2018

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***Abstract*—The modularisation of hardware and software is one approach to handle the demand for increasing flexibility and changeability of automated material flow systems that are, for example, utilised in flexible production systems. In such automated material flow systems, autonomous modules communicate with each other to coordinate and execute transport tasks. In this paper a strategic material flow control is introduced, which is distributed on several modules realised with a multi-agent system. The strategic material flow control agent coordinates transport tasks with advanced logistical requirements, such as sequencing. A transport task states for a transport unit the system source and sink together with arrival criteria at the sink, e.g. sequence In order to fulfil the arrival criteria the strategic material flow agent selects additional destinations within the automated material flow system to buffer a transport unit. For the selection of suitable buffer modules, several strategies are proposed and evaluated in a simulation study.**

Keywords—Automated Material Flow Systems, Distributed Material Flow Control, Convertible and Flexible Material Flow Systems, Multi-Agent Systems

I. Introduction

Automated material flow systems (aMFSs) transport goods from a source to a predefined sink and are particularly utilised in the production supply, warehousing and commissioning. In addition to the transport, aMFSs with a more complex layout are also able to perform advanced logistical tasks such as establishing a predefined order of transport units (TUs) or an arrival as a contiguous batch. Present day conventional aMFSs are mostly operated by an individual central controller, namely a Programmable Logic Controller (PLC). Developing the specialised control software demands manual effort. The basic task of the control software on the PLC is the execution of transports and tasks at decision points (e.g. junctions, handling equipment, etc.). At decision points, the PLC either receives tasks from a superior instance, i.e. material flow control, or follows programmed rules. The specialised control software for a PLC is developed by manual programming, "Copy and Paste" of already existing code, parametrising code modules and employing supporting engineering tools [1]. The superior material flow control usually consists of predefined software modules which offer different functions for typically deployed aMFSs, e.g. commissioning or storing. During the development of the aMFS, the software modules are parametrised and modified. Flexibility is usually only facilitated within predefined limits. New demands on an existing conventional aMFSs, requiring flexibility not originally considered, such as the extension of the system cannot be realised or only with great effort. These new demands arise for instance from changed manufacturing or logistic processes, which are caused by new products requiring different operations, a fluctuating production volume, a modification of the layout in the production process due to new machinery. Also, aMFSs in the field of production may strongly differ from application to application because of long term grown structures in the production and individual production processes. Therefore, when requirements are expected to frequently change during the system's lifetime, using an conventional aMFS is not favorable or it is supplemented by manual processes [2, 3]. To deal with changing requirements and enable a fast adaption of aMFSs to changing market conditions, so-called convertible aMFSs are used as a response to reconfigurable manufacturing systems [4]. There are several system approaches for specialised convertible aMFSs such as automated guided vehicles, cellular conveyor systems or standardised conveyor modules [5–7]. Once deployed, these convertible systems can easily be adapted to new requirements and layouts.

Particularly in grown structures, conventional aMFSs, e.g. conveyor systems or rail-mounted carriers, are already deployed. Apart from the missing flexibility, conventional aMFSs possess other advantages in comparison to specialised convertible systems. For example, conventional conveyors can achieve a higher throughput on distinct routes than automated guided vehicle systems. For long distances, rail-mounted carriers can be more cost efficient and at sites with installation restrictions on the ground, overhead mounted conventional aMFSs and lifts can be deployed. At many sites, conventional aMFSs already exist and an operator will rarely replace the entire aMFS hardware for a specialised convertible aMFS. Therefore, convertible aMFSs should also be realised with conventional hardware. In order to utilise the different advantages of conventional aMFSs, different types of hardware modules should be deployed within a convertible aMFS.

The way to realise a convertible aMFS is a function-oriented modularisation of the hardware and software [8]. In this approach, an aMFS consists of independent automated material flow modules (aMFM) which can handle one or more TUs at the same time shown in Fig. 1. The control of convertible aMFSs can be realised by dividing the monolithic software usually implemented on a single PLC in accordance with the system's aMFMs, which then cooperate with each other. The advantages are a reduced software complexity and eased re-configurability [9]. aMFMs are able to perform autonomous self-configuration and control the material flow. The material flow control should be distributed on the control hardware of several aMFMs in order to obtain redundancy (in case of module failure), and scalability (to allow a flexible extension of the aMFSs). The concept of multi-agent systems allows a control architecture in which various independent aMFMs communicate and coordinate tasks and, additionally, in which aMFMs can be flexibly added or removed [10].

A convertible aMFS receives transport tasks from a superior system and the order in which TUs are let into the system cannot be influenced. For that purpose, a route is determined and conflict-free routing must be assured. Conflict-free routing avoids deadlocks, e.g. two TUs transported in opposing directions on one conveyor. In addition to the transport, advanced logistical requirements of delivering TUs in a contiguous batch, delivering TUs in a predefined sequence and delivering TUs at a predefined point of time should be fulfilled. In order to fulfil advanced requirements, transports dependent on each other must be organised. Depending on the state of the other TUs from a batch or the predecessor TU in a sequence, a TU must wait for a designated time or event, e.g. arrival of predecessor TUs. Usually a superior material flow control organises advanced logistical requirements. In order to enable convertible aMFSs for applications, e.g. production or commissioning, with advanced logistical requirements, elements of a superior material flow control must be adopted to a distributed and modularised aMFS. The aMFS must be able to decide when a transport is released to arrive at a destination or to assign alternative destinations, e.g. for buffering or identifying a TU.

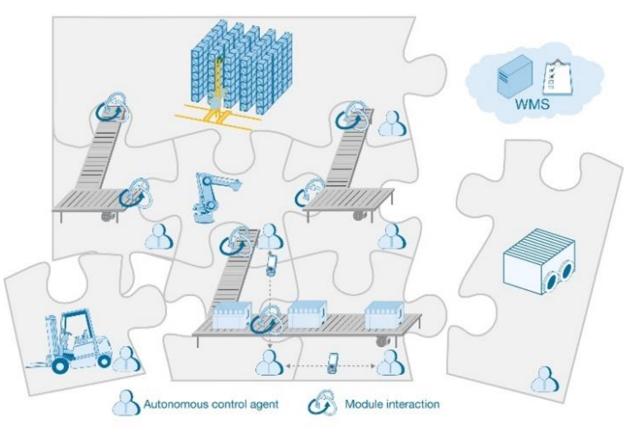

Fig. 1. Convertible aMFS consisting of several autonomous aMFMs and different types of hardware modules.

Some elements of the superior material flow control can be integrated into the routing and scheduling process. However, a strategic material flow control for convertible aMFSs enables an optimisation of releasing transports and buffer assignment while changes in the layout or material flow are incorporated. Subsequently, the performance of the aMFS can be increased.

The following section gives an overview of existing approaches for self-configuration and control of convertible aMFSs. Subsequently, Section III describes the control architecture and concept of the routing, scheduling and strategic material flow control function for a convertible aMFS. Section IV introduces different strategies for selecting buffers in a convertible aMFS and in Section V, the strategic material flow control is evaluated with a simulation model. The paper concludes with an evaluation and summary of the introduced concept and an outlook on future work.

II. Related Works

Autonomous entities that are able to execute predefined tasks, such as the aMFM mentioned in this paper, can be realised by means of agents that communicate with other agents. Vogel-Heuser et al. state that the utilisation of such agents allows the implementation of cyber-physical production systems for Industry 4.0 applications [11]. Several approaches have introduced standardised modules to build reconfigurable aMFSs controlled by multi-agent systems, with either a centralised or decentralised control. Priego et al. present an agent-based approach for reconfigurable automation systems that assures availability during runtime, in the case of a PLC failure [12]. However, the approach focuses on the control hardware and does not consider system reconfigurations due to the addition or removal of a module to or from the system. Black et al. developed an multi-agent system for baggage handling systems using IEC 61499 Function Blocks, where each block represents a module [13]. The approach focuses on the execution of transports and not on flexible routing, strategic material flow and selection of suitable buffer spaces.

Flexible and conflict-free routing can be accomplished by non-planning and planning methods [14]. Non-planning methods require many computational resources and may be inefficient. Planning methods firmly schedule transport in advance and avoid deadlocks. There are different approaches to implement such a firm scheduling process. For example, aMFMs can be exclusively reserved for an individual TU. In this case, another TU can only reserve the aMFM after the transport of the predecessor TU is completed. A more efficient approach is the use of time windows. In this approach, an aMFM is only reserved for a TU during a predefined time frame. Before and after this time frame, other TUs can reserve the module [14–16]. Approaches that rely on a completely centralised control hardware [17, 18] lack flexibility in terms of scalability and redundancy for convertible aMFSs and are not further considered. The selection and assignment of buffers can be integrated into the routing and scheduling procedures. However, present approaches either use static buffer assignments for sources and sinks or buffers are selected by chance depending on the route or current position of the TU [19]. A strategic and dynamic selection of buffers is not yet considered.

III. Distributed Strategic Material Flow Control for aMFSs

The agent for a strategic material flow control is based on the routing and scheduling procedures of the aMFS. In the following section the system architecture, the routing, the scheduling and the strategic material flow control are explained on the example of the aMFS shown in Fig. 2.

A. System Architecture

The aMFMs possess a knowledge base which describes the available logistical functions, geometrical data and further abilities of the module and which is manually created in the engineering phase [20]. The knowledge of the layout is generated automatically during the self-configuration process of an aMFM, when an aMFM detects its neighbourhood and establishes the material flow interfaces to neighbouring aMFMs. The neighbourhood information is aggregated at a central instance (coordinator). The central coordinator aggregates data and provides consistent information for all aMFMs. However, a central instance represents a single-point-of failure, as its malfunctioning often leads to a standstill of the entire system. In order to avoid this drawback while taking advantage of the benefits of central coordination, a dynamically allocable coordinator is used [21, 22]. Instead of defining a specific aMFM to perform the coordination tasks, every aMFM in the aMFS has the ability to activate itself as the coordinator. The main objective of the coordinator is to receive, store and send data to aMFMs. The processing of data is locally performed on an aMFM using local and system knowledge in order to ensure scalability. Nevertheless, for aMFSs with a great number of aMFMs, at least one aMFM should possess a powerful PLC to act as coordinator.

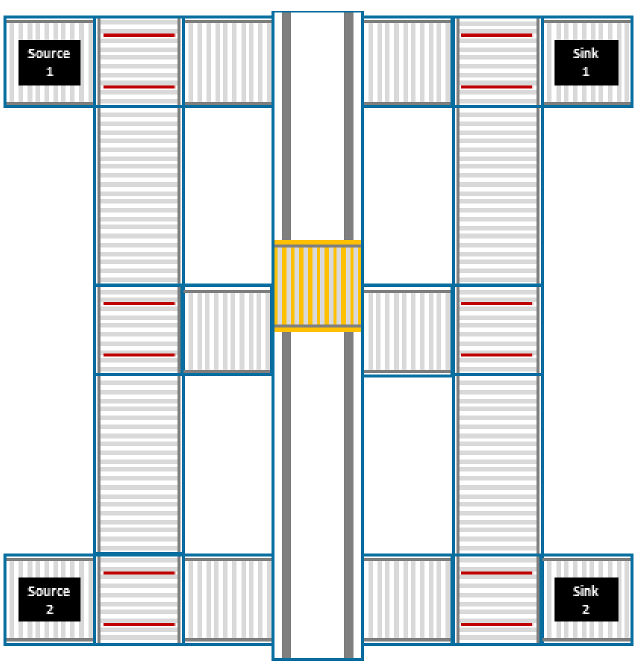

Fig. 2. Layout of a simplified aMFS with a transversal carriage.

B. Routing and Scheduling

After the autonomous self-configuration, an aMFM is ready to execute transport tasks. Determining an individual aMFM path for each transport task allows high flexible routing for alternating layouts, alternating material flow relations, or adaption to current traffic. But highly flexible routing causes a high communication load with regard to traffic in decentralised aMFSs. Changing the layout in aMFSs requires manual effort in the installation or removal of aMFMs from the operator. Therefore, the layout usually changes at most on a daily basis, and otherwise less frequently. Even in dynamic production networks, the material flow relations do not change fundamentally within a minute or even an hour. A material flow relation states how many TUs are transported from a system entrance (source aMFM) to a system exit (sink aMFM). Also, in dynamic production networks the operator aims to level the utilisation of the resources over time in order to avoid waiting times or standstill of single resources. Subsequently, stable material flow relations often develop where the average transport volume from a source to a sink only fluctuates slightly for a period of time. Therefore, an alternative to highly flexible routing are semi-static routes in aMFSs, based on the multi-label protocol switching concept used in communication networks [23]. For each material flow relation, a route is negotiated in the aMFSs, based on already existing routes and required capacity, priority, etc. of the material flow relations. Basis for the route calculation is the system topology which is stored at the coordinator. The result is a path of aMFMs through the aMFS and a granted capacity for the material flow relation, which is called a "semi-static route" in this paper. All affected aMFMs in this route are informed and the semi-static route is established [21]. A semi-static route does not guarantee conflict-free routing because the routes are only determined on the basis of on average available capacity, i.e. two opposing routes on one aMFM can occur. Therefore, for conflict-free routing a reservation and scheduling algorithm is applied. During reservation phase, a reservation request collects from all aMFMs on the route planning information and a time window is finally determined which provides sufficient capacity for the transport. Afterwards, from the destination to the start aMFM, a confirmation message is forwarded and processed at each module which determines a firmed TU sequence on each aMFM of the semi-static route [14, 16, 21].

C. Strategic Material Flow Control

There are three material flow roles for an aMFM: Start, destination and intermediate destination. The material flow agent of an aMFM is only active when a role is assigned. A strategic material flow control releases TUs and assigns intermediate destinations on demand to perform material flow tasks. The functions of the material flow agent depend on the role of the aMFM. The start aMFM of a transport has other responsibilities than a destination aMFM. However, an aMFM can act for one transport as a start and for another as a destination at the same time.

1) Workflows: Superior systems send transport tasks to the coordinator. The coordinator processes the transport task for a TU and generates workflows through the aMFS shown in Fig. 3. For each start / intermediate to a destination / intermediate aMFM a workflow is generated. The workflow states the TU ID, arrival time, start (start or intermediate), destination (destination or intermediate), workflow ID, task at destination, optional batch ID and optional predecessor TU (in case of sequencing). Hereafter, the start, intermediate and destination aMFMs of the TU are informed about their role and the workflow.

2) Destination aMFM: The material flow control incorporates the logistical pull principle. The destinations decide whether a TU is released for transport. Subsequently, destinations release TUs on demand depending on the state of the transport task and the destination aMFM. Additionally, the system state can be considered for the release of a new TU to avoid a decrease in system performance due to congestions and mutual blockings. Predecessor start or intermediate aMFMs inform the destination of a workflow about the state of a TU. Destinations cyclical check the state of the workflows and apply release criteria, e.g. releasing a TU in a sequence only when the arrival of the predecessor TU is confirmed. If a destination is not ready to release a workflow, the destination can determine or estimate when the workflow may be released. Depending on the waiting time until the workflow may be released, the destination is responsible for selecting a suitable aMFM to buffer the TU. In this case, a new sub-workflow is created, shown in Fig. 4. When a buffer aMFM is added to the workflow, a sub-workflow is generated from the start to the buffer and from the buffer to the destination. In the case that one buffer does not provide a sufficient time of buffering, an additional following buffer is selected till a TU can stay on a buffer for an infinite time. Subsequently, several of sub-workflows can be created, i.e. to establish a chain of buffers. Only destinations are allowed to assign buffers because they can determine the demand. When a destination releases a buffered TU it requests the arrival of the TU from the last buffer aMFM in the chain. If the arrival from the last buffer aMFM is too late, the request is forwarded to the buffer or start which can match the desired arrival time. The aMFM which matches the arrival time then sends an offer to the destination and cancels all successive buffers shown in Fig. 5.

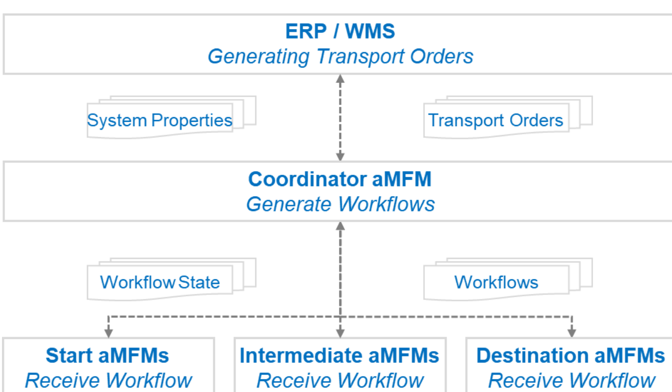

Fig. 3. Process of receiving a transport task from a superior system and generating workflows for aMFMs with roles.

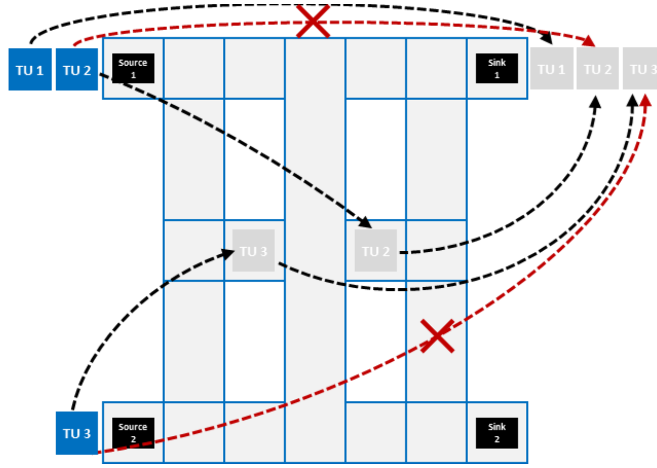

Fig. 4. Substitution of a workflow from a source to sink with two sub-workflows from a source via an intermediate to a sink aMFM.

*3) Start aMFM:*Start aMFMs update destinations about the current state of a workflow or request a transport when the aMFM must be cleared. When a start aMFM acts as a source of the aMFS, new TUs which are put on the aMFM manually or automatically are detected. The start aMFM informs the destination and requests a transport in order to clear the source for other entering TUs. Before a transport can be requested, the arrival time at the destination must be determined. For that purpose, the start aMFM searches for an existing semi-static route to the destination. If no route is yet established from the start to the destination, the start calculates a new route. The objective of the initial route calculation is to quickly establish a valid route to execute the transport. The more effort and time-consuming optimisation of the routes is not an objective at this point. The start aMFM requests a current system topology matrix from the coordinator, containing transport times and free capacities between aMFMs.

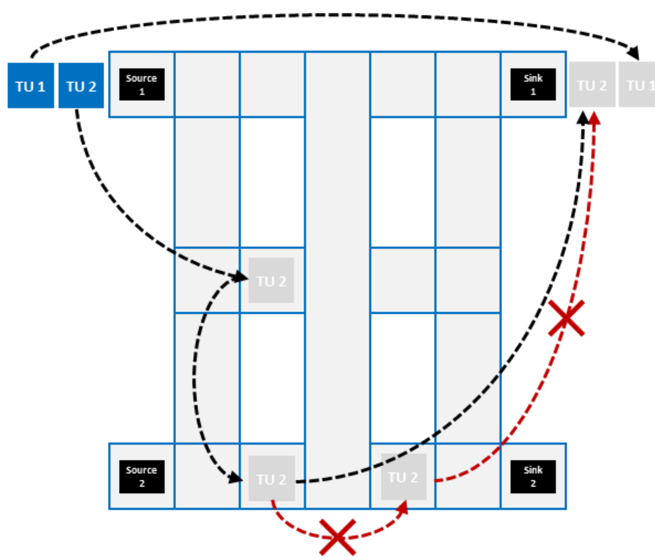

Fig. 5. Cancellation of a buffer aMFMs chain in order to arrive at a destination aMFM earlier than originally planned.

For the routing a constraint-based routing algorithm is applied where all entries are removed which do not provide sufficient capacity for the projected material flow relation from the start to the destination. The required capacity for the new semi-static route is calculated from the workflow forecast, if applicable. The start aMFM tries to find a route. If no route is found, the constraint-based routing procedure is repeated with reduced capacity until a route is found. This procedure ensures the execution of the requested transport but may cause bottlenecks at certain aMFMs. Bottlenecks can only be eliminated when other routes are changed. Therefore, the elimination of bottlenecks is postponed to the route optimisation procedure which is performed after significant changes in the layout or material flow relations. After an existing route is found or a new route is established, a transportation request with arrival times can be sent to the destination. When a destination receives a transport request from a start aMFM, the destination either releases the workflow or selects and proposes a buffer.

4) Intermediate aMFM: Intermediate destinations act as start and destination at the same time. Intermediate aMFMs receive transport requests and decide about releasing workflows or assigning buffers. Intermediate aMFMs also request transports at their successor. Transports are requested, if TUs cannot stay at the intermediate aMFM because other TUs also require visits to the intermediate aMFM. In that case a received transport request is forwarded to the successor and checked for release again and again until the transport request arrives at a safe aMFM, i.e. sink or an intermediate on which the TU can stay without interfering with other TUs. Subsequently, a chain of several intermediate aMFMs is built where all intermediate aMFMs need to agree in order to release the transport. This ensures that a transport is only released if all the required intermediate destinations (resources such as identifying or measuring units) are available and preconditions (predecessor TUs) are fulfilled. If the safe aMFM releases a transport the confirmation is sent from intermediate to intermediate until it arrives at the aMFM from which the transport originally was requested. If a successor, intermediate or sink aMFM cannot release the transport, the aMFM selects and assigns a buffer.

*5) Deadlocks:*When a TU on a source aMFM requests a transport but the destination cannot release the transport and no buffer is available, a deadlock might occur. The TU blocks the source aMFM and another successor TU cannot enter the aMFS from the same source. But this successor TU might be necessary to release the transport of the TU blocking the source. The destination observes the buffer states and recognises when no buffer movement (offer and book capacity) occurs anymore. Subsequently, deadlocks due to an overcrowding of the aMFS are detected and can be recovered. The operator is responsible for only allowing transport tasks with batch and sequencing conditions, if the aMFS layout provides sufficient buffer space. Otherwise deadlock handling strategies are activated and the aMFS might not fulfil the requested advanced logistical requirements.

IV. Buffers

In the case that a destination is not ready to receive a TU yet, another aMFM for buffering is required in order to clear a intermediate destination or source for other arriving TUs. In the following, an intermediate aMFM which is assigned the task to buffer a TU is also called buffer aMFM. A material flow agent can strategically assign buffers in dependence of the current system state, layout and buffer demands. Before the routing and scheduling function, the material flow agent decides whether a buffer is required and assigns a buffer aMFM to a TU workflow. In the following, different strategies for selecting a buffer aMFM are proposed.

Every aMFM can act as buffer and so determines the maximum number of TUs it can take at the same time. Also, the current available capacity is determined by subtracting all TUs on the aMFM that are currently or planned to be buffered from the maximum capacity. The maximum and available buffer capacity are communicated to the coordinator. The coordinator initially forwards the name of a new buffer aMFM and firmed properties, e.g. maximum capacity, to all destinations. When a TU requires a buffer, the material flow agent of the destination checks whether a buffer aMFM can be reached from the start and whether the destination can be reached from the buffer. Afterwards, the destination aMFM strategically selects a buffer set with one or more buffer aMFMs and requests an update for the set of buffers from the coordinator on the current state. The coordinator sends to the destination all buffers from the set which have a available capacity greater one TU. This procedure may be repeated with an increased buffer set, until at least one buffer with currently available capacity is transmitted. Afterwards, the destination aMFM makes a final selection, reserves the buffer for the TU and informs the start aMFM. Subsequently, the start requests a transport to the buffer aMFM. Because every aMFM can act as buffer, a buffered TU may block an aMFM which is required for a transport. Therefore, a buffer must be cleared when a reservation request for another TU is received. The buffer follows the same procedure as a source and requests a transport to the successor aMFM. The destination either releases the transport or assigns another buffer aMFM for the TU. In the following, different strategies for selecting buffers are introduced and shown in Fig. 6.

The first strategy selects the buffer which is closest to the start shown in Fig. 6 top left. The TU arrives within a short transport time at the buffer and the majority of the transport is not accomplished yet. On the one hand, the destination has to plan releases further ahead to consider the transport time from a buffer at a remote start to the destination, which limits the agility of short term releases. On the other hand, a remote buffer enables more flexibility for selecting another buffer or route to the destination because there are more options to reach other aMFMs on the route to the destination.

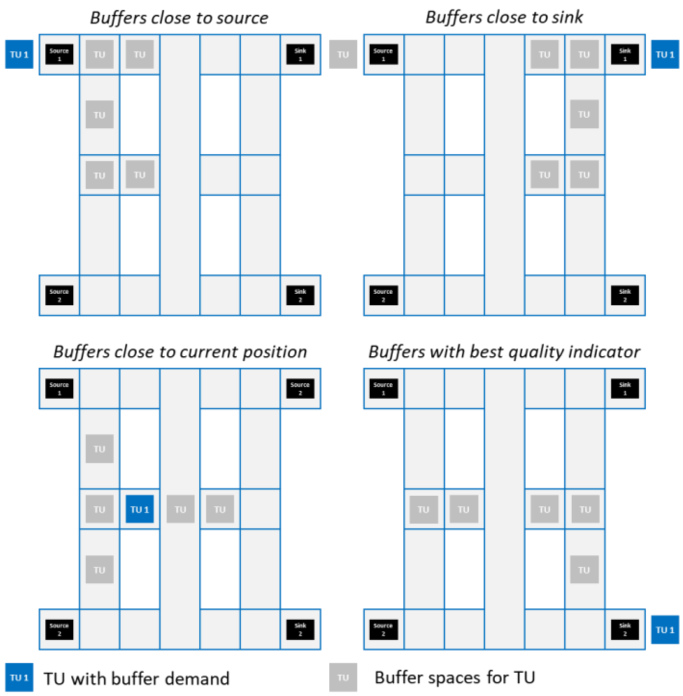

Fig. 6. Buffer set with different aMFMs which are selected in dependence of the strategy.

The opposite strategy selects a buffer which is closest to the destination shown in Fig. 6 top right. The TU already accomplishes the majority of the transport to the destination. Subsequently, a destination gathers waiting TUs in its proximity and is able to release TUs very flexibly. But in the case of system layouts with several aMFMs which only allow one-way transports, a close buffer limits the options to move the TU to another buffer.

Another strategy is the selection of buffers close to the current position of the TU shown in Fig. 6 bottom left. In the case that a TU is already buffered and requires an additional buffer, the selection of a buffer close to the current position leads to some advantages. The TU only has a short transport to the next buffer which decreases the probability of clearing another buffering aMFM and reduces transports in general. But the selection of close buffers may lead to a misbalanced distribution of buffered TUs in the aMFS because buffered TUs stay in the proximity of their last destination.

An advanced strategy for buffer selection considers the system layout and utilisation of the aMFMs shown in Fig. 6 bottom right. In order to evaluate the qualification of an aMFM to act as a buffer, an indicator is introduced. The indicator assumes that a good buffer aMFM can buffer a TU for a long time without clearing the aMFM for another transport. Therefore, the indicator expresses the additional transport time which is caused by clearing the aMFM for transports. The additional transport time is stated for a fictive buffer usage of one hour. There are several properties which are considered for the indicator. The most important factor is the utilisation of the aMFM for transports. If a buffer is cleared for the transport of another TU, the buffered TU must be relocated to another buffer. The buffer calculates the average transport time to another buffer from past TUs. Thus, buffers which are located very remotely from other buffers or destinations and therefore cause long transports for relocating TUs are negatively considered. The average transport time to another buffer is then multiplied by the average throughput of the aMFM, which is stated in TUs per hour. Another factor is the capacity and access to buffered TUs on the buffer. For example, 3 conveyors with a buffer capacity of 1 are better than one conveyor with a buffer capacity of 3 as shown in Fig. 7. If a TU in the middle of a conveyor with 3 TUs is released, all TUs ahead of the released TU have to be relocated to clear out of the way of the conveyor. On the other hand, a conveyor with the capacity of one does not need to clear the buffer in order to release a TU. Therefore, buffers calculate from past TU the average buffer time on the aMFM and the number of releases per hour.

Depending on the type of the aMFM, the average number of TUs which have to be relocated for a release is determined. For one-way conveyors, the maximum capacity is deducted by one because for the TU at the very front no relocation is required, e.g. *TU1* in Fig. 7 left. Then the reduced maximum capacity is divided by two. Subsequently, the aMFM assumes that on average half of the buffered TUs need to be relocated for a release. For aMFMs with direct access to all buffered TUs, e.g. automatic storage and retrieval systems, the average number of relocations is null. Conclusively, the average number of relocations is multiplied by the average number of releases and the average time to another buffer and added to the indicator. If three conveyors with a capacity of one are aligned in a row, the behaviour is similar to a conveyor with a capacity of three. But in that case, routes from start aMFM to buffers and from buffers to destinations lead through the conveyor aMFMs aligned in a row. Subsequently, a higher transport volume is considered in the indicator and equalises the apparent effect of better accessibility. The consideration of the buffer capacity and accessibility leads to a preference of buffer aMFMs from which TUs can flexibly be released without causing relocations which take time in planning and execution.

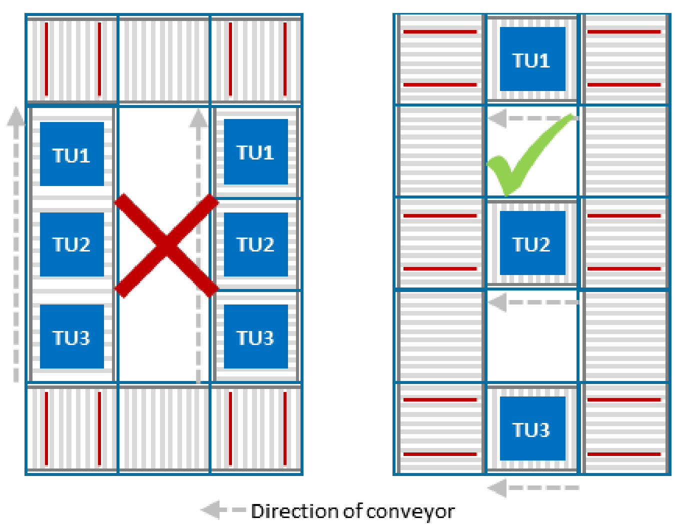

Fig. 7. Comparison of different aMFMs types and their ability to buffer several TUs.

V. Evaluation and System Behaviour

In a simulation model, the material flow agent and buffer selection strategies were evaluated. In this paper the simulation software "Siemens Tecnomatix Plant Simulation" was used. For the evaluation, a layout with several sources, sinks, buffer spaces and different types of aMFM was utilised similar to Fig. 2. The material flow agent concept was implemented and also the different buffer strategies. The different buffer strategies were evaluated with different material flow scenarios. The material flow scenarios varied in the average size of a batch and with or without a sequencing condition. For each buffer strategy and material flow scenario, the average system throughput was determined. The average system throughput of a strategy is compared to a random selection of buffers, in order to determine whether a strategic material flow agent achieves better results. The results from the simulation run are shown in Fig. 8. The strategies to select a buffer close to the start or destination have a negative impact on the system performance compared to a random selection of buffers. Since every aMFM can act as a buffer, aMFMs which are also required to perform transports are selected many times. Subsequently, buffered TUs only stay for a short time before the aMFM needs to be cleared for another transport and the TU is relocated. Challenging scenarios with large batches and sequencing requirements have a high demand for buffers. In these scenarios, several TUs attempting to clear an aMFM at the same time often block each other. This effect is amplified when TUs are buffered close to each other, which is the case for the strategies close to the start or destination. Mutual blockades are solved by selecting alternative buffers using different routes. But solving blockades requires time for coordination and execution, which lowers the system throughput. An approach to reduce the demand of relocations is to disable an aMFM for buffering if it is required for transports in the near future. An aMFM can determine from the reservation requests whether a transport is planned in the near future. In this case, it can inform the coordinator that it has no capacity to buffer a TU, so the aMFM is not selected for buffering. The disabling of aMFMs reduces the buffer capacity of the aMFS, which limits the performance of challenging scenarios, i.e. large batches and sequencing.

The strategy to select buffers with the introduced indicator showed the best results. Hence, further strategies are derived and the quality indicator is combined with the buffer position. First, a set of buffers is selected after the quality indicator and then ordered in dependence of the distance from the start, destination or current position. The results are shown in Fig. 9. Still, the strategy solely selecting buffers after the quality indicator showed the best results.

Scenario	Close to Sinks	Close to Sources	Close to Position	Buffer Quality	All Strategies
	Buffer Strategy				
Max. Size 5, Sequence	-98%	-92%	-13%	84%	-6%
Max. Size 3, Sequence	-75%	-96%	133%	152%	68%
Max. Size 5, No Sequence	-24%	-87%	19%	112%	-8%
Max. Size 3, No Sequence	10%	-68%	24%	29%	-2%
All scenarios	-39%	-83%	32%	83%	

Fig. 8. Variance of the system throughput for different buffer strategies compared to a random buffer selection.

Scenario	Buffer Quality	Quality Sinks	Quality Sources	Quality Position	All Strategies
	Buffer Strategy				
Max. Size 5, Sequence	84%	72%	50%	35%	-6%
Max. Size 3, Sequence	152%	53%	157%	205%	68%
Max. Size 5, No Sequence	112%	93%	-42%	-39%	-8%
Max. Size 3, No Sequence	29%	29%	2%	59%	-2%
All scenarios	83%	59%	30%	55%	

Fig. 9. Variance of the system throughput for different buffer strategies considering the quality indicator compared to a random buffer selection.

In the next step, two different layout variants are investigated. In the first variant, the distance between the sources and sinks is increased and the results are shown in Fig. 10 above. For scenarios with a sequencing requirement, the performance for buffers close to sinks increases because TUs waiting close to sinks for their predecessor can be released flexibly. Nevertheless, the strategy selecting only after the quality still performs better because there are not enough buffers close to the sink. Therefore, evenly distributed buffering in the aMFS on suitable aMFMs is preferred. This might change in bigger aMFSs where sufficient buffer space is provided close to the destination, therefore the strategy is considered in further works. The second variant consists of several one-way aMFMs so that transports are limited to certain areas after they passed a one-way aMFM. The results are shown in Fig. 10 below, and the strategy buffering TUs close to sources only increases the performance for some scenarios slightly. Also, the strategy only selecting after the quality showed the best results and automatically utilises buffers close to the start and destination dependent on the demand.

VI. Conclusion

Convertible aMFSs utilise a decentralised control which is distributed on several aMFMs, allowing scalable and redundant convertible aMFSs. Several approaches already covered the routing and scheduling in decentralised aMFSs. For advanced logistical tasks, such as building a batch or sequencing, the transport from a start to destination can not be executed directly but an additional intermediate destination for buffering or passing another TU is required. A strategic material flow agent which is also distributed on several aMFMs increases the system performance.

Scenario	Buffer Quality	Quality Sinks	Quality Sources	Quality Position	All Strategies
	Buffer Strategy				
Max. Size 5, Sequence	239%	148%	106%	214%	99%
Max. Size 3, Sequence	99%	67%	31%	40%	36%
Max. Size 5, No Sequence	64%	34%	54%	34%	-3%
Max. Size 3, No Sequence	3%	-17%	0%	0%	-17%
All scenarios	70%	36%	34%	45%	

Scenario	Buffer Quality	Quality Sinks	Quality Sources	Quality Position	All Strategies
	Buffer Strategy				
Max. Size 5, Sequence	47%	-27%	-33%	51%	5%
Max. Size 3, Sequence	13%	-61%	18%	2%	11%
Max. Size 5, No Sequence	83%	19%	27%	70%	41%
Max. Size 3, No Sequence	84%	50%	95%	59%	40%
All scenarios	51%	-11%	24%	41%	

Fig. 10. Different layouts: Top for a layout with great distances between sources and sinks and below for a layout with several one-way aMFMs.

The strategic material flow agent is activated on start, intermediate and destination aMFMs. The main objective is to coordinate the release of new transport tasks, to decide whether a buffer aMFM is required and to select a buffer on the basis of a selection strategy. In the case of a new intermediate destination, e.g. for buffering, the material flow agent generates a new workflow for the TU and informs the affected aMFMs. Besides generating new workflows, the material flow agent can revoke workflows and dynamically adapt the workflows and intermediate destinations to the current state of the transport task. In a simulation study, the concept of the material flow agent was implemented and different selection strategies for buffers were investigated in terms of system throughput. Selecting buffers only after the introduced buffer quality indicator showed the best overall results for the investigated scenarios and layouts. However, the strategy only performs well if sufficient buffer capacity in the aMFS is provided. Otherwise, blockades occur which negatively impact the system performance while solved. Semi-static-routes also have a negative impact on blockades because the route is predefined and cannot flexibly change due to a blockade. Therefore, semi-static routes have a negative impact in overloaded aMFSs where dynamic buffering, i.e. TUs only stay for a short time on an aMFM before the buffer needs to be cleared, of TUs is required. In future, the buffer strategies are further developed. Additionally, the planning function of the semi-static routes also considers suitable buffer aMFMs and avoids transports through such aMFMs.

Acknowledgement

We thank the German Research Foundation (DFG) for funding this project (GU 427/25-1, VO 937/24-1).

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