making directly affects the execution layer.

At last, sensors and actors are infrastructure components in the execution layer. They enable logistic objects to interact with their environment in terms of sensing environment data and initiate activities of environmental objects. Although they operate in the execution layer, they determine the information that is processed in the second layer as well.

The infrastructure components enhance usual logistic objects with appropriate hardware and software components which enable data gathering, processing, and distribution as well as higher order decision making and decision execution by logistic objects themselves. On a closer look, the additional components form small computer systems that are embedded into a logistic object. Indeed, they are embedded into the overall logistic system, too. For this reason, autonomous logistic control systems are one type of embedded systems [21]. As embedded systems, they are "computer systems that are parts of larger systems and realize dedicated functions." and "comprise sensing, actuating, computing and wireless communication capabilities" in order to exchange information with other system elements [22]. Further, they are context-

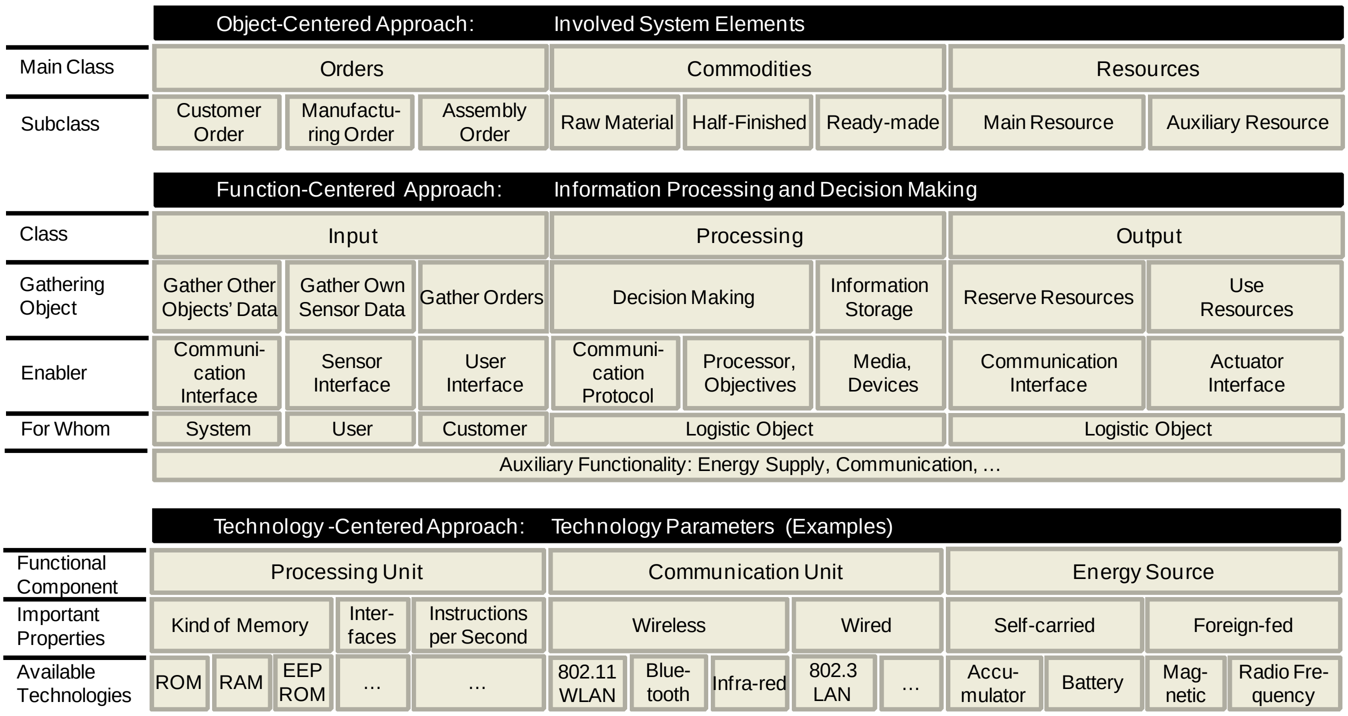

Fig. 7 Ontology for Infrastructure Components (Examples)

aware and contain all capabilities being required in order to work autonomously.

Determination of a control systems infrastructure in the domain of autonomous control requires consideration of three dimensions: object, function, and technology. Each of them is displayed in form of an ontology (Fig. 7) which provides examples of important issues but is not fully complete in all details. First, the object-centered ontology located on top of Fig. 7 outlines three main classes and subclasses of relevant elements of logistic systems which have to be enhanced with new capabilities. The main classes are orders, commodities, and resources. Second, the function-centered ontology assigns main enablers for each gathering object of a functional class. For instance, a sensor and its corresponding interface provide own sensor data as input for the succeeding information processing step. In addition, auxiliary functions support the autonomous logistic objects with general services, for instance energy supply and communication capability. Third, the technology-centered approach links functional units and their instances' parameters to specific technologies. All three dimensions have to be connected with each other in a kind that the technologies are able to fulfill the parameterized functions of specific logistic objects.

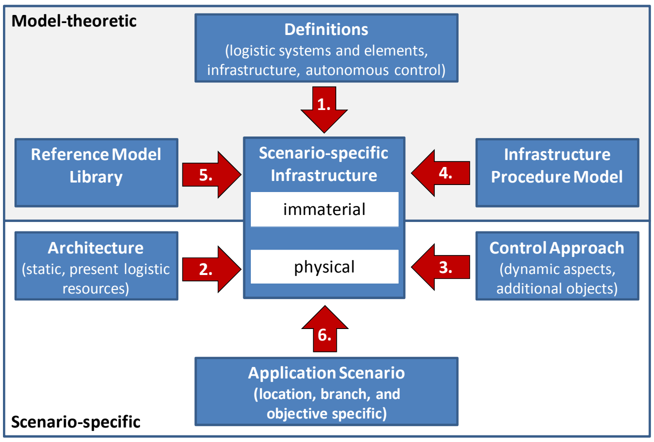

Fig. 8 Drivers of Infrastructure Configuration [7]

D. *Drivers of Control Systems Infrastructure*

Several scenario-specific and model-theoretic drivers influence the configuration of a control system's infrastructure. Figure 8 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 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 infra-structure layer model: "*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.*"

Hence, a configuration of infrastructure components is an arrangement of hardware and software objects that are inserted artificially into a logistic system in order to use them for a specific higher order purpose. The type of a possible configuration depends on a systems' elements logical design and characteristics. A basic configuration is a recurring or frequent arrangement of objects. Predefined basic configurations reduce the efforts on configuring a system. They are a starting point for further infrastructure modifications and ensure inclusion of all necessary objects. Reference models are examples of basic configurations. This understanding leads to two different types of configurations. On the one hand, an investigated scenario requires specific additional components which enable autonomous control. The scenario-specific infrastructure components are unique and have to be designed and customized for each scenario. On the other hand, basic predefined infrastructure configurations can be designed in advance and stored in libraries for later use. These are for instance basic configuration patterns for control approaches, production types, e.g. resource parallel job shop scenario patterns, as well as technologies that are described by their parameters.

Furthermore, the definition of autonomous control specifies additionally required functionalities and locates them in different functional classes, i.e. information input, processing, and output. The combination of components of these classes into one infrastructure composite creates a computation subsystem that is located at every logistic object. In result, autonomous control is an embedded, decentralized, and autonomously working control system.

Besides the definitions, a method is required in order 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. Such a model has to ensure that all relevant aspects are designed correctly and in accordance to the requirements derived from the underlying logistic scenario.

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. There are three important reference models: for predefined control approaches, logistic scenarios, as well as for registered infrastructure components and composites. For example, a database can be used to register all relevant infrastructure components and composites for a specific functional class by their technology name and its properties.

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 drivers, 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.

References

[1] M. Hülsmann and K. Windt, Eds., *Understanding of Autonomous Cooperation and Control in Logistics – The Impact of Autonomy on Management, Information, Communication and Material Flow*. Berlin: Springer Verlag, 2007.

[2] B. Scholz-Reiter and H. Höhns, "Selbststeuerung logistischer Prozesse mit Agentensystemen," in *Produktionsplanung und -steuerung: Grundlagen, Gestaltung, Konzepte*, G. Schuh, Ed. Berlin: Springer, 2006, pp. 745–780.

[3] J. Kolditz, "Fachkonzeption für selbststeuernde logistische Prozesse," Ph.D. dissertation, Universität Bremen, Berlin, 2009.

[4] B. Mikus, "Strategisches Logistikmanagement: ein markt-, prozess- und ressourcenorientiertes Konzept," Ph.D. dissertation, Wiesbaden, 2003.

[5] W. Delfmann, „Kernelemente der Logistik-Konzeption," in *Logistikforschung: Entwicklungsgrundzüge und Gestaltungsansätze*, ser. Unternehmensführung und Logistik, Berlin: Schmidt, E., 1999.

[6] S. Klaus, "Deregulierung der netzbasierten Infrastruktur," Ph.D. dissertation, Universität Zürich, 2009.

[7] B. Scholz-Reiter, St. Sowade, and D. Rippel, "Modeling the infrastructure of autonomous logistic control systems," in *Advances in Communications, Computers, Systems, Circuits and Devices. European Conference of Systems (ECS'10)*, V. Mladenov, K. Psarris, N. Matorakis, A. Caballero, and G. Vachtsevanos, Eds. Tenerife: WSEAS Press, 2010, pp. 295–300.

[8] R. Jochimsen, *Theorie der Infrastruktur : Grundlagen der marktwirtschaftlichen Entwicklung*. Tübingen: Mohr, 1966.

[9] P. Prechtl and F.-P. Burkard, *Metzler Lexikon Philosophie: Begriffe und Definitionen*, 3rd ed. Stuttgart: Metzler, 2008.

[10] R. Zarnekow, W. Brenner, and A. Hochstein, *Serviceorientiertes IT-Management: ITIL-Best-Practices und -Fallstudien*, ser. Business Engineering. Berlin, Heidelberg: Springer, 2005.

[11] B. Scholz-Reiter, H. Höhns, J. Kolditz, and T. Hildebrandt, "Autonomous Supply Net Coordination," in *Proceedings of 38th CIRP Manufacturing Systems Seminar*, Florianopolis, Brazil, 2005.

[12] F. Böse and K. Windt, "Catalogue of Criteria for Autonomous Control," in *Understanding Autonomous Cooperation and Control in Logistics – The Impact of Autonomy on Management, Information and Communication and Material Flow*, M. Hülsmann and K. Windt, Eds. Berlin: Springer, 2007, pp. 57–72.

[13] B. Scholz-Reiter, St. Sowade, D. Rippel, M. Teucke, M. Özsahin, and T. Hildebrandt, "A Contribution to the Application of Autonomous Control in Manufacturing," *NAUN International Journal of Computers*, vol. 3, no. 3, 2009, pp. 279–291.

[14] B. Scholz-Reiter, J. Kolditz, and T. Hildebrandt, "Engineering autonomously controlled logistic systems," *International Journal of Production Research*, vol. 47, no. 6, 2009, pp. 1449–1468.

[15] B. Scholz-Reiter, D. Rippel, and St. Sowade, "Modeling and simulation of autonomous logistic processes," in *Advances in Communications, Computers, Systems, Circuits and Devices. NAUN European Conference of Control (ECC'10)*, V. Mladenov, K. Psarris, N. Matorakis, A. Caballero, and G. Vachtsevanos, Eds. Tenerife: WSEAS Press, 2010, pp. 148–153.

[16] I. Dumitrache, "From model-based strategies to intelligent control systems," *WSEAS Transactions on Systems and Control*, vol. 3, no. 6, 2008, pp. 569-575.

[17] B. Scholz-Reiter, J. Kolditz, and T. Hildebrandt, "UML as a Basis to Model Autonomous Production Systems," in *Digital Enterprise Technology: Perspectives and Future Challenges*, P. F. Cunha and P. Maropoulos, Eds. Berlin: Springer, 2007, pp. 553–560.

[18] A.-W. Scheer, *Business Process Engineering - Reference Models for Industrial Enterprises*. Telos: Springer, 1994.

[19] A.-W. Scheer, *ARIS - Modellierungsmethoden, Metamodelle, Anwendungen*, 4th. Ed. Berlin: Springer, 2001.

[20] H.-O. Guenther and H. Tempelmeier, *Produktion und Logistik*, 8th ed. Berlin: Springer, 2009.

[21] D. Hristu Varsakelis and W. S. Levine, *Handbook of Networked and Embedded Control Systems*, 1st ed. Boston: Birkhäuser, 2005.

[22] C. Holzmann, *Spatial Awareness of Autonomous Embedded Systems*. Wiesbaden: Vieweg+Teubner / GWV, Wiesbaden, 2009.

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