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Performance Availability Analysis of Autonomous Intralogistic Systems: An Agent-based Simulation Approach

Leistungsverfügbarkeit autonomer intralogistischer Systeme: Ein agentenbasierter Simulations-Ansatz

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Abstract: In recent years, the ability to respond to real time changes in operations, agility in the turbulent market environment, and reconfigurability in equipment are likely to become essential characteristics for next generation intralogistics systems to deal with the dynamic environment. The Cellular Transport System (CTS) that aims to cope with these new requirements provides an efficient way to increase the flexibility and changeability of intralogistics systems. The main objective of this paper is to analyse the performance availability of the Cellular Transport System under various pre-defined scenarios in order to support the design process. Since analytical models have several simplifications and constraints, agent-based simulation (ABS) is used to evaluate the performance. Our results show that delays due to collisions between agents significantly impact throughput capacity, cycle times and performance availability.

1 Introduction

In recent years, the ability to respond to real time changes in operations, agility in the turbulent market environment, and reconfigurability in the equipment are likely to become essential characteristics for next generation intralogistics systems to deal with the dynamic environment. Hence, firms need to develop strategies and technologies that provide flexibility to succeed in reaction to changing conditions. However, it seems to be difficult to achieve within the rigid, specific and specialised world of automated material handling systems which offers static and inflexible solutions (Marin and Carrasco-Gallego 2013). In this regard, autonomous vehicles have been widely adopted as a key component to intralogistic systems in order to improve adaptability by physical flexibility in disposition, routing and space consumption (Güller and Hegmanns 2014). Furmans et al. (2010) offer an alternative approach called the FlexConveyor to conventional conveying systems, which is

a decentralised modular, unit-sized conveyor system. In this system, each module is able to convey in the four cardinal directions and connected by a serial connection, which is used to exchange all necessary information between adjacent modules. Seibold et al. (2013) analyse how powerful the FlexConveyor is in sorting of goods and what kind of layouts are most suitable. An extension of the FlexConveyor system is KARIS project developed by the Institute for Conveying Technology and Logistics (IFL) at the Karlsruhe Institute of Technology. It consists of several vehicles which are able to drive at the floor or stand at the floor while acting as a conveyor (Ommen et al. 2009). KARIS is a decentralised controlled system that enables quick installation and reaction to changing requirements by autonomous reconfiguration of the KARIS vehicles (Trenkle et al. 2013). It provides a wider range of scalability and reconfigurability. Based on the idea of puzzle-movement, a high-density storage system for physical goods called GridStore is introduced by Gue (2006). Some recent work has addressed autonomous vehicle based storage and retrieval systems (AVS/RS) as an alternative to crane-based AS/RS (Roy and Krishnamurthy 2011; Heragu et al. 2009; Ekren and Heragu 2011). Instead of aisle captive cranes, AVS/RSs employ a number of autonomous vehicles that are used to carry palletised loads and are capable of providing horizontal movement within a tier. More recently, a new automated material handling technology called the Cellular Transport System (CTS) is developed by Fraunhofer Institute for Material Flow and Logistics (IML) for the storage and order picking of small items. In order to cope with rigid design limitations, a group of dynamic, flexible mobile vehicles called Multishuttle Move (MSM) replace with the inflexible continuous conveyor system. The Multishuttle Move (MSM) is a novel fusion of conventional shuttle and automated guided vehicle system (Kamagaew et al. 2011). In contrast to automated guided vehicles (AGVs), MSMs can move on rack levels as well as freely within the warehouse. In other words, all transports in the rack and the surrounding area are covered with an autonomous vehicle swarm.

Since analytical methods have some limitations to handle the degree of complexity inherent to real-world problems, simulation method is today recognised as among the most promising tool for detailed investigations and reliable problem solving of complex systems (Chen et al. 2013). Most of the research concerning warehouse simulation (Liong and Careen 2009; Colla and Nastasi 2010; Ekren and Heragu 2011) has concentrate on the discrete-event simulation technique. However, using this technique, it is difficult to model the control of autonomous components in a system. Hence, researchers have shifted their attention on the agent-based modelling and simulation (ABMS) approach. Agent-based simulation, which is composed of different interacting computing entities called agents, offers an alternative way to design and implement complex behaviours of system components (Wooldridge 2002). Güller et al. (2013) have recently developed an agent-based simulation model of CTS for an experimental hall. In this paper, we extend the previous research through evaluating a novel performance measure called “performance availability” and the average cycle time with different time components.

2 Definition and Overview of the Performance Availability

Various performance indicators have been proposed and applied to warehouse operations in the literature, such as the utilisation which denotes the fraction of time in which the server is occupied and the system throughput which is defined as the number of customers served in a single time unit. Other major performance indicator is the performance availability that is defined in VDI-Guideline 4486 as “the degree of fulfilment of processes agreed between contract parties in accordance with the requirements and deadlines and in compliance with the agreed basic conditions” (VDI10 2010). Two measures are used to quantify the degree of fulfilment of the performance availability; the waiting time and the running time. The term "performance availability" was first introduced by Wittenstein (2007). It is defined as the state of a system in which a process is carried out according to requirement and the required result can be completed on time. Four essential steps are defined to reach the performance availability (Maier 2012):

1. Formulation of the business objective: The new system has the task of the operator to facilitate the achievement of its business objectives or facilitate. Therefore it is necessary that these goals are concretely defined.
2. Formulation of logistics processes: The business objectives are achieved by various logistics processes that are carried out successfully on the system. These processes must also be defined and quantified.
3. Formulation of boundary conditions: In order to measure and evaluate the performance in a meaningful way, reliable boundary conditions must be defined, based on which the necessary resources can be scheduled.
4. The difference between consequences when process disturbances occur:

If undesirable waiting times occur at the considered workplace due to a disturbance, the performance availability η_W of this workplace is calculated as follow (T_B is the observed time and T_W is the waiting time in observed period):

$$\eta_W = \frac{T_B - T_W}{T_B} \tag{1}$$

If the process is not completed at a certain time due to the lack of availability, the performance availability η_L is calculated as follow (N is the total load and n is the delayed loads in observed time):

$$\eta_L = \frac{N - n}{N} \tag{2}$$

Nevertheless, the above definition is not utilised directly for the assessment of performance of entire logistic systems. According to Klaus and Krieger (2009), a logistic process consists of a number of activities that is comprised of a measurable input, which is converted by a transformation into a measurable output. To meet business objectives, output of processes must be controlled by performance indicators, which usually involve efficiency and effectiveness metrics (Schmelzer and Sesselmann 2008). Implementing an appropriate performance measurement in increasingly dynamic and complex environments is critical to ensure that the agreement between the provider and customer is aligned with performance requirements of the system. However, defining, setting up and implementing an

effective performance management system for a highly turbulent business environment are challenges to be reached in order to adjust to fluctuating conditions of customer needs (Azevedo and Francisco 2007). These fluctuating conditions in internal and external environment must be already considered in the planning phase (Schuh et al. 2012). The system has to be ensured that these changes can be realised within a pre-defined and limited scope of action called flexibility corridor as shown in Figure 1. Until recently, little attention has been paid to the relationship between the performance availability and flexibility corridors.

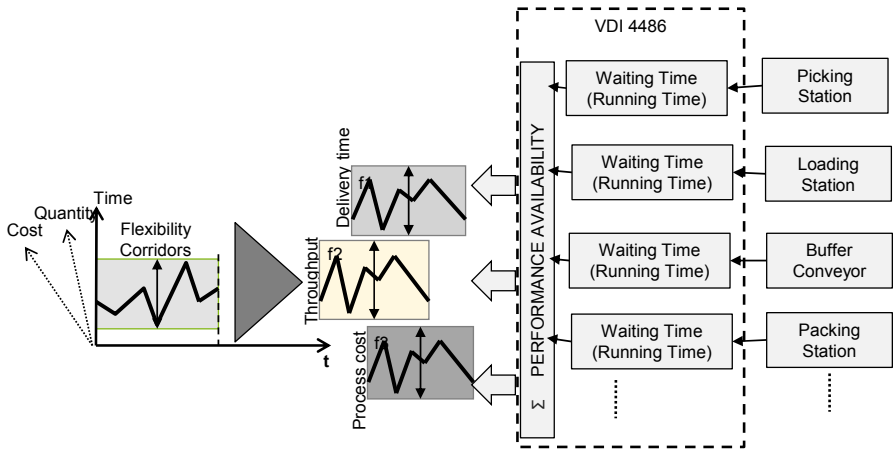

Figure 1: *Performance availability with flexibility corridors of performance dimensions*

3 Agent-Based Modelling for the Cellular Transport System

In order to manage the complexity of autonomous control of the Cellular Transport System, we have developed a simulation environment using agent-based modelling. Agent-based modelling (ABM) can be performed either by using programming languages or by using readily available simulation software packages that address the special requirements of agent modelling. Our simulation has been implemented in AnyLogic™, which is Java-based simulation software (AnyLogic 2013). One major advantage of AnyLogic is that it allows the user to create a simulation model combining differential equations; discrete events and agent based modelling. Another reason to use AnyLogic is the possibility to use Java code at any place of the program and an object oriented structure. This allows high freedom to expand the standard feature set of the tool.

There are several issues which must be considered during the simulation of mobile shuttles such as the number of shuttles, the path determination, and the control logic for dispatching shuttles. However, using traditional simulation approaches it is difficult to model the autonomous control of shuttles in a warehouse. Besides, they are insufficient to model complex behavioural patterns. Collision detection and deadlocks contribute to the complexity of autonomous shuttles' behaviour in an

open path manner in which shuttles are not guided by a floor path. In this context, ABM provides good background for solving collision detection and avoidance issues in distributed and decentralised approaches. Another contribution of ABM are decision-making capabilities, based on perception of the environment and knowledge obtained by interaction between agents. The developed simulation model is composed of a set of agents that communicate with one another by asynchronous message passing. The different developed agents that are captured to model consist of MSM agents, Lift agents, Enter/Exit agents and Workstation agents as illustrated in Figure 2. All these agents have their own characteristics and logic of behaviour.

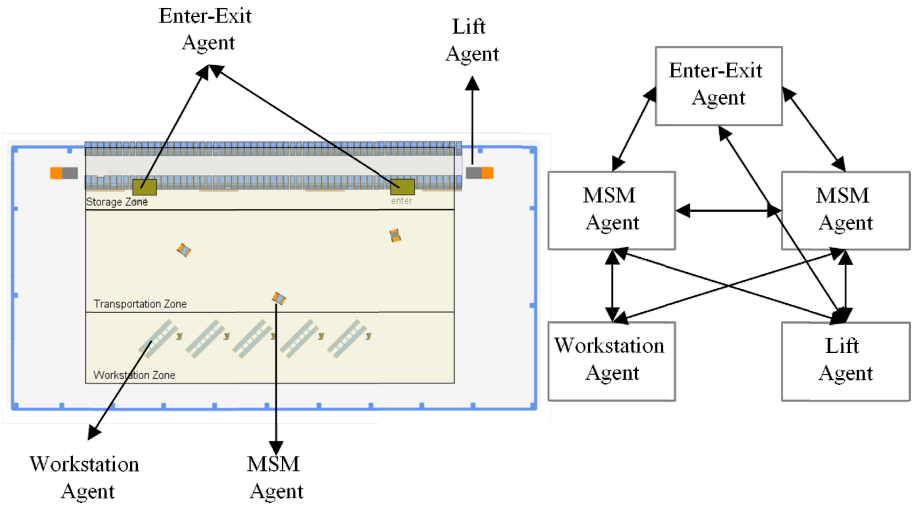

Figure 2: *Agent-based simulation concept of the Cellular Transport System*

MSM Agent: each MSM in the system is controlled by an MSM agent that is responsible for transporting bins to their destination. An MSM agent sends and receives information from the lift agent, workstation agent, enter/exit agents, and other MSM agents in the same environment. It receives information from the order pool regarding location of pick-up and drop-off workstations. Furthermore, agents can be programmed to move in x, y, and z directions. *moveTo(x, y, z)* is an example of the built-in function of the agent that starts a straight movement to a given destination point (x,y,z) in 3D space.

Enter/Exit Agents: there are two main reasons for adding these agents. One is to perform the rotation duration of the MSM at storage entry and exit points. When an MSM is moving inside/outside the storage area, it spends time within the enter/exit zone to perform the rotation of the MSM. The other reason is to avoid deadlock at storage entry/exit point. When an MSM agent arrives at the enter zone, the enter agent communicates with the lift agent to check the queue length between the entry point and the lift. Depending on the situation of the free space between the enter point and the lift, the MSM agent receives the permission to enter the storage area. On the other hand, when an MSM agent is ready to leave the storage area, the lift

agent communicates with the exit agent. If there is enough space between the lift and exit point, the MSM agent receives the permission to continue the movement.

Workstation Agent: each one of the order picking stations in the system is represented by a workstation agent that is responsible for the execution of tasks for corresponding orders at the picking station. Order pickers collect the orders from Eurobins and pack them into custom bins. After one bin is processed by the picker, it can be taken back by the MSM agent to its home position in the rack.

Lift Agents: These lift agents are introduced to control the vertical movement of MSMs in the rack system. Whenever an MSM agent arrives at the lift, it informs the lift agent about the target tier and the lift agent performs the vertical movement.

4 Simulation Experiments and Results

The goal of this section is to analyse the performance availability of the Cellular Transport System under different scenarios by using the developed Agent-based Simulation model. Simulation scenarios consist of different environmental factors, such as varying the number of order lines, stochastic demand, and number of Multishuttle Moves (MSM) in the system. The system is triggered by orders that enter the system at any time. Customer orders can have one or more order lines (product line), where each order line consists of a particular item type and quantity of the requested orders. Each of these items can be created as a separate line item, which rolls up into one order. In order to show the effect of different order structures on the performance of the system, the number of order lines per order is varied from 1 to 4. Other assumptions used in the simulation model are summarised below:

- The sample problem is considered with approximately 600 storage positions.
- The model is run for 15 independent replications and one day shift (8 hours length).
- Customer order arrivals in the system follow an exponential distribution with the arrival rates 60 per hour.
- The order size varies between 1 and 6 units and is generated from a uniform distribution.
- The transactions are served by MSMs on a first-come first-served (FCFS) rule.
- The system uses pure random storage policy. According to this policy, the probability that a retrieval transaction is required in a certain storage point is identical for each point.
- Vertical velocity of lift is assumed 2 m/s. The MSM move their loads with a speed of 1m/s on the floor and 2m/s in the rack system. Acceleration and deceleration delays for the MSM and lift are not considered.

In particular, we are interested in throughput of goods (the mean number of order that can be handled per hour by the system) and average cycle time (the time from arrival of an order until the time the order is disposed). As throughput may be estimated as the inverse of the average cycle time in conventional automated systems (i.e. AS/RS), AVS/RS this approach is not applicable due to the use of different resources (i.e. lifts and vehicles). Furthermore, throughput is a function of bottlenecks (i.e. of vehicles or lift). The creation of bottlenecks is a function of the rack configuration and kinematic features of vehicles and lifts. As Equation (1) shows, the cycle time (τ) is the sum of four time components, namely the time spent

in the transportation zone, the time for vertical movements, the waiting time for lifts and the travel time in the rack.

$$\tau = \tau_1 + \tau_2 + \tau_3 + \tau_4 \quad (3)$$

where:

τ_1: is the time spent in the transportation zone (time-transport);

τ_2: is the time for vertical movement (time-lift);

τ_3: is the waiting time for lifts and the entry point of storage (time-waiting);

τ_4: is the time spent in the rack (time-storage).

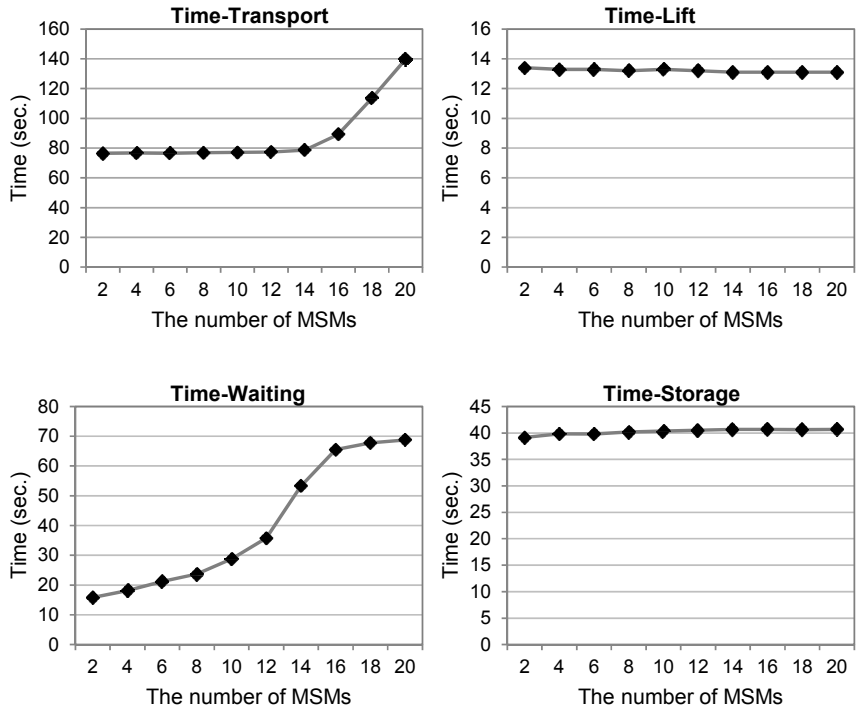

Figure 3: *Illustration of the impact of the number of MSM on the cycle time component*

Figure 3 shows the relationship between the cycle time components and the MSM number under the scenario I. Clearly, the MSM number does not significantly affect the travel time of lift (τ_2) and storage (τ_4) whereas it has a high impact on the waiting time for lifts (τ_3). Furthermore, it is interesting to observe that as the number of MSMs increases, time spent in transportation area (τ_1) remains nearly same. However, the transport time increases significantly with the respect to the increase of the number of MSMs, when it is higher than 14. This is due to the fact that

collision effects at the transportation area and congestion at the entrance of storage start to become significant when the number of MSMs increases to a large number. As Figure 3 shows, the waiting time for lifts increases as the number of MSMs in the system is increased, but when it is higher than 14, the slope of the diagram is lower, because the enter agent limits the entry capacity of storage.

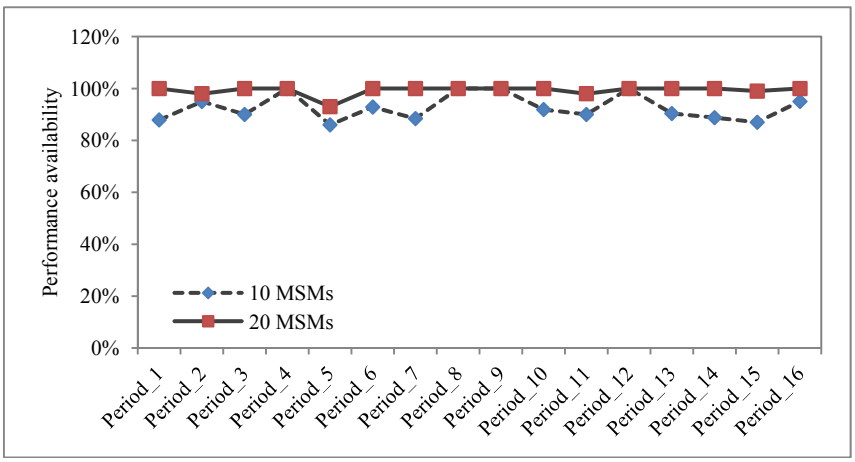

Figure 4: *Performance availability of the CTS and order picking process related to the number of MSMs*

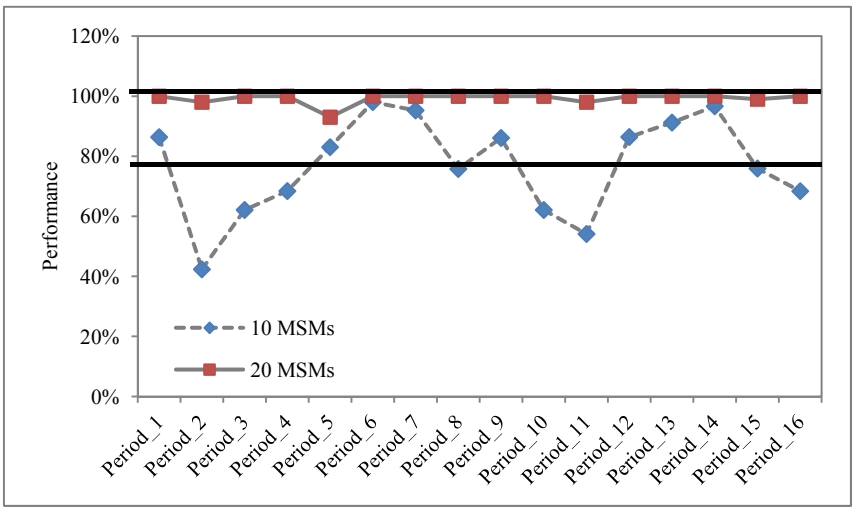

Figure 5: *Performance of the CTS based on on-time delivery*

The required performance of 60 item order/hour at the order picking stations corresponds to a cycle time of 60 s. The order picking stations are considered not available as long as the order picker must wait for the next item box. The performance availability of order picking process is calculated based on Equation 2. Figure 4 shows

the performance availability of the system in different time intervals of the observed period related to the number of MSMs. The throughput capacity and performance availability of the order picking process can be increased by increasing the number of MSMs. Performance of logistic processes is often measured from dimensions such as, time, quality, quantity, product, and cost. Figure 5 illustrates the performance of CTS based on on-time delivery dimension for different periods. The flexibility corridor of service level is assumed between 80% and 100%. As it can be seen, the system is out of the performance corridor for most of the period under 10 MSMs.

5 Conclusion

The evolution in intralogistics systems put forward new challenging requirements. Today, flexibility, reconfigurability, and high availability are more important than level of automation, cost effectiveness, and maximum throughput. Due to dynamic changes and uncertain environment, such as order variations, product diversity, and load variations, vehicles must be able to adapt their behaviour with changing circumstances. The Multishuttle Move (MSM) allows for a more efficient usage of available floor space and does not require any prior path definition. In this paper, we have presented an agent-based simulation approach to investigate the performance availability of Cellular Transport System that aims to cope with these new requirements. The simulation platform presented provides a basis to collisions with other vehicles in motion. Experiments have demonstrated that there is a relationship between throughput of the system, the performance availability and the efficient number of MSMs in the decentralised architecture.

The presented simulation model is today limited to the laboratory or trial hall installed at Fraunhofer IML. However, it is possible to extend the developed model to the simulation of an entire warehouse using an agent-based modelling architecture. Another limitation of this case study is that collisions are always solved by the prioritisation algorithm and the right-of-way rule. A possible solution would be the application of reducing its speed. In the near future, we are about to add architectural models to cope with order assignment and deadlock avoidance. Remaining challenge in Cellular Transport System is to optimise the physical layout of a distribution centre. In the long run, further experiments that are backed up by real-world validations are needed to be able to derive a model for a general design of Cellular Transport System.

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