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Autonomous control in closed dynamic logistic systems

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Abstract

The material flow in dynamically changing logistic systems underlies specific conditions, as destinations and stop-overs only exist temporarily. The order-dependent circulation of rental articles constitutes such a case, where the articles are on the move between the lender and one or more customers. The related planning and control processes are highly complex and challenging as they comprise the scheduling of orders, the compilation of transports and the determination of suitable routes. This paper introduces an autonomously controlled approach for the distribution of rental articles, including the autonomous decision-making and the representation of the involved objects as autonomous entities. A use case from the field of event logistics illustrates the proceeding for the integration of the approach in real world processes.

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Keywords: Autonomous control, dynamic logistic systems, event logistics, cyber-physical systems

1. Introduction

The business field of event logistics constitutes a dynamic and complex environment regarding the logistic planning and the corresponding control processes [1, 2]. Generally, event-related rental articles circulate between the lender and one or more customers, using a steadily changing logistic network [3]. At this, the different venues

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only exist temporarily and can change due to varying orders. Further, occurrences such as damages or thefts of articles and/or transport devices as well as versatile traffic conditions complicate the logistic planning. The result is a frequent replanning of transports and routes that often also affects the general scheduling of orders and the related personnel planning [4, 5].

From a scientific point of view, the order-related distribution of rental articles in closed dynamic systems touches three well-known problems; order-dependent resource allocation (resource distribution/scheduling), transport planning and route planning [6]. Therefore, a manual and centralized accomplishment of the logistic planning is time-consuming and often leads to inefficient and costly processes [1]. Besides the further optimization of established centralised control approaches, the application of alternative approaches, such as the paradigm of autonomous control, seems to be promising in order to deal with the above mentioned challenges.

The Colloborative Research Center 637 "Autonomous Cooperating Logistic Processes – A Paradigm Shift and its Limitations" focused on the development, implementation and evaluation of autonomous control methods in production and logistic networks [7]. This paper introduces a concept that combines methods from the CRC 637 and transfers them into practical application. At this, it deals with a distribution system for the resource allocation in event logistics that includes the compilation of transports and the determination of the best routes within the logistic network. The system applies three methods from the field of autonomous control, namely the Autonomous Logistics Engineering Methodology (ALEM), the Platform for Simulation with Multiple Agents (PlaSMA) and the Distributed Logistics Routing Protocol (DLRP), to compute all required planning decisions within scenario-based simulations of a Multi-Agent System (MAS) [8, 9, 10, 11, 12, 13, 3]. Altogether, the combined application of the three methods can be seen as a Cyber-Physical System (CPS), as the representation of the logistic objects and the transport network forms a digital image of the real world that comes into operation to make decisions that are viable for the physical objects [14].

An example company acts as a use case to demonstrate the specific conditions related to event logistics and to illustrate the starting points of the autonomously controlled distribution system. At this, the structure of the paper will be as follows: directly after the introduction in section 1, the following section 2 introduces the use case and the field of event logistics in general. The third section deals with the autonomous control approach, the implementation and an integration concept regarding the use case, followed by section 4 with first experimental results. Finally, section 5 summarizes the paper and gives a short outlook on future work.

2. Use Case

The example company is a full-service agency from the field of event management [1]. With its 60 employees, spread over the company headquarters and several branches for marketing and customer services as well as an annual turnover of 7 million euros, the company constitutes a small or medium enterprise (SME) [1] At this, the company offers all services related to the execution of public and private events, such as weddings, company anniversaries, product presentations, exhibitions and so on [2]. The service package includes the artistic programme planning, the letting of event-equipment, ranging from chairs and tables over catering devices up to complex stagecraft as well as the related logistics. Further, the company takes over the construction and dismantling of the event equipment at the venues [2].

The logistics operates from the central storage directly at the company headquarters and comprises an internal car pool of three vans (3.5tons), two medium trucks of 7.5 tons and a lorry with 40 tons. Additionally, four cars are available for the transport of small devices and/or personnel [3]. The logistic planning processes of an event take place within the five staged general planning that starts with the order receipt (stage 1) [1]. In the following, a rough planning (stage 2) determines the artistic requirements in cooperation with the customer and derives the preliminary demand of event equipment. The detailed planning in stage three specifies the latter, before the realization begins in stage 4. The event accomplishment follows in stage five and comprises the transport and setup of the event equipment. An event ends with the dismantling and backhaul to the central storage or to a subsequent event. Formally, an event ends with the post-processing and billing [1]. Table 1 enumerates the single phases and the related activities, as they take place within the example company.

Table 1. Phases of the event execution.

Phase of Event Execution	Activities
Phase 1: Acquisition/Idea generation	Customer Query/Local inspection/First conversations
Phase 2: Ascertainment	Concept generation/Rough planning
Phase 3: Detailed Planning	Milestone definition/Resource planning/Bookings/ Detailed calculation
Phase 4: Realisation	Execution/Additional purchases/Personnel planning/internal orders
Phase 5: Event execution	5.1 Warehouse: Picking/Loading 5.2 Venue: unloading/Setup/Event/Dismantling/ Possibly picking for subsequent events/Loading 5.3 Warehouse: Unloading/stocking
Phase 6: Postprocessing	Billing/Feedback

Generally, in event logistics as well as in the example company, dynamic occurrences complicate the logistic planning [2]. At this, new and changing orders require a frequent replanning of transports and routes. In addition, the changing availability of resources due to damages and thefts often influences the event planning and execution. This results in inefficient transports, insufficient capacity and resource utilization as well as a large planning and control effort [4].

In the use case, all planning activities apply to a so called project manager. This person is responsible for the complete event execution, including both the resource allocation and the customer contact [5]. The project manager performs all planning tasks manually, without the support of corresponding software. The only access to the relevant data takes place in form of availability charts within the enterprise resource planning program (ERP). These overviews resemble Gant charts and mostly rely on the inventory data of the storage [6]. Unfortunately, the automated material flow documentation only covers the ingoing and outgoing event equipment at the warehouse entrance. Therefore, the material flows at and between different venues mostly stays unrecorded. As a result, the project manager can only fall back to event equipment currently located at the storage [6]. This often leads to the case that the example company needs to rent additional equipment or transport devices, although the spatial and temporal distance between already planned and new events would allow the utilization of resources at the venues for subsequent orders [6]. This lack of information transparency leads to additional costs and effort regarding the handling of foreign equipment.

Summarised, the example company faces a frequent replanning due to dynamic and unexpected occurrences. This replanning takes place manually and is correspondingly time-consuming and incident to a high effort. Additionally, the insufficient material flow documentation at the venues leads to partly unnecessary costs for the renting of foreign event equipment and transport devices for order peaks, rush orders or short-term resource shortages [1, 4, 2]. Fig. 1 illustrates the major process vulnerabilities regarding the planning and execution of events, both use case specific and in general.

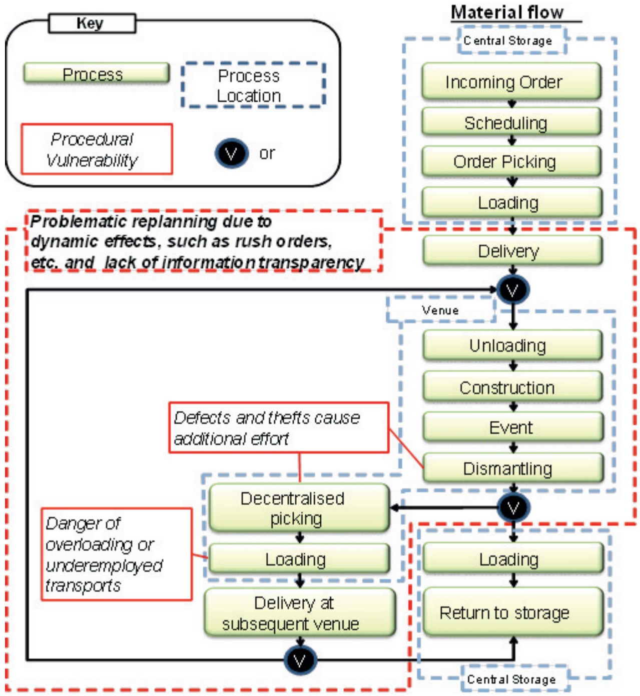

Fig.1. Process vulnerabilities in event logistics, specific for the use case (1) (4).

3. Autonomously controlled distribution

The autonomously controlled distribution aims to efficient and more robust logistic processes. At this, the system assists the project manager through the complete planning process by replacing the manual steps with an automatic calculation of the relevant planning results [1]. This proceeding reduces the complexity, effort and time-consumption related to the frequent replanning that is typical for the field of event logistics. In order to reach these objectives, the distribution approach combines three autonomous control methods.

3.1 Applied Methods and general approach

The first is the Autonomous Logistics Engineering Methodology (ALEM). ALEM constitutes a multipart modeling framework especially designed for the requirements of designing complex autonomous processes in logistics [7]. The framework consists of a notation (ALEM-N = ALEM-Notation) for the representation of all relevant system aspects. ALEM-N defines the required notational elements and a corresponding meaning within the framework. The desing process in ALEM follows a specific guideline for the analysis and specification of the intended logistic system named ALEM-P (ALEM-Procedure) [1]. Finally, the ALEM-Tool (ALEM-T) is a software tool for the modelling process that combines both ALEM-N and ALEM-P as well as adds a reference for a possible reuse of existing models [8]. The result of an ALEM-driven modelling process is a system description consisting of object descriptions in form of classes. These classes define the autonomous logistic objects with their features, abilities and knowledge.

The second autonomous control method within the proposed system is the Platform for Simulations with Multiple Agents (PlaSMA) [9]. PlaSMA is a Multi-agent Simulation (MAS) with special adaptions for the simulation of autonomously controlled production and logistic systems. Originally, PlaSMA comes into operation to evaluate and compare the performance of different autonomous control methods and algorithms. The introduced distribution system adapts PlaSMA in order to compute planning results that are directly applicable in the daily business of the example company [1, 4] This means, the order situation as well as the available resources find entrance to simulation scenarios in PlaSMA. The results of the simulations form the basis for the general allocation of resources to orders. Further, the PlaSMA-simulations compute all relevant operation instructions, such as pick- and cargo lists, routes and the personnel plan of action, similar to the former activities of the project manager [2]. The latter is still responsible for the planning tasks, as the approval of the results still applies to him. This is especially the case, when the internal resources are insufficient to execute all open orders. Then, the project manager can manually approve the letting of additional transport devices and/or event equipment [5].

The route finding process within the PlaSMA-simulations bases on the third autonomous control method, the Distributed Logistics Routing Protocol (DLRP) [10]. This protocol follows the proceeding of route finding in information networks, basing on the similarities between both network types. In information networks, such as the internet, data packages search for the shortest path between two servers. As commodities in logistic networks have comparable objectives, namely to determine the shortest path between their origin and their destination, the underlying strategies are generally transferable [11].

The autonomously controlled distribution system implements an adaption of the DLRP as a behavior of agents representing transport devices. At this, those agents negotiate with each other in order to find the optimal routes between the central storage and the venues. Simultaneously, the transport compilation aims to an efficient utilisation of both the transport devices and the event equipment, while the distance travelled is reduced [11].

Summarised, the general process flow regarding the logistic planning is as follows. The autonomously controlled distribution system takes over the results of the rough planning, consisting of the order-related data and a first deployment of the required event articles. The order-related data comprises the place, begin and end of the event, while the corresponding preliminary deployment of event articles constitutes a list of article families (e.g. one microphone, one complete stage, 50 chairs and so on). Basing on these preliminary planning, the autonomous distribution determines the specific event equipment (microphone nr.1, brand x, stage type 6, chair type 2, etc.), compiles the transports, determines the routes for the transport devices and assigns the personnel for driving as well as for the setup and removal of the equipment at the venue [1].

3.2 Implementation and technical details

Due to its implementation and operation principle, the autonomously controlled distribution system can be seen as a cyber-physical system. As such, the system creates a virtual representation of the complete logistic system, including the event equipment, personnel, transport devices, orders, venues and the transport network [4]. During the planning process, this representation serves as the basis for the allocation of the real-world resources to orders. Further, the system combines available inventory data from the Enterprise Resource Planning (ERP) of the use case with material flow information that is acquired directly at the venues [2, 11]. The resulting information transparency enables a frequent adaption of the digital representation to the physical conditions and possible dynamic occurrences in the real-world.

The representation of the relevant objects and/or resources within the logistic system as a digital scenario takes place mostly in ALEM and works as follows [4]. The object representation bases on a detailed modelling of every logistic object using the complete ALEM view-concept. Starting point is the definition of every object as an autonomous entity with specific properties, abilities, objectives and a corresponding knowledge. From a methodical point of view, every single aspect is covered by a diagram type that is suitable for the respective modelling step. For example, the general definition of object types takes places in class diagrams basing on the Unified Modelling Language (UML) [12].

The results of the modelling process in ALEM are mostly comparable or compatible, respectively, to the underlying ontologies in PlaSMA simulation scenarios. These ontologies provide all basic elements for the simulation of logistic systems in PlaSMA, such as commodities, transport devices as well as parts of the traffic infrastructure [9]. As the different ALEM-views on modelling aspects and the object definitions in PlaSMA-ontologies show a great accordance, it is possible to transfer an ALEM-based system model into a PlaSMA-scenario quite easily. Fig. 2 shows a comparison between the modelling of transport devices in PlaSMA and ALEM as an example.

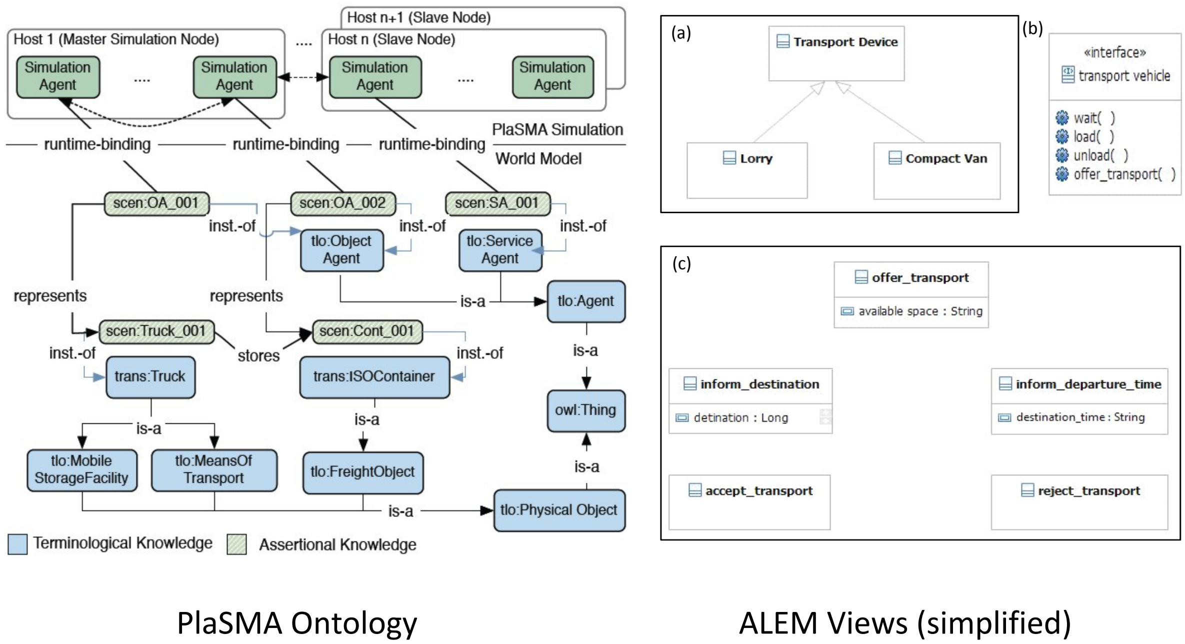

Fig. 2. Comparison between PlaSMA ontology and ALEM views [9] [1].

The left part shows an excerpt from the PlaSMA ontology, where object agents (OA) represent real-world objects within the simulation. The object agent OA_001, for example, represents Truck_001 in the simulation scenario. At this, the agent is an instance of the class "Truck" from the transport ontology in PlaSMA. Regarding its knowledge and abilities, a truck is a mobile storage facility in the means of transport and simultaneously constitutes a physical object that is able to store freight objects, such as a container. The right part of Fig.2 shows a simplified excerpt from the different views in ALEM that also regard the definition of transport devices. Part (a) constitutes the definition of the general class "Transport Device" and the two derived classes "Lorry" and "Compact Van". All three classes have some abilities in common, for example, they can wait for orders, offer transport or can be loaded or unloaded (b). Although the derived classes "Lorry" and "Compact Van" inherit their general abilities from their parent class, they have specific features, for example a different load volume (available space) [1].

The autonomously controlled distribution system uses this accordance between ALEM-model and PlaSMA-scenario for the automatic generation of simulation scenarios. At this, all relevant parts of the logistic system find entrance into an ALEM-model. Those parts are, for example, personnel, transport devices, event equipment and the basic elements of the logistic network. Further, the model contains objectives, abilities and the explicit knowledge of every object as well as a definition of the processes they are involved in. In order to obtain a complete PlaSMA-scenario, the distribution system has to add some dynamic aspects and the simulation-specific abilities for every object. These mainly comprise the number, position, state and availability of the resources and the current order situation. Correspondingly, the scenario consists of static object definitions that are derived from the ALEM-model and current situation-dependent information.

The implementation of the autonomously controlled distribution system comprises both soft- and hardware. The software part mainly consists of the adapted PlaSMA version and the related data base containing the stock list of the event equipment, the list of employees, the available car pool and the current orders [3]. At this, the planning data comes from the database of the example company`s ERP system. For cases, where the automatic exchange of planning data is not possible, for example due to proprietary interfaces or by patent law, the autonomously controlled distribution system provides a graphical user interface for the manual input of data and for the output of the planning results [3].

The hardware part consists of a module for the automated documentation of the material flow directly at the venues. As a kind of telematics, the module provides the information and communication technologies (ICT) to determine the actual position of the transport device, to document the material flow movements using motion sensors and Radio Frequency Identification (RFID) and to transmit the collected data to the distribution system via the cell phone network [6]. For a possible use with foreign rental vehicles, the module can be mounted and removed easily. Fig. 3 shows the overall system architecture for both the software and the hardware part.

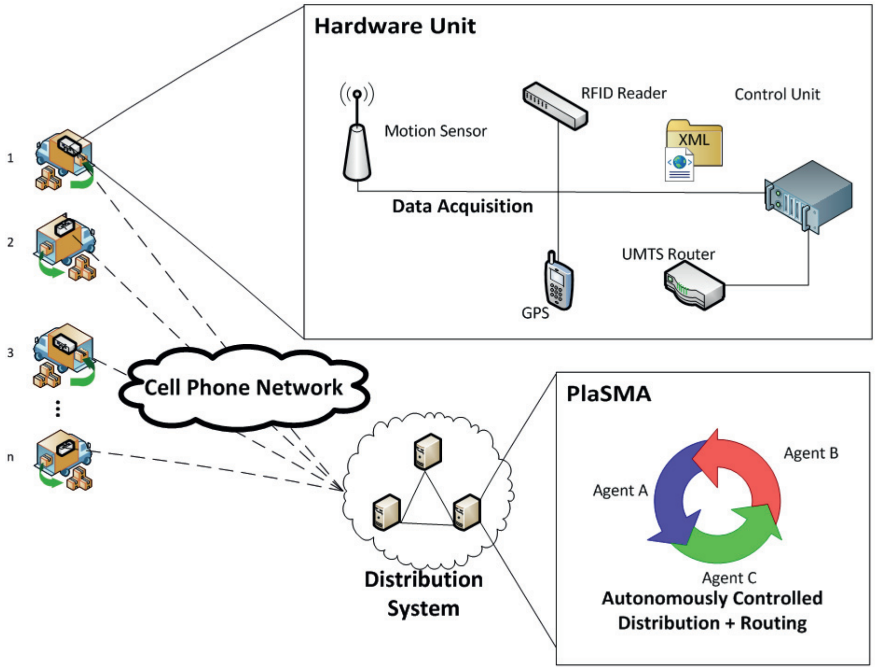

Fig. 3. Overall system architecture (5).

The operation of the distribution system can take place on an own server, in a virtual machine or parallel to the ERP-system. The data transmission from the hardware module uses the File Transfer Protocol (FTP). The file format is XML (Extensible Markup Language), a parser transfers the file content into the data base [3].

3.3 Agent representation and autonomous decision-making

The outlined distribution system computes planning resulting through negotiations between autonomous logistic objects within the PlaSMA multi-agent simulation [1, 4]. As described in the previous sections, the ALEM-model of the logistic system is transferred into a simulation-ready PlaSMA scenario. Within the simulation, all logistic objects have a representing agent with the abilities, knowledge and objectives that are predefined in ALEM. The current situation in form of the number, state, position and availability of resources as well as the order situation originates from the ERP-database, the integration takes place at the begin of the simulation. The decision-making procedure is as follows.

As the distribution system takes over the planning activities after the rough planning, every event (= order) has a representing agent called list manager [4]. This agent has all order-related information regarding the place, start, begin and duration of the corresponding event. Further, every list agent starts with a preliminary list of required articles that reflects the results of the previous planning steps. Through the following negotiations, the list manager is responsible for the allocation of all resources required for his event. This takes place under consideration of all available resources and dependent on all other active events. The initial point is an availability request to all article managers on the list. These article managers are responsible for a number of technically identical event articles, called an article family. This organization results from the internal structure of the article data within the database of the example company`s ERP-system [4]. The article managers forward the request to all article agents belonging to their respective family. If an article is not available through the requested event duration, it immediately sends a rejection to its article manager. In the following, the availability requests take the way top down through the agent hierarchy, until the negotiations reach the vehicle manager. This agent represents the complete car pool and is therefore responsible for the allocation of transport capacity to the potentially available event articles. As the car pool is limited, the transport devices and their capacity denote a kind of bottleneck. Correspondingly, an allocation of an event article to a concrete event can only take place, if the transport can be ensured [2]. At this, the transport devices have the final word in the negotiation process. Their approval of an availability request depends on several criteria, such as the required capacity and the corresponding route finding. The approval can only happen, if the transport device can store the requesting article and the compilation of the cargo leads to an efficient route between the storage and the venue(s) to be supplied. For the latter, the transport device agent considers the distance travelled as well as the time constraints for all stored articles [11].

The negotiations end with a chain of request approvals in a bottom up manner, reaching from the transport agents up to the list agents. The complete simulation comes to an end, if all list agents were able to allocate the required event articles for their individual event. If this is not possible, the simulation stops with a corresponding error request and the project manager can manually allow the application of additional rental articles or transport devices. In this case, the scenario gets a corresponding update and the simulation starts again. In some situations, such as order peaks and/or resource shortages, a sufficient planning of all events may take several iterative simulation runs [1].

4. Experimental results

The following experiments show the overall performance of the autonomous distribution system in comparison with the current manual planning. They comprise six different scenarios with up to 35 events (spread over a period of 10 days), comprising between 95 and 950 articles. Central point, regarding the logistic performance measurement, is the reduction of the distance travelled for the complete car pool, as the overall km directly represent the efficiency of the autonomous transport compilation and corresponding route planning (Fig.4, part a). At this, the autonomous distribution system attains better results for five of the six scenarios. Only for the scenario with 15 events, the established manual approach is able to serve the events with a lower mileage of 168 km. For the remaining scenarios, the manual approach requires between 97 km (20 events) and 2700 km (35 events) more.

The efficient utilisation of the given transport resources also leads to less leasing of transport devices (Fig.4, part b). At this, the rental kilometers denote the distance, rental devices have to travel through the execution of the events within the scenario. The autonomous distribution system is able to solve four of the six scenarios without the usage of additional rental vehicles. The manual distribution in contrast, falls back to rental vehicles in every scenario, except the one with 10 events. Within the scenarios with 15 and 25 events, both approaches work with rental vehicles, but in both cases, the manual approach makes more use of these vehicles.

In general, the efficiency of both approaches depends on the amount of events and articles required. Further, the spatial and temporal distance between the events plays an important role. Especially the spatial distance affects the transport compilation. The more events take place in a spatial proximity, the more it is possible to aggregate transport for one or more events and therefore to serve those events on a coherent route. If a transport aggregation is possible, the autonomous distribution has an advantage, a greater distance between single events is beneficial for the manual approach.

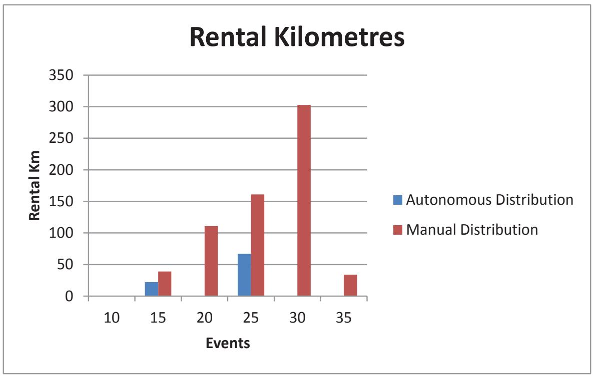

Fig. 4. (a) Distance travelled in comparison.

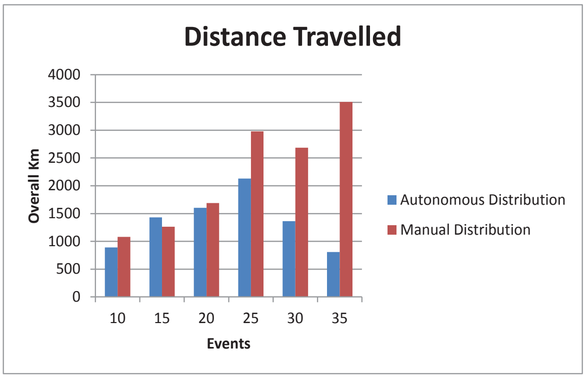

Fig. 4. (b) Rental kilometres in comparison.

Altogether, the constrains resulting from the dependencies between single events, their spatial and temporal proximity influence both the logistic performance of the distribution as well as the computing time of both approaches. Fig. 5 shows the amount of constraints involved with the scenarios (part a) and the resulting runtime of the autonomous control approach (part b). At this, the manual planning is represented by a script that recreates the behaviour of the responsible project planner. The modelling of the script follows a detailed analysis of the expert`s practice and shows a generally very short runtime of not more than 1 second. The multi-agent simulation within PlaSMA requires more time, the difference amounts between 200 and more than 1300 seconds (cpu-time). As the later corresponds to approximately 21 minutes, the autonomous distribution is still much faster than the human expert.

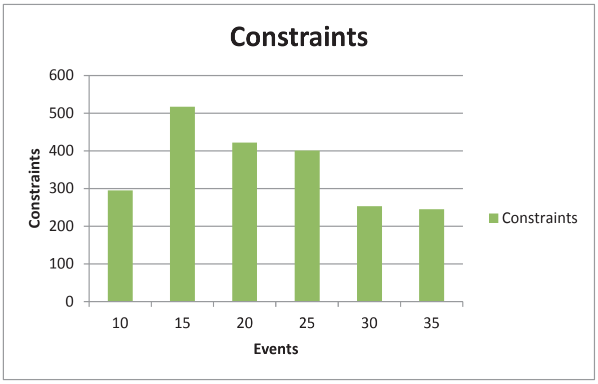

Fig. 5. (a) Amount of constraints for the six scenarios

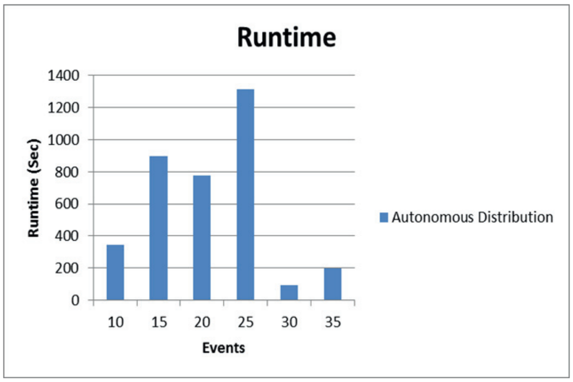

Fig. 5. (b) Runtime of the autonomous control approach.

Finally, the capacity utilisation of the transport vehicles is from interest. At this, the experimental results only show a slight utilisation between four and 23% (regarding the volume) of the available resources for both approaches. Those values result from the wide range of different shapes and weights among the event equipment and are typical for this field of logistics. As both control approaches do not comprise a load planning in three dimensions, these comparably weak results are not surprising.

5. Summary and outlook

This contribution introduces an autonomously controlled distribution system for the allocation of resources in the field of event logistics. At this, the system is responsible for the compilation of transports and the corresponding determination of efficient routes within the closed and dynamic logistic system of venues and storage(s). The presented system determines the allocation of transport devices and event equipment to orders and bases on the distributed decision-making in iterative multi-agent simulations. Those simulations consider both the warehouse data from the ERP-system of the respective logistics company as well as actual material flow information directly from the venues. The latter is acquired using a mobile hardware module that comprises all sensors for the determination and documentation of position and condition of the event equipment. Together with the simulation framework PlaSMA, the resulting distribution system constitutes a cyber-physical system that renders real-world applicable decisions within a virtual representation of the logistics system.

Experiments basing on different order situations within an example company show sufficient results regarding the reduction of the distance travelled, while the capacity utilization of the transport vehicles stays improvable. The deficient utilization mostly results from the generally inhomogeneous character of event equipment regarding shape and weight [2]. These properties complicate the efficient loading, as the equipment is often not stackable or requires a sophisticated protection during transport. Correspondingly, an efficient utilization of the transport vehicles regarding volume and weight is from central interest for future research. Objective of this enhanced planning is the consideration of all three dimensions through the negotiations and the corresponding compilation of transports.

Acknowledgements

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