Development of a Priority Rule Based Traffic Management Policy for Standardized AGV Conflict Zone Coordination

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ABSTRACT (English)
The use of Automated Guided Vehicles (AGVs) has proven to be effective in companies across industries. In intralogistics, AGV fleets are constantly growing, making their coordination a challenge, especially in conflict areas such as junctions. Therefore, this paper presents a novel traffic management policy that promises reliable coordination of AGVs in dynamic traffic situations through the use of prioritisation rules in user-specific scenarios. The focus is on improving the adaptability and scalability of the often rigid coordination methods in current control systems, by providing scheduling templates in order to prepare them for increasing coordination requirements. The contribution thus provides a basis for the further development of the application of standardised control systems and contributes to the sustainable optimization of automated material flows.

ABSTRACT (German)
Der Einsatz von fahrerlosen Transportsystemen, sogenannten Automated Guided Vehicles (AGVs), hat sich in Unternehmen, insbesondere in der Intralogistik, als effektiv erwiesen. Da die Zahl der AGV-Flotten stetig wächst, wird ihre Koordination, insbesondere in Konfliktbereichen wie Kreuzungen, zunehmend herausfordernder. In diesem Beitrag wird daher eine neuartige Verkehrsmanagementrichtlinie vorgestellt, die eine zuverlässige Koordination von AGVs in dynamischen Verkehrssituationen durch die Verwendung von Priorisierungsregeln in benutzerspezifischen Szenarien verspricht. Der Schwerpunkt liegt auf der Verbesserung der Anpassungsfähigkeit und Skalierbarkeit der oft starren Koordinationsmethoden aktueller Steuerungssysteme durch Bereitstellung von Planungsvorlagen, um sie auf steigende Koordinationsanforderungen vorzubereiten. Der Beitrag liefert somit eine Grundlage für die Weiterentwicklung der Anwendung standardisierter Steuerungssysteme und trägt zur nachhaltigen Optimierung automatisierter Materialflüsse bei.

1. Introduction

It is evident that companies have recognised the central role of technological enablers such as robotics, in the realization of the Industry 4.0 vision (Deloitte 2023). As a result, solutions that lead to the digitalisation and automation of operational processes are taking a central position within organizational hierarchies (Kagermann et. al 2023). Automated Guided Vehicles (AGVs) are a key tool in this context, particularly within in production and logistics. This is because AGVs facilitate the execution of transport processes with increased efficiency and reduced operating costs compared to traditional material flow approaches (Fottner et al. 2022, Nikelowski & Wolny 2020).
However, the implementation of automation projects to integrate AGVs is progressing at a slow pace (Aguiar et al., 2019). This is due to the high investment costs and limited budgets of users, which prevent the implementation of transformation plans all at once. It is common for new product innovations to appear on the market between projects. As a result, heterogeneous vehicle fleets emerge with each new tender. To make matters even worse, AGV manufacturers are often reluctant to cooperate between their technologies, resulting in system incompatibilities that make communication and coordination between material handling systems difficult. The challenge currently facing companies is to integrate multiple, usually proprietary, control systems of AGVs from different manufacturers into the higher-level control architecture in order to ensure error-free operations (Ullrich & Albrecht 2023). This leads to more inefficiencies instead of the planned gains that should result from the proposed synergy effects.
To solve this problem and exploit the potential of automated material flow in the future, the VDA-5050 guideline has been developed in Germany by the Association of German Automobile Manufacturers starting in 2019. This guideline provides a basis for companies to implement specialised solutions for the standardised control of AGVs on the basis of MQTT-communication interfaces. By now the first-come, first-served (FCFS) principle is now widely used for traffic management due to its low complexity character (Nils 2022). This means that AGVs are sorted according to their arrival time at junctions. It

is also important to note that the coordination is based on only one decision parameter (arrival time at junctions) and does not take into account priorities or queues when determining the right of way.
As fleet sizes increase, the complexity of traffic management based on a centrally controlled system with one decision parameter is likely to become unmanageable. As the coordination effort increases with each additional vehicle, it is necessary to analyse whether current coordination methods can continue to meet the requirements of efficiency and safety. Especially at high vehicle densities, there is a risk that the FCFS principle will reach its limits in terms of the efficient coordination of all vehicles especially in terms of efficient throughput.
Think of the presence of AGVs with orders that have different priorities, or sections of the layout with higher traffic volume and therefore longer queues. It is therefore essential to explore ways of improving the control system to ensure robust AGV coordination in the future. This is because the challenges posed by high traffic density can be applied to intralogistics systems by referring to scenarios from the real world of transport, where a higher risk of disruption at junctions is expected as the size of the system increases. Avoiding congestion due to bottlenecks or deadlocks is crucial. In particular, disruptions to the flow of traffic have the potential to cause delays in throughput times, which in turn can set off a detrimental chain reaction with the potential to spread throughout the system.
The risks associated with such disruptions highlight the challenges of coordinating future fleets based on the current 'first come, first served' (FCFS) principle. The inability to compare and prioritise AGVs based on their order information is a problem due to the limited adaptability in coordinating heterogeneous fleets. Consequently, there is a need to extend traffic management with a novel coordination methodology that is capable of coordinating conflict areas of a traffic network not only from a safety point of view, but also with increased efficiency in the long run. Therefore, the aim of this paper is to design traffic rules that specifically exploit the intersection control for AGVs under consideration of several different decision parameters. Special attention is paid to the integration of these rules into a policy and then into an automated decision process, which can be implemented in existing control architectures or systems with little effort.
The remainder of the paper is structured as follows. In the next section, we introduce and summarise the evolution of AGVs for logistics automation and traffic management methods, highlighting current challenges and approaches. We then present the design of the new traffic policy and its integration into an automated decision making process based on the functionality of the VDA5050 guideline. The result of this process is the formulation of four novel priority rule-based scheduling approaches that serve as templates for specialised combinations. The extensions are implemented in the existing control infrastructure through the configuration of an interactive auction process (intersection as a market), which is based on the autonomous intersection management approach (AIM) by Dresner and Stone in 2006 and its extension, the platoon-based intersection management approach (PAIM) by Bashiri and Flemming from 2017. Finally, a first validation is performed and our research is summarised and directions for future research are highlighted.

2. Logistics automation and traffic management

Firstly, the functionality of driverless transport systems is explained. In addition, a review of the existing literature has been undertaken to identify the current state of the art in traffic management concepts and the prevailing challenges in this area.

2.1 Driverless transport systems

AGV systems can be categorised as automated material flow systems. They are considered to be floor-bound discontinuous conveyors that are used to transport goods from a source to a sink (Scholz 2019, Müller 2011). The term therefore covers scenarios of goods transport processes in production and warehouses that are realised by automated floor-bound vehicles (Ullrich and Albrecht 2023). According to the VDI 2510 guideline, AGVs are: '*floor-bound systems that can be used inside and/or outside buildings. They essentially consist of one or more automatically controlled, contactless guided vehicles with their own traction drive and, if required, of a) a guidance control system, b) equipment for determining location and position detection, c) data transmission equipment and d) infrastructure and peripheral equipment.'* AGVs are the operational workers of the internal transport system. Due to their variety of applications, they can differ in their mode of operation (structure, payload) and their degree of automation (sensor technology, communication, decision-making ability) (Ullrich and Albrecht 2019). It is therefore necessary to consider two categories of vehicles separately, firstly AGVs, and *A*utonomous *M*obile *R*obots (AMRs). The latter can navigate freely through sophisticated software modules and thus offer greater flexibility in dynamic material flow situations (Fragapane et al. 2021).
Every AGV includes navigation technology and a guidance system for master control (Pichler 2011; Schwarz et al. 2013).
Navigation can be seen as the 'eyes' of the system, with AGVs being unable to orient themselves in unfamiliar environments (Kubasakova et al. 2024). They also lack the ability to make independent decisions about braking, acceleration or other actions. Rather, they use sensors to detect whether they are on the correct path of their transport route or deviating from it (Ullrich & Albrecht 2023). This limitation highlights the need for two coordinate systems to enable navigation, which can refer to a stationary layout and a reference system located in the centre of the vehicle (Conette 2013). The result of this dual-based method is a map with x, y and z coordinates

through which the vehicle navigates. Guidance and localisation methods are then used for operational control, with position determined by measuring wheel revolutions (odometry) (Pichler 2011). In addition, bearing is used to periodically interrogate the position using passive or active localisation technologies such as markers or line guidance (Hertzberg et al. 2012).
The *master controller* symbolises the "brain" of the driverless transport system (Dickmann et al. 2015). Its functional modules integrate the AGVs into the operational transport system, it serves as an interface between the clients and the operational vehicle level (Scholz 2019). Clients are either manual users or the internal material flow control system, which automatically generates transport orders. As soon as these are received, the transport order processing is activated. Firstly, all orders are grouped together and organised hierarchically as part of order management. If there is an order priority, this ensures that all orders can be allocated on time and in accordance with requirements. This also involves finding a suitable AGV and its optimal route. Taking into account the database, route planning algorithms simulate the route from the start to the end point (Dilefeld 2023). As a result, a free AGV can be tasked with the execution via vehicle scheduling. Furthermore, the information flow of the operation is not only downstream, but also upstream, as the vehicles report the order status via defined communication protocols. Ultimately, the control system links the host systems Enterprise Resource Planning (ERP), Warehouse Management System (WMS), Production Planning and Control System (PPC) and Internal Transport System (ITS) with the operational AGVs, thus enabling cross-system processes to be handled.

2.2 Traffic management methods

Traffic management concepts include the modelling of the overall environment as well as traffic coordination and its scheduling principles. Despite their different approaches, management concepts share a common goal. Coordination aims to maximise the efficiency of the overall system (Le Anh 2005). To achieve this goal, it is necessary to minimize bottlenecks and eliminate deadlocks and collisions. Three main concepts can be derived from the literature, which can be categorised as fully centralised, partially centralised and decentralised (Nils 2022). It should be noted, however, that these concepts do not have static boundaries. Rather, it is possible to combine functional modules of different procedures, so that hybrid solutions are possible (Fottner et al. 2021).
The evaluation of the performance of a traffic control concept is based in particular on the coordination of conflict areas. These are perceived as constraints or bottlenecks in the system. Conflict areas are therefore characterised by an overlap of at least two AGV routes (Braun-Schweiger 2017).
In the following sections, the state of the art of traffic management systems is discussed, coordination with rule-based approaches is introduced, and challenges are highlighted.

2.2.1 State of the Art

There are two ways to implement a fully centralised approach (Nils 2022). In the query-based approach, AGVs transmit their planned route to the control centre when they wish to pass and wait for approval from the central control (Dresner and Stone 2008). There is also the assignment-based approach, where the central control instance transmits trajectories in the form of time-window-based assignments to AGVs in the detection zone (Yang et al. 2016). Although this requires more planning effort, the assignment allows the integration of further control mechanisms such as priority rules (Khayatian et al. 2020).
Furthermore, in the partially centralised approach, AGVs act autonomously in individual steps. In particular, route planning is carried out by the vehicle itself (Nils 2022). This concept often involves a combination of centralised and decentralised components, which is precisely why experts see great potential in it, especially in terms of improved scalability compared to fully centralised approaches (Qian et al. 2017). Unlike the two centralised approaches, the decentralised approach does not require a central control system. Vehicles operate in multi-agent systems (MAS) and coordinate themselves according to their planned routes (Schaffer and Weidenbach 2019). This form of coordination often takes place using token or auction procedures (Carlino et al. 2013). In areas of conflict, AGVs then communicate via pre-defined negotiation protocols. In this context, we can also speak of a cooperative control concept (Basile et al. 2019) which some companies describe this as swarm based.
Throughout the literature review, there is disagreement as to which of the three concepts has the highest system/coordination efficiency. Depending on the scenario, conflicting claims are made, with Pratissoli et al. arguing that centralised control systems generally have an advantage over decentralised systems (Pratissoli et al. 2023). In contrast, Fragapane et al. argue that large vehicle fleets in particular cannot be coordinated efficiently by centralised entities. In general, the results of application-specific simulations of research projects should be treated with caution. This is because central instances have access to global information and thus encompass the entire intralogistics system, whereas decentralised structures mainly use local information for the coordination decision (Fragapane et al. 2021). From this it can be concluded that centralised instances in complex systems do indeed have statistically higher processing times (Schmidt et al. 2020). However, this does not mean that they are less efficient than decentralised approaches in general. The centralised instance searches for the maximum performance of each vehicle and takes into account all possible points of conflict (Siegfried and Bourafa 2023). Decentralised concepts are based on local information, so it may happen that a new route solution has to be found for a vehicle at every conflict point along its route from source to sink (Preisler 2016). This leads to the conclusion that although sub-problems can be solved more quickly with decentralised methods, their overall

processing time in complex traffic situations may be longer than with a centralised solution.

However, research agrees that centralised approaches make the system less robust against failures (vulnerability to failure) (DeRyck et al. 2020). This is related to the fact that the coordination effort for a higher-level instance usually becomes too high with increasing system size (Günthner et al. 2012). In general, the functioning of a centralised lead authority is fundamentally opposed to the idea of autonomy, which proposes flexibility (Fottner et al. 2011). However, centralised concepts still have more areas of application than decentralised structures, as MAS are not yet sufficiently mature (Pratissoli et al. 2023). Although the potential of decentralised processes in terms of increasing flexibility and scalability is evident from practical applications, the development step from research to widespread application has not yet taken place (Schreiber 2013). However, it is expected that this will change in the coming years due to increasing complexity and ongoing research in this area.

2.2.2 Coordination with rule based approaches

When intralogistics traffic control systems are based on rule-based approaches, FCFS is the most common method in practice (Nils 2022). If a conflict area, e.g. an intersection, is currently occupied by a vehicle, each additional arriving vehicle sends a request to the traffic control system to pass through. This results in a time-ordered queue. This queue is then processed in order of registration time ('first in first out' (FIFO)). It should also be noted that other control concepts, better known as scheduling policies, have been established in real traffic scenarios over the years. These are usually tailored to the needs of the particular transport system and often use more than one decision parameter for the coordination decision (Nils 2022). Most designs are based on rights of way, which can be enforced on the basis of priorities and are implemented in the form of sorting procedures of requests within the central intersection control system (Guney and Raptis 2020). In this way, decision parameters can be defined depending on the focus of the performance orientation.

The AIM (Autonomous Intersection Management) project by Dresner and Stone in 2006 paved the way for this type of planning at conflict areas. The results of the project were to control autonomous vehicles (AVs) at real intersections not only using the FCFS principle, but also taking into account priority classes and making appropriate adaptations to traffic signal control for transit (Dresner and Stone 2008). As a result, prioritised vehicles achieved better throughput times, reduced delays and better on-time performance. Building on these findings, Bashiri and Flemming extended the AIM approach by considering whole groups from the same intersection entries. The PAIM (Platoon Based Autonomous Intersection Management) approach achieved lower average waiting times compared to the FCFS approach (Bashiri et al. 2017).

It can be seen that the coordination of traffic flow is often achieved by a combination of different control concepts. A skilful combination promises a positive effect on the performance indicators of the overall system (Nils 2022). Based on the results of the literature overview, a partially centralised approach seems to be the best choice for the current level of automation. Thus, a hybrid approach is being developed that combines the strengths of decentralised and centralised approaches and attempts to mitigate their weaknesses.

2.2.3 Challenges of traffic flow

In the context of AGV coordination, there are three main traffic flow challenges to be considered, namely *collisions*, *congestion* and *deadlocks*. These lead to interruptions in the traffic flow, which in turn affect the performance of the system (Fottner et al. 2022). In practice, there is a risk of collisions between AGVs and obstacles. Collisions can occur between two road users vehicle-to-vehicle (V2V) or collisions with an obstacle in the driving environment vehicle-to-obstacle (V2O) (Dharmasiri et al. 2019). Collisions of any kind are the cause of congestion, as temporary reductions in capacity create a bottleneck in the system (Zheng et. al, 2019; Deutscher Bundestag 2020).

Another cause of congestion can be excessive traffic demand in relation to the available infrastructure (Deutscher Bundestag 2020). These natural bottlenecks are often located at conflict points, resulting in low average speeds, longer waiting times and longer throughput times for road users (Strohhäussl 2007). As the proportion of self-driving or automated vehicles increases, so does the risk of congestion. This phenomenon occurs when one or more competing processes in a system block each other because the resource requirements of the processes, for example the release of the road section ahead, can never be satisfied (Lu et al. 2021). However, a simple traffic jam does not imply a deadlock, because according to Coffman (1971) four conditions must be met. Firstly, there must be 'mutual exclusion', as the resource (route section) cannot be used by more than one vehicle according to the VDA5050 guideline. Secondly, AGVs must occupy resources that have already been reserved while waiting for others to be released ('hold and wait'). Thirdly, a deadlock requires that resources are held by vehicles until completion and cannot be released in any other way ('no preemption'). Fourth, tasks must form a chain so that each task waits for one or more resources held by the next task in the chain ('circular wait') (Coffman 1971).

3. Development of rule sets for the systematic coordination of conflict areas

Our aim is to enhance the FCFS control system by implementing rule-based scheduling decisions. These could ensure that both order priorities and other decision parameters can be taken into account in the future. This section describes the development of a priority rule-based traffic management policy for standardised AGV conflict zone coordination. The focus is on the systematic derivation of priority rules aimed at efficiently resolving conflicts and ensuring smooth AGV operation at critical junctions.

3.1 Preliminary considerations

The basic system requirements for an adaptive control extension are already in place; we assume that the order priority and more detailed order information is already transferred from the control systems to the assigned AGV via the VDA5050 interface. However, due to the FCFS logic, this information is ultimately not used in the coordination process. In this way, a potential is lost that could presumably have a positive effect on the ability to react in dynamic traffic situations. To build on this idea, the following points are necessary to prepare the control extension of intersection management: i) AGVs operate in a network of nodes and edges, ii) the control extension is based on the functionality, notation and guidelines of the VDA5050 guideline version 2.0.0 (VDA 2019).
Therefore, if an AGV wants to drive along an edge that is part of a conflict area, this edge must first be free. A crossing is considered free if all its involved edges are neither reserved nor occupied, or if the maximum number of AGVs has not yet reached its threshold:The 'maxAGVCount' parameter limits the number of AGVs that can be in the crossing area at the same time (capacity regulation).
The intersection is not accessible if it is currently reserved for or occupied by another vehicle. If the conflict zone is currently inaccessible, the AGV will stop at the node defined in the configuration as a holding/last stoppoint, because its released part of the route (base) can not be extended. Normally a holding point is set at the last node before the actual entry into the junction.
The intersection is released according to the control logic of the VDA5050 interface at the first node that is no longer included in the intersection area. This means that the release takes place n+1 nodes after the actual departure from the intersection. If the junction is free for the next AGV in the queue, all edges of the planned route (horizon) within the junction and as many edges as possible after the junction are reserved for the AGV and transferred to the vehicle-specific base. This process is repeated for each additional AGV.

3.2 Novel rule-based traffic management policy

The following sections describe the development of the novel rule-based traffic management policy. In section 3.2.1, general assumptions regarding the structure and application of the later rules are highlighted, while section 3.2.2 focuses on the auction process for traffic management. The core of the traffic management extension are the four new rule-based control approaches (templates) with their scheduling policies in section 3.2.3. Finally, a security protocol is added to the policy in section 3.2.4, primarily to integrate security mechanisms for operational purposes.

3.2.1 General assumptions

As long as there is only one AGV in a conflict area (intersection), or only one AGV wants to enter the conflict area, it can be assumed that the FCFS principle will continue to apply without any problems. The FCFS principle therefore remains as the basic control principle and fallback option. However, it will be replaced by the new set of rules as soon as a number of $n \geq 2$ AGVs are in the detection range of the conflict area and they do not reach the same access route. In order to decide which AGV attains the right of way first, an *auction process* with a decision protocol is needed. Further the idea is, that each AGV arriving at the intersection sends its order information to the master control, which then determines the rank in the dispatching list based on the active approach. Precisely this process integrates the mentioned decentralized component into the centralized master control and should allow us to gain the ability of adaptive scheduling in dynamic traffic scenarios. While taking several decision paramteres from each AGV into account, our hybrid control mechanism takes action of the auction between the vehicles. Firstly the implementation of the control approaches within an auction process requires a restructuring and extension of the map logic according to the VDA 5050 guideline. Figure 1 shows the new conflict area and its map elements. Compared to the original logic of the VDA5050-guideline the function of entry, exit and release nodes of the intersection does not change. In contrast the new additions are the triggers registration node and decision node. In the following the differences between the original VDA5050 logic and the extension will be explained in detail.

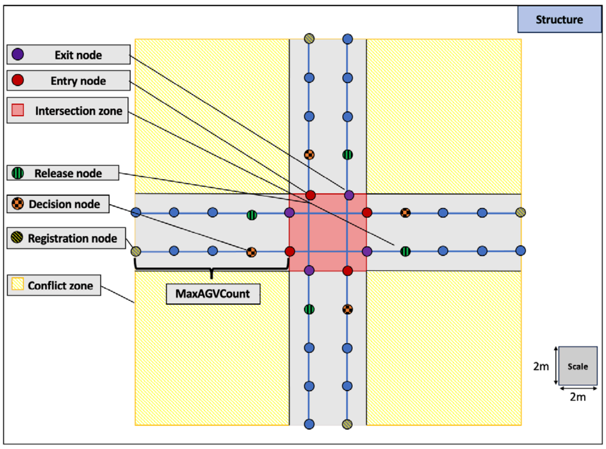

Figure 1: Illustration of the new conflict area

Detection range

Currently the VDA5050 logic is based on the idea, that the request and decision to extend the specific AGV-base is only made shortly or directly at the intersection entry node (Figure 1, red node). However, this request must be made in advance , both in terms of time and space, since

the sorting of transit requests from multiple AGV is implemented by an automated process, signals need to be exchanged and processed by the master control software. Conversely, this sorting process requires a time buffer for effective decision making. For this reason, the detection range is defined in such a way that it can guarantee a distance between the request of the AGV and its actual arrival at the intersection. It is therefore possible to include other AGVs transit requests in the same decision run. In summary, the registration node of a conflict area is always embedded n nodes in advance to the actual intersection entry node. The maxAVGCount for the intersection arm is then determined by the amount of nodes between and including the registration node and intersection entry node. As soon as the maxAGVCount reaches its threshold value at the intersection arm, it is considered occupied. If no space becomes available, no further vehicle can register for transit via this intersection arm (complexity reduction).
In practice, each conflict area can be adapted according to its requirement profile. It should be noted that the distance between the registration node and the intersection entry node affects the maxAGVCount variable. Depending on the distance between the two nodes, the maximum queue length per junction arm is determined. It is also possible that conflict areas have different access times, in which case an exception would have to be configured to use a control approach.

Decision node (trigger)

The decision node (Figure 1, orange-black patterned node) is the trigger for stopping the sorting procedure in the decision run. As soon as a vehicle reaches this marker, the recording of new transit requests in the respective decision run is temporarily stopped. The master controller must determine whether the AGV at the decision node can pass the conflict area directly or whether it must wait at the entrance to the intersection. Depending on the two options, either the junction and the maximum number of nodes behind the junction are reserved and transferred to the base of the vehicle. Or the horizon remains unchanged due to another vehicle with right of way and the AGV continues its route only to the end of its current base, which is normally the intersection entry node. From a functional point of view, the trigger should therefore be located in the immediate vicinity of the intersection entry node to ensure a sorting interval that is as long as possible to allow the best coordination decision. However, reaction and communication delays must also be taken into account when determining the exact position. In general, the decision node can theoretically be assigned to any node on the crossing arm. However, the interdependence between the length of the sorting path and the safety buffer for information transmission must be taken into account. As the decision point is moved closer to the crossing entrance, the buffer for the sorting process is reduced. The decision node with its trigger is assigned to the last node before the actual entrance node to the crossing (rule of thumb). The decision node interrupts the sorting process of the transit requests in the CrossingManager. The trigger function is activated as soon as an AGV reaches the decision node. The activated trigger function is ignored if the intersection is occupied when the AGV arrives at the logon node.

3.2.2 Interactive auction process

The master control is responsible for coordinating the intersection area. It collects and processes the transit requests of incoming AGVs. The processing is carried out by using a sorting process that sequences requests according to the active control approach, thereby creating a ranked scheduling list.
As a result of the request to the master control, the vehicles are initially assigned to the conflict area for organisational purposes until they have successfully passed through it. Within the conflict area, system rules adapted for AGVs apply (see Table 1).

Table 1: System rules

Rule	Description
(1)	AGVs reduce or increase their speed (v) to 1 m/s and maintain it until they reach the decision node.
(2)	AGVs can only travel to the next node when the AGV in front of them has reached the node after next (collision prevention).

Each AGV registers its transit request with the following information in order to be included in the sorting process: agvId (vehicle identification number), orderId (order identification number), timestamp (time stamp), priorityvalue (priority value), requestnodeId (identification number of the registration node), orderdeadline (deadline) and speed value (transit time).
Within the request list, the crossing sequence is updated during the sorting process in the decision run with each newly added request. If the first AGV triggers the decision node, the sorting freezes and the vehicle at the first queue position is given clearance to pass. The sorting runs and their interruptions are now referred to as hot and frozen gaps:

- *Hot gap*: Refers to the time interval for sorting new or existing transit requests within a decision run.
- *Frozen Gap*: This refers to the time interval during which the sequence is frozen and no new requests can be sorted.

As soon as the AGV at the first list position has received the transit clearance and passes the intersection accordingly, the interruption can be cancelled. Since the intersection is occupied at this point in time, requests can be considered again for the next decision run. At this point in time, no other AGV is able to pass the intersection area according to the deadlock safety logic. The second hot gap can be maintained until the AGV (or the last vehicle of a platoon) reaches the intersection exit node. Then the sorting is closed again and the decision run comes to the conclusion which AGV/group is allowed to pass the intersection area next. This results in a cycle that repeats itself as long as there are $n \geq 2$ requests from different

request nodes in the list, until all AGVs waiting to pass the intersection have been processed.
The following rules apply to the hot and frozen gaps. The starting point is an empty conflict area.

Table 2: Hot gap and frozen gap rules

Rule	Description
(1)	The first hot gap extends over the time interval between an AGV registering and reaching the decision node.
(2)	The AGV with the earliest transit request also reaches the decision node first, in accordance with system rule (1) (table 1).
(3)	The arrival of the AGV at the decision node interrupts the sorting process and is considered the catalyst for the start of the frozen gap (transition to the frozen gap).
(4)	Frozen Gap 1 lasts until the AGV with the travel clearance passes the entrance node of the intersection, thus enabling the next hot gap (transition phase).
(5)	The next decision run takes place while the passing AGV is between the entry and exit nodes of the intersection.
(6)	Frozen Gap 2 interrupts the sorting process again until the next AGV (n+1) reaches the intersection entry node.

It should be noted that AGVs can still register during the frozen gap period if the maxAGVCount threshold for one of the junction arms has not yet been reached. However, the transit request will not be considered until the next decision run (hot gap).

3.2.3 Prioriry rules

This section presents the four novel scheduling rules for heterogenous fleets at intralogistics intersections. Each approach is build upon using cascadic decision protocols which try to enhance the overall efficiency of coordination at junctions while maintaining deadlock prevention and safety measures for operational workflow. Please note that these approaches serve as templates for further combinations and ongoing optimization. Table 2 includes an overview for all operators with their respective descriptions.

Table 2: „List of operators“

Variable	Naming and Description
D	*orderdeadline* – Remaining time until the order deadline (in seconds).
F	*VehicleId*- Unique identifier for an AGV in the system.
F*	*VehicleId* with the right of way (determined by the master control in the active decision run).
F_{max}	*VehicleId* with the highest priorityvalue (P) in a queue.
G_{active}	Speed orientation mode
K	*CrossingarmId*- Unique identifier for a specific intersection arm.
N	*GroupId* – Platoon of AGV sharing the same R and $T \leq T(F^*)$.
P	priorityvalue-priority of the order
Q	*QueueId* – Ordered list of AGV waiting at a crossing arm.
R	*RequestnodeId* – Unique identifier for a crossing arm (entry point of an AGV).
S	Speedvalue – Estimated transit time for an AGV
T	*Timetstamp* – Time of AGV transit request submission.
Z	Z_H = Zone assignment for the main road (high priority)
	Z_{NB} = Zone assignment for the side road (low priority)

First and foremost F* are not necessarily located at the first position (nearest node to intersection zone) on the crossing arm. In practice, the way intralogistics layouts are designed makes it hard to guarantee possiblites for overtaking. Thus we assume that overtaking is not possible in general. This issue gives rise to the problem that F* can be blocked by other AGV with lower order values and a respecting lower position in the scheduling list. To counteract gridlocks based on this problem, the following rule set of a sequential entry system is applied across all approaches, see Table 3.

Table 3: Rule set „Sequential Entry System (SES)“

Rule	Description
(1)	Determine all F with identical R (requestnodeId).
(2)	Identify the blockade group N
(3)	Process this group N as a platoon (anti-blockade protocol)

For the determnination of our platoon for the crossing sequence the following applies:

$$N(F^*) = \{ F \in Q \mid R(F) = R(F^*) \wedge T(F) \leq T(F^*) \}$$

i) Priority approach P (earliest due deadline)

In the first extension, vehicles are sequenced under comparison of their priority values. The master control reads the *priorityvalue* variable from the AGV's transit request and inserts it into the crossing queue accordingly. In the case of conflict where competing vehicles have the same priority value further decision parameters are used to allow distinctive decision making. Thus includes $P \in \{1,2,3,4\}$ and $P = 1$ represents the highest priority. For two competing vehicles at different intersection arms the following applies:

$$F_X < F_Y \Leftrightarrow \begin{cases} P_X < P_Y & \text{(P1)}, \\ P_X = P_Y \wedge D_X < D_Y & \text{(P2)}, \\ P_X = P_Y \wedge D_X = D_Y \wedge T_X < T_Y & \text{(P3)} \end{cases}$$

P2 allows us to include the orderdeadline as a decision parameter if P1 cannot find a distinctive decision. Altough using more than one parameter the occurrence of a deadlock event is still possible if two competing AGVs have the same *priorityvalue* and the same remaining time to their *orderdeadline*. The control approach thus falls back on the underlying control system with the FCFS principle as a last resort to make a clear decision on right of way in P3. The sorting mechanism then compares the *timestamp* variable and selects the AGV with the earliest registration on the registration node registration nodespoint (transmitted request).

ii) Queueing approach W (longest queue first)

In this approach, the longest AGV queue should be preferred and given priority. To determine the AGV-queue of an intersection arm, the master control reads the *requestnodeId* variable from the transit requests. With that all AGV with the same Id are grouped (vehicles of the intersection arm that have already been processed are no longer included in the list). For two competing intersection arms the following applies:

$$F\_max\ (Q) = (\_F\ \in Q\ \hat{}\ argmin)(P, D, T)$$

$$Q_X \prec Q_Y \Leftrightarrow \begin{cases} N_X < N_Y & \text{(W1)}, \\ N_X = N_Y \wedge F_{max}(Q_X) \prec_p F_{max}(Q_Y) & \text{(W2/3)}, \end{cases}$$

Similar to the priority approach this scheduling orientation encounters a conflict, if two competing queues have the same length. For equal lengths, the highest priority vehicle F_{max} within each queue is compared (W2). Thus the priority approach with its three instances is also implemented in the cascadic decision process as a fallback option.
Addtionally when Q_i is selected via W2 / W3 only the part of the queue upon and including F_{max} will get the right of way for transit. Thus counts:

$$N_{transit} = \{ F \in Q_i \mid T(F) \leq T(F_{max}(Q_i)) \}$$

This is primarily because the trailing vehicles do not impede the highest priority vehicle. Moreover, it is probable that, during the course of platoon processing, new queues will form on other arms of the intersection. In the event of the entire intersection arm being processed in accordance with the priorisation function, the fundamental principle of enhancing the overall throughput times for all vehicles would be contravened.

iii) Zone approach Z (constant priorisation)

The third control approach represents a zone-based focus to traffic control. In practice, driving lanes are usually frequented to different degrees. In particular, the main traffic lanes of a intralogistic layout are subject to high vehicle densities. Accordingly, the queueing approach makes sense, but does not guarantee that main streets (H) can generally be given priority over side streets (NB). If a NB queue is the same length as an H queue, the priorities clash and, conversely, there is no guarantee of right of way. If it is not possible to consistently prioritise main streets, there is a risk of congestion and traffic gridlock.

$$Q_X \prec Q_Y \Leftrightarrow \begin{cases} Z_X = Z_H \wedge Z_Y = Z_{NB} & \text{(Z1)}, \\ Z_X = Z_H \wedge Z_Y = Z_H \wedge Q_X \prec_W Q_Y & \text{(Z2)}, \\ Z_X = Z_{NB} \wedge Z_Y = Z_{NB} \wedge Q_X \prec_P Q_Y & \text{(Z3)} \end{cases}$$

This approach also sees a conflict, if more than one arm with the zone assignment Z_H leads into an intersection. In this sense, in Z2 the queueing approach is used for decreasing the average waiting time at the intersection. In light of the higher waiting times that are generally expected on side roads, Z3 makes use of the priority approach directly to minimize the chance for high value orders to miss their deadlines.

iv) Hybrid approach H (shortest processing time)

Lastly, a combined control concept with switching rule sets could be used to prioritise vehicles not only according to order values but also according to their transit speed (not in conflict with system rule 1 because the application only remains until the AGV arrives at the decision node). In this case the priority orientation and a speed orientation (G) are combined. G refers to the Shortest Processing Time (SPT) rule from production scheduling theory. As long as only vehicles with priority values 3 and 4 (where 4 is the lowest of all priorities) are registered at an intersection that represents a bottleneck, the speed orientation counts to maximise the throughput of an intersection in normal operation. If vehicles with priority values 1 and 2 reach the conflict area, the priority orientation takes effect with the next decision run, which then guides the “priority vehicles” through the intersection as quickly as possible.

$$G_{active} \Leftrightarrow \begin{cases} True & if \forall F \in \text{requests}, P(F) \geq 3, \\ False & otherwise \end{cases}$$

As soon as these vehicles have successfully passed the conflict area and the master control only recognises priority values of 3 or 4 in the sorting list again, the system can switch back to the speed-oriented SPT approach with the following decision run.

$$F_X \prec F_Y \Leftrightarrow \begin{cases} S_X < S_Y & if\ G_{active}\ \text{(H1)}, \\ F_X \prec_p F_Y & otherwise\ \text{(H2)}, \end{cases}$$

3.2.4 Concept of a safety protocol (Deadline fairness)

If new vehicles to be prioritised keep arriving at the intersection arms, there is a risk of starvation for AGVs with a) low priority values, b) in short queues or, c) at zones with side road assignments.
To ensure that those AGVs can still reach their destination by the deadline using the specific control approaches, an external counting factor can be implemented in the decision-making process. This measures the time until the deadline D and sets a threshold for the maximum number of iterations that a request can be in the sort list without being processed. As soon as the threshold is reached, the traffic management system has to take action. When setting the threshold, the planned route of the AGV should also be taken into account. The more intersections a vehicle has to pass on its way, the lower the threshold should be for that vehicle for each conflict area.

Machine learning is a suitable method for determining the respective threshold value. With each executed order, the system learns to better adapt threshold values for the specific layout in the next run. As a matter of logic, as many order scenarios as possible should be simulated before the operational phase so that the definition of the threshold values for the start of regular operation has reached an appropriate level of maturity. The following concept including all operators from Table 4 could be used as a starting point:

Table 4: „List of operators for safety protocol“

Variable	Description
$C(F) \in N$	Count of unresolved decision iterations for vehicle F
$C_{max}(F)$	Deadline-dependent threshold for vehicle F
$C_A\ (F)$	Intermediate reporting point of the threshold value for vehicle F
P_{eff} (F)	Effective priorityvalue (temporary) for vehicle F

The possible application in priority control, speed and queue control is configured by adapting the priorityvalue of an vehicle depending on the unresolved decision iterations of the request in the scheduling list. Thus the simulated priorityvalue is decreased by factor 1 over n number of iterations until the counting factor reaches its maximum. With that the master control has no other option than permitting the request for transit by selecting priorityvalue 1, this measure should be sufficient because until this mark the specific vehicle has the oldest timestamp at the intersection. The intention is not to give direct clearance for transit, as this could lead to the risk of the safety protocol handling more and more vehicles directly over time and thus losing the actual application of the prioritization approaches. However, the efficiency of the protocol stands and falls with the definition of the threshold values.

$$P_{eff}(F) \Leftrightarrow \begin{cases} \mathrm{P(F)} & \text{if } \mathrm{C(F)} < \mathrm{C_A}\ \mathrm{(F)} \\ \max\ (1, \mathrm{P(F)} - 1) & \text{if } \mathrm{C_A(F)} \leq \mathrm{C(F)} < C_{max}\mathrm{(F)} \\ 1 & \text{if } \mathrm{C(F)} > C_{max}\ \mathrm{(F)} \end{cases}$$

The possible zone application is configured by adapting the zone assignment of the affected AGV. The assignment should be switched from a side to a main road assignment for resolving the gridlock in the intersection queue, if the amount of unresolved iterations of the request meets or exceeds the threshold.

$$Z_{eff}(F) \Leftrightarrow \begin{cases} Z_H & if\ \mathrm{C(F)} \geq \mathrm{C_A}\ \mathrm{(F)} \wedge Z\ (F) = Z_{NB} \\ Z(F) & otherwise \end{cases}$$

After the successful transit the master control can adapt the maximum threshold for the remaining part of the transport order of the AGV and the other vehicles of a possible crossing platoon to counteract the increasing deadline pressure dynamically.

$$C_{max}^{new}(F) \Leftrightarrow \begin{cases} \max(1, C_{max}\mathrm{(F)} - 1\ ) & if\ Z(F) = Z_{NB} \\ C_{max}\mathrm{(F)} & otherwise \end{cases}$$

In this case the remaining amount of junctions which the vehicles have to pass on their routes have to be taken into account. As a rule of thumb the threshold can be decreased by factor 1 for training purposes. Furthermore the implementation of an additional priority adaption after the transit is conceivable, but needs to be tested.
Overall the effectiveness of a additional priority based adaption is dependent on the next zone assignment of the affected vehicles, because if they enter a side road zone again, the priority value only matters if side road queues negotiate for the right of way.

4. Initial Validation Case

To get an first overview on the impact of the four new control approaches on their own, a small test scenario is applied. The object under investigation is an intersection with four crossing arms (see Figure 1). Within Table 12 the scenario specific parameters are listed:

Table 4: Parameters for validation

Parameters	Approach 1&2	Approach 3	Approach 4
Arrival rate	[2s, 4s]	[2s, 4s]	[1s, 3s]
Arrival distribution	P1 = 0,05 P2 = 0,10 P3 = 0,70 P4 = 0,15	P1 = 0,05 P2 =0,10 P3 =0,70 P4 =0,15	P1 = 0,05 P2 =0,10 P3 =0,70 P4 =0,15
Simulation time	5 min	5 min	5 min
Crossing time	1m/s	1m/s	[2s,4s]
AGV distribution	Equal	H = 0,5 NB = 0,1667	Equal
Order Deadlines	P1=[25s,50s] P2=[30s,60s] P3=[70s,100s] P4 = D >100	P1=[25s,50s] P2=[30s,60s] P3=[70s,100s] P4 = D >100	P1=[25s,50s] P2=[30s,60s] P3=[70s,100s] P4 = D >100

Each approach is compared individually with the FCFS-principle using four key performance indicators for every AGV priority class: lead time, delay, vehicles on schedule and throughput.
By reason of the different priorisation methods the comparability between the three classes is not given at the moment, rather this could be a future research topic. The results in Appendix 1 show that by implementing priority rule based scheduling decisions specific AGV groups can be temporarily leveraged, but on the other side some vehicles suffer in their performance. In total approach 4 achieved the best results in view of the majority of AGV in the scenario. The successful attempt to combine two scheduling approaches with a different focus in parallel and thereby unite their strengths promises a starting position that can be built on further. The hybrid approach thus represents a functional dynamic control concept that stands out among the control approaches in this research paper. In detail approach 4 increases the total throughput from 85 percent of AGV by about 2 percent, additionally the lead time, average delay and the percentage of on schedule vehicles are enhanced by 10 to 15 percent.

5. Conclusion and Outlook

To counteract the lack of responsiveness of the current control principle in the future, the implementation of coordination extensions based on rule-based decisions is suitable as the first validation has shown. The ability to extend the static character of the FCFS principle with priority-rules based on scheduling methods from the production field makes it possible to achieve the desired flexibility in the event of dynamic traffic situations and in regards to handling high volumes of vehicles. It is important to note that conflict areas differ in their structure and functionality. As a result, control approaches also differ in their coordination effectiveness for specific AGV-groups. Therefore, it is recommended not to rely exclusively on one control approach, as shown, for controlling the fleet management system, but rather to use hybrid coordination methods if challenges arise in the traffic flow. In addition, it is conceivable to consult further sequencing rules and to create new control methods from their combination. Based on the constructed templates of this paper, it is also possible to develop an individual configuration for specific layouts. This capability could help companies to take matters into their own hands after a successful first implementation. Finally, with regard to the feasibility of this recommendation, it should be noted that the control methods are designed in such a way that they can be embedded in the background of current centrally oriented control systems. Their activation can be integrated for as long as its necessary or useful. This also helps to limit the increasing complexity for the central control system until decentralized methods achieve the desired level of maturity and spread in industrial applications.

With further regard there are still topics for additional research.First of all in this paper the extension for a systemwide route analysis mechanism couldn't be realized by now. Its implementation could deliver a key tool to gain deeper insights into route and scheduling predicition, which are essential for a successful implementation of the safety protocol and ongoing coordination efficency. Furthermore after the consideration of our simulation results, the question of the "most efficient" coordination approach for intersections stays open. It therefore remains to be critically questioned to what extent the results from the limited test scenarios can also be transferred to other traffic situations. In order to achieve more accurate statements on the efficiency of the presented coordination approaches field testing in simulation environments is needed. Only after successful validation the consideration should be given to implementing the control extension. Within the tests, further questions and open points need to be answered that could not be identified within the scope of this work:

- The various asset categories and their structure cannot be uniformly defined, so the conflict area structure developed must be transferred to other conflict areas.
- For the transition of the control methods, clear trigger and stop conditions must be formulated (this point could be particularly complicated if more than two control methods are used).
- Although the pilot of the Deadline Fairness Protocol could be configured, the specific threshold values for the individual priority values still need to be determined.
- The observation horizon currently only takes into account the first five queue positions of an EntryPoint in the decision run. This means that if the queue under consideration has five AGVs with priority value 4 waiting at an Entry Point, the DFP effects late. As long as no position becomes free, for example, the next AGV in line (usually queue position 6) with priority value 1 cannot be recorded in the decision run and therefore the DSP cannot intervene. The bottleneck vehicle therefore has no chance of meeting its deadline. A method must be found to counteract this problem in the future.

The results also raise the question of whether it is less the underlying control strategy and more the maxAgvCount of 1 that leads to the restricted performance (throughput) of the intersection. As long as only one AGV can pass the intersection and, conversely, only one intersection arm/access route is served in parallel, an improvement in specific performance factors can only be achieved to a limited extent, even with dynamic control approaches. This statement is supported by the test runs of the initial approaches, as no increase in throughput could be achieved for the overall system even with prioritization procedures. At last the consideration of the trajectory and the envelope curve could play a decisive role in possibly serving more than one crossing arm at the same time. This is because, as long as AGVs from different access routes do not collide during their transit, several AGVs could pass through the intersection at the same time in the future. Consequently, the efficiency of the coordination could increase and the application of the envelope curve could show a further improvement to the dynamic control concepts in this work. However, the implementation of this new concept would require further adaptation of the conflict area into smaller zones and the establishment of a timed sequence plan. The resulting complexity for a central control system could be too high with the use of envelopes and trajectories, especially in large layouts, so this proposal must be compared with a completely decentralized method.

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Appendix 1

	FCFS	Approach P + SES	Delta	FCFS	Approach W + SES	Delta	FCFS		Approach Z + SES				FCFS	Approach G + SES	Delta
							H	NB	H	NB	Delta (H)	Delta (NB)			
Lead Time (in sec)	43,00	38,18	-12,62	43,00	41,73	-2,95	41,48	44,68	27,43	53,16	-51,22	15,95	56,00	20,80	-62,50
Priority 1	45,40	28,51	-59,24	45,40	41,71	-8,13	47,67	49,89	25,67	61,90	-85,70	-85,70	45,00	12,00	-77,78
Priority 2	43,50	34,66	-25,50	43,50	41,03	-5,68	26,61	50,64	18,17	58,71	-46,45	-46,45	54,00	12,73	-75,93
Priority 3	42,20	44,17	4,46	42,20	42,64	1,04	45,42	44,42	35,84	58,22	-26,73	-26,73	57,00	23,56	-57,89
Priority 4	41,10	45,37	9,41	41,10	41,56	1,12	46,23	33,75	30,03	33,79	-53,95	-53,95	69,00	34,90	-49,28
Delay (in sec)	39,00	33,93	-13,00	39,00	37,65	-3,46	37,45	40,67	23,45	49,07	-59,70	-59,70	58,00	17,79	-69,33
Priority 1	41,40	24,51	-40,80	41,40	37,71	-8,91	43,67	45,89	21,67	57,89	-101,52	-101,52	42,00	9,00	-78,57
Priority 2	39,50	30,36	-23,14	39,50	36,69	-7,11	22,61	46,64	14,17	54,74	-59,56	-59,56	51,00	10,06	-80,27
Priority 3	38,50	40,17	4,34	38,50	38,62	0,31	41,32	40,39	31,93	53,90	-29,41	-29,41	73,00	20,11	-72,45
Priority 4	36,70	40,69	10,87	36,70	36,56	-0,38	42,22	29,75	26,04	29,77	-62,14	-62,14	66,00	32,00	-51,52
On Schedule (in percent)	69,50	77,39	11,35	69,50	74,06	6,56	76,37	54,50	77,40	51,16	1,33	1,33	59,00	99,00	67,80
Priority 1	50,30	73,89	46,90	50,30	59,17	17,63	50,00	33,33	50,00	11,10	0,00	0,00	25,00	100,00	300,00
Priority 2	49,80	61,45	23,39	49,80	59,84	20,16	80,56	48,89	86,11	39,44	6,45	6,45	54,50	100,00	83,49
Priority 3	77,80	74,21	-4,61	77,80	77,23	-0,73	74,93	68,90	91,40	54,10	18,02	18,02	54,10	98,60	82,26
Priority 4	100,00	100,00	0,00	100,00	100,00	0,00	100,00	100,00	100,00	100,00	0,00	0,00	100,00	100,00	0,00
Throughput (units/AGV)	75,00	75,00	0,00	75,00	75,00	0,00	39,00	36,00	40,33	34,67	3,30	3,30	100,00	103,00	3,00
Priority 1	6,00	6,67	11,17	6,00	5,67	-5,50	1,30	2,30	1,30	2,30	0,00	0,00	4,00	5,00	25,00
Priority 2	8,70	9,33	7,24	8,70	8,67	-0,34	3,70	5,00	3,70	4,00	0,00	0,00	11,00	14,00	27,27
Priority 3	50,70	50,33	-0,73	50,70	51,00	0,59	28,00	25,70	29,00	25,00	3,45	3,45	74,00	74,00	0,00
Priority 4	9,70	8,67	-10,62	9,70	9,67	-0,31	6,00	3,00	6,30	2,70	4,76	4,76	12,00	11,00	-8,33