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Multi Agent Systems for Rail Transport

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Abstract: The macro-logistic structural change of the goods traffic market induced by substitution, goods structure, logistics and integration effects leads to modified requirements on the structures and processes of goods traffic and to increasing losses of market shares of the rail freight transport. A reason for this is a lack of conformity of customer requirements and the services of rail transport. This paper presents a new logistics concept for the railway sector, which increases flexibility in rail freight transport by interlinking organisational and operating processes. Combined with the use of small autonomous transport units, this helps to meet changed market requirements for freight transport. Initial simulation results of an agent based system prototype prove feasibility of the concept and give qualitative results indicating the effects of individual strategies of distinct actors on quality of service and overall system performance.

Key Words: Multi Agent System; Rail Transport; Organisation and Operation; Train Control; Train Protection

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1 Introduction

Increasing international trade integration, combined with changed goods structures in the whole economy (fewer bulk cargoes, more high-quality industrial goods), is resulting in a customization of transport, ever smaller transport lots, and changes in freight forwarders' logistics concepts (e.g. just-in-time). To be able to cope with the growing traffic volumes and meet increasing customer requirements, rail freight transport services must be adapted to the new environment, i.e., the railway industry must offer marketable solutions that can compete with the services offered by road transport, without neglecting its original market. At the same time, its logistics structures and processes will have to be adapted, which will in turn require organisational adjustments and far-reaching changes in the planning and operation of rail transport.

This paper starts by briefly outlining the specific characteristics of logistics in rail freight transport. Next, it proposes a new concept for operations and organisation that uses multi agent technology. It then gives details of the design of DOGMA (Decentralised Organisation of Guided Transport by Multi Agent Systems), an experimental platform used to cooperatively interlink logistics structures that are suitable for rail transport, and apply them in combination with a new operating concept for rail freight transport. This operating concept uses traditional trains and small autonomous transport units that can cooperate, providing an alternative to road transport.

2 Specific Characteristics of Logistics in Rail Freight Transport

Logistics comprises all activities for planning, controlling, monitoring, storing, and transporting goods or people within or among enterprises (see also [3]). Given the differences between the individual transport systems, rail transport requires fundamentally different logistics structures and processes than road freight transport. The railway system allows transportation of large quantities at a low energy cost; however, because of long stopping distances and passive guidance, it also requires a strict coordination of track capacities (lines), and the use of control and safety technology. When planning shipments, logistics personnel therefore have to not only allocate staff to vehicles and contracts, but also consider the additional factor "line", which results in high planning costs and long planning times. In addition, the drop in large traffic volumes and the rise in small-lot shipments have resulted in a reduction of the traditional point-to-point traffic with block trains, and an increase in the number of wagonload transports. This involves collecting and delivering wagons, as well as aggregating and rearranging them into block trains, i.e. additional logistical and operative measures that have a negative effect on planning and transportation times, and costs. These characteristics, which are specific to rail transport, need to be taken into account when designing logistics processes for this transport system.

3 Proposed Solution: Decentralised Cooperative Systems

A sustainable concept for operations and organisation must closely reflect market requirements and provide a demands-oriented service. The demands for a combination of the ability to schedule and a high degree of flexibility, as well as for information transparency require coherent and dynamic planning and organisational structures that can respond both to long-term and to short-term demand, which makes the task even more complex. With the shift away from monolithic complete solutions, a decentralised concept for operations and organisation to plan and run shipments in rail freight transport, called DOGMA (Decentralised Organisation of Guided Transport by Multi Agent Systems), is being realized at the Institute for Traffic Safety and Automation Engineering of Braunschweig Technical University. In this connection, it is the aim and objective of current research carried out to create an experimental platform to be used as a conceptional, systemic and information technological framework to study decentralised organisational and operating concepts. Such a framework allows testing logistical partial solutions regarding their suitability for rail freight transport, and their integrability into the entire operations concept. In addition, an operating concept for virtual train formations based on this experimental platform is designed and validated the context of the Bahn 2050 project initiated by Siemens Transportation Systems (see also [4]) and carried out in collaboration with the Institute of Electrical Measurement and Fundamental Electrical Engineering.

3.1 Interlinking of Organisation and Operations

In today's operation structures for rail freight transport, sub processes with long-term planning horizons are higher-ranking in the hierarchy than those with short-term planning horizons, and also reactionless. The whole complex planning task is split into separate sub processes, which makes it manageable, but does not allow taking into account short-notice requirements. This is a significant shortcoming of the system, particularly since the reactivity of organisational and operating processes to short-notice demand or changes in demand is of considerable importance for a vast majority of customers in the rail freight market. Ultimately it results in road transport services being given preference.

These considerations give rise to a concept for operations and organisation that interlinks the different planning processes and levels and extends them into operations. Figure 1 shows a schematic architecture of such a system as compared to the current system. The hierarchical division of the planning processes is replaced by a cooperative network that goes beyond a reactionless connection, enabling a holistic approach to planning. The mutual integration and time overlapping of the different planning processes ensures that changes in demand or operating situation can be taken into account. By extending planning horizons into operations, reactivity to short-notice demand is improved without long-term plannability being restricted. The high level of similarity between the methods used, i.e. the use of similar mechanisms for planning tasks and operations alike, ensures maximum flexibility and availability.

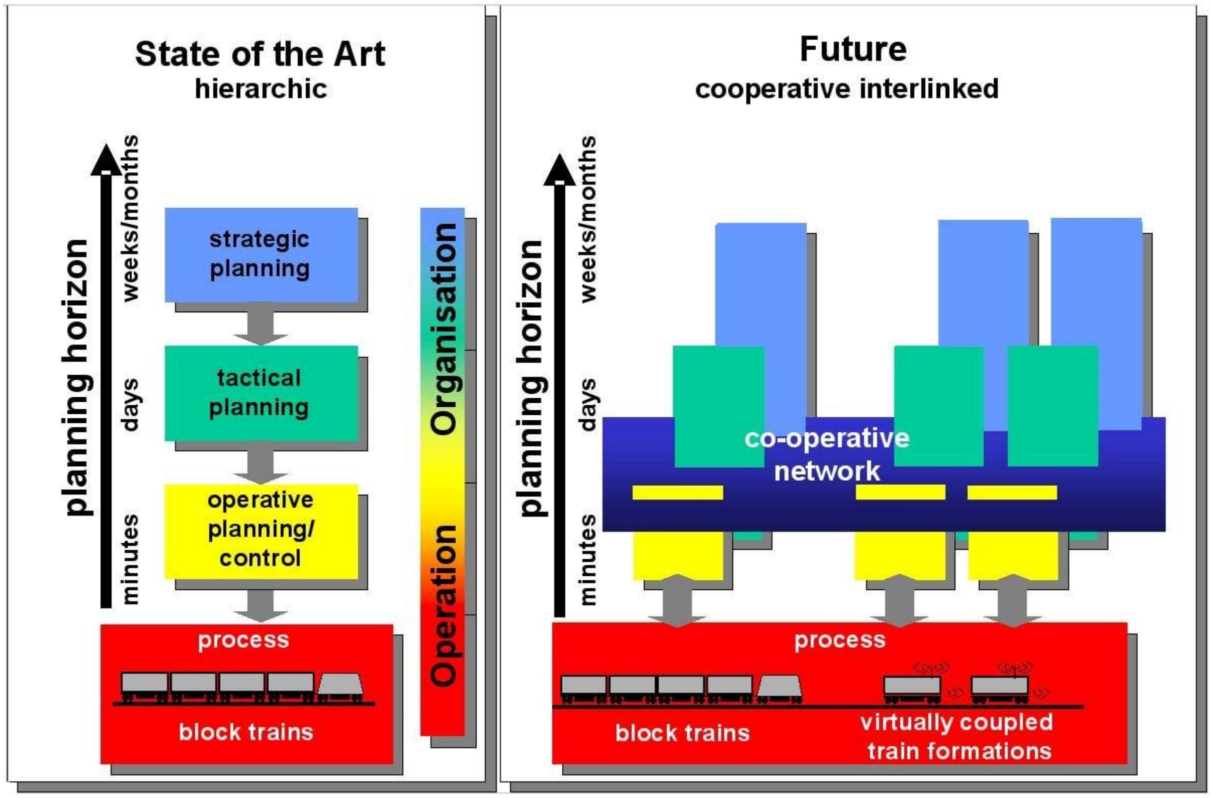

Figure 1: Architecture of current and future operations and management concepts for rail freight transport

This system concept offers maximum flexibility, but results in a high level of complexity. Due to this, a traditional top-down approach for design may not be feasible , which in addition does not take into account the interlinked character of the integrated planning and operating processes. A modular approach using multi agent technology appears to be more promising, as this concept shows inherent analogies to the system itself. In terms of optimising individual logistical tasks, an agent based bottom-up design would provide suboptimal yet still acceptable solutions; but it would bring flexibility, robustness, availability, adaptivity and scalability to the whole system.

3.2 Agent based Systems

The basic concept of agent based systems (see also e.g. [5]) comes from operations research, and it can be considered an extension of object orientation. Agent based technology is suitable for implementing complex, distributed systems with strong requirements regarding scalability and robustness. The use of many comparatively simple autonomous entities, so-called agents, instead of complicated monolithic structures makes the system easier to control. These agents have their separate goals, their behaviour is governed by relatively simple rules, and they interact with their environment. The cooperation of individual agents in a multi agent system results in target-driven, robust system behaviour of the whole system. Although agents have their own, local goals without any knowledge of the global objectives, they coordinate their individual goals and plans to achieve the required system behaviour.

3.3 Customized Transport

The changes in the rail freight market have resulted in an increasing demand for customized transport services, i.e., services have had to be adapted to accommodate freight forwarders' operation processes, ad-hoc shipments, and smaller consignments. This transport can no longer be entirely bundled, and the traditional operation processes used in rail transport are therefore unsuitable. To respond to these new requirements, rail transportation must therefore extend its range to include suitable transport services. One approach to opening up this previously road-centred market for rail transport is the use of small, self-propelled units that operate autonomously (see also e.g. [6]).

Although previous studies have considered the idea of introducing self-propelled units in rail freight transport (see also e.g. [7], [8]), these concepts did not lead to solutions of significant market shares. A major reason why these concepts have failed was the high demand of line capacity required by the individual small transport units in traditional, block-based operations, resulting in high line costs for each transport unit (see also e.g. [9]).

This fundamental flaw of self-propelled transport units, both in economic and operational terms, can be corrected if the technology and operation of such units allows them to be aggregated into train formations, thus enabling simultaneous use of the track (see also [10], [11]). The aggregation and disaggregation of train formations reduces both the necessary line capacity, and the work required for marshalling, collection and delivery before and after bundling. Moreover line costs per transport unit may be reduced for the individual transport units, since the cost May be distributed among transport units.

Self-propelled transport units represent technological system components for customizing transportation; however, they have to be combined with a proper concept for operations and organisation to achieve greater flexibility of the transport process. The next section presents the structure and content of the concept for operations and organisation, DOGMA, which represents an approach to providing demand-driven transport services.

4 DOGMA System Overview

This section gives an overview of how the concept for operations and organisation, DOGMA, is structured. Based on this structure, it then describes the individual logistics subtasks and their possible implementation in an agent based system. Figure 2 gives an overview of the basic sub processes that a concept for operations and organisation in rail-bound freight traffic has to include, namely the acquisition of orders, fleet management, transport planning, and transportation. The actors interacting in these processes can be grouped into the categories principal (sender/receiver), freight forwarder, transport unit, and network operator. In the technical implementation of the individual sub processes, they are represented by agents. The consistent replacement of actors with software agents helps to merge the planning processes in information technology, and avoids media breaks between sub processes. By reducing the

number of media breaks and supporting human actors with software agents, efficiency is increased as errors are avoided and processing times are reduced.
Upgrading system components that have been traditionally treated as (passive) process objects only, and classing these components as actors (e.g. autonomous transport units) opens up opportunities for a fundamental redesign of the processes themselves. For instance, if the transport units take an active part in the allocation of contracts within the fleet, decentralised mechanisms can be applied to solve the problem of allocation. The efficiency of such mechanisms and their advantages over centralised approaches have already been shown (see also [12]).

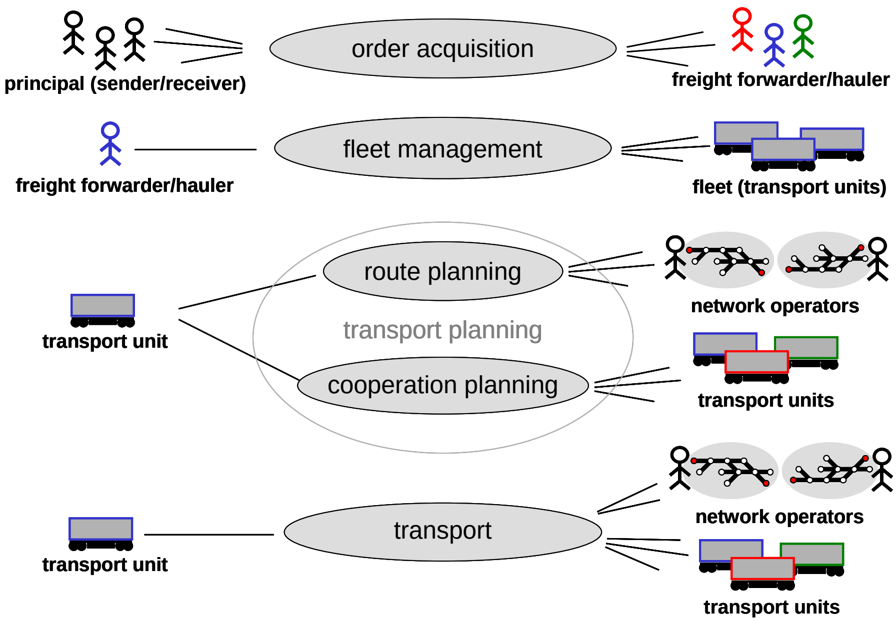

Figure 2: Subprocesses within the DOGMA concept for operations and organisation

The following subsections give details of the individual logistics sub processes within the DOGMA framework. They show that the research tasks cover a wide range of individual topics (see also [13]), some of which are currently being researched by different working parties, while others have already been partly implemented as commercial products (see also e.g. [14]).
Moreover, it becomes clear that in general, the planning processes at the higher hierarchy levels (see also Figure 1) are yet much better covered by research. One reason for this is that these planning processes (fleet management, route planning) are not or less specific to one specific transport mode, and thus transferable.
A second reason is that these levels are traditional fields of application for agent based approaches; their concepts are thus easier to integrate than those of other approaches. We shall discuss the content of the sub processes mentioned and propose solutions below.

4.1 Order Acquisition

The sub process of placing orders and securing contracts includes arranging, tracking, and invoicing transport contracts or services between principals and freight forwarders. Subtasks include support in making contact with the participating actors, in order handling, and in invoicing and analysis. Cooperative mechanisms can be either demand- or supply-driven, or a combination of both. A demand-driven cooperative mechanism is based on the initiative of a principal who publishes tenders; a supply-driven cooperative mechanism is initiated by a freight forwarder offering spare capacity. The latter is particularly suitable for allocating surplus capacity.

One possible solution for implementing a cooperative platform involves implementing an electronic marketplace based on electronic freight exchanges that are already in use (see also e.g. [14], [15]).

4.2 Internal Fleet Management

In internal fleet management, freight contracts are allocated to available capacity. A freight forwarder aims to achieve an allocation that generates maximum profit by finding the best possible slot for a contract in his transport schedule, to minimise deadhead trips, and combine several contracts.

This task is made more difficult in rail transport, where transport planning must take into account the availability of network capacity; in contrast to road transport, detailed scheduling is necessary to avoid the disruption of operations. This problem is further aggravated by the requirement of a logistics system, resulting from customer demand, to take into consideration short-notice contracts or changes.

In DOGMA, a solution is proposed that is based on the active participation of transport units in the allocation process. Transport units are defined as economically responsible entities (profit centres), which are represented in the planning process by suitably configured agents. Freight contracts are allocated in a multi-level process, which continues until actual transportation takes place, and can thus deal with a constantly changing number of orders. In a first step, a freight forwarder auctions an incoming freight contract to the transport units available. Each transport unit determines the likely costs of the contract, based on its current orders situation, the related time and physical constraints, its internal goals, own experience and forecasts, and submits an appropriate bid. In addition to simple auctions, combined value auctions are also possible, where transport units bid not only for contracts, but also for contract bundles that would be more profitable to them because of synergy effects (see also e.g. [16], [17]). A comparative study of different auctioning mechanisms in transport planning can be found in [15].

Since a transport unit's orders situation may change over time, a contract once acquired may prove disadvantageous at a later point. Transport units can therefore sell contracts to each other at a later point. One suitable method for this is simulated trading, which allows adapting the initial allocation that results from a one-off auction to changing framework conditions, thus improving it (see also e.g. [18]). The potential for improvement is limited by the amount of time left before a shipment is due to leave, and by the dynamism of the changing orders situation. This method makes it possible to quickly identify acceptable allocation solutions for a contract, and to successively optimise solutions. The optimisation process can be stopped at any time, always providing an acceptable solution to the problem (see also [19]).

4.3 Cooperative Planning for Transport Units

Cooperative planning aims to arrange collaboration agreements between individual transport units to gain economic and operational benefits by bundling consignments. Such planning needs to ensure that both freight forwarders and network operators benefit from the cooperation between transport units in economic and/or operating terms. Benefits for the fleet include cost savings due to the simultaneous use of slots; energy savings resulting from travelling in convoys and aggregating trains; and the maximum use of free capacity. For network operators, such cooperations can help increase quality of operations, which they need to guarantee, and bring financial benefits through the use of previously idle network resources, thus increasing throughput. To achieve the maximum benefit from cooperation, cooperative planning in DOGMA comprises three forms of collaboration.

- Strategic collaborations are arranged based on a blackboard system. This allows finding collaboration partners before the transport planning stage, whose routes are similar without directly overlapping, and who cannot be allocated using any other cooperative planning mechanism. A fleet's internal strategic specifications, e.g. regarding partnerships, can also be taken into consideration.
- Booking-induced collaborations are initiated during the booking phase because of existing overlaps between the individual transport units' routes. Such collaborations contribute particularly to using additional idle capacities in high-volume sections of the network.
- Allocation-induced collaborations are arranged at short notice during transportation if disruptions occur. Spontaneous collaborations between transport units in such cases help to eliminate disruptions and may, for instance, make it easier to solve bottlenecks.

These mechanisms use different time horizons, but very similar methods. Agreeing collaborations results in contracts between the participating transport units. Compliance with such contracts is binding and non-performance incurs penalties. To nevertheless give a transport unit maximum flexibility in the planning of contracts as explained, there are mechanisms to dissolve collaboration agreements by mutual agreement of the parties involved.

4.4 Route Planning

For route planning, a transport unit has to find a route and book it through negotiation with a network operator, who is responsible for management and coordination of the network. The route finder offers possible routes across the rail network to a transport unit, taking into account scheduled use. It also provides information about the quality of each route and lists properties such as collaboration options, duration, cost, or length. Based on this information, cooperative planning as shown above can be initiated.

DOGMA, one possible realisation uses an ant-based algorithm for the route finder (see also e.g. [20], [21]). This offers a transport unit a number of possible routes, based on topological network information and the approximate predictable use. Through direct interaction with so-called network operator agents, a transport unit then books the slots it requires, possibly also naming a collaboration partner.

4.5 Transport

Once the transport planning process has been successfully completed according to the cooperative and route planning mechanisms described above, a consignment is transported by the transport units using an innovative operating concept, which comprises a basic concept and an advanced concept.

The main features of the *basic operating concept* and its requirements in terms of on-board and trackside infrastructures correspond to an ETCS level 3 operating concept (see also [22]). Trains are guided through the network without collision by using local trackside coordination and the distance-based moving block system. This allows shorter distances between trains than is possible with today's fixed-block operation.

The *advanced operating concept* has the option of dynamically aggregating and disaggregating train formations during a trip. This has additional operational benefits, such as a further increase of line capacity due to reduced distances between trains, and improved elasticity in operations to prevent and eliminate disruptions. Transport units are equipped with telematic and control units to use the advanced concept, and can thus aggregate into "virtual train formations" (see also [10], [4]). With the switch from the basic to the advanced operating concept, responsibility for train protection among the involved trains is transferred from the trackside coordination equipment to the transport units. Following the agreement of all participating transport units and coordination between them, a local communications network between the trains is established (see also [11]). With the additional use of distance sensors and distance control equipment, this allows a controlled penetration of interaction spaces, which are blocked for all other actors.

Since trains can be operated on the network using either the basic or the advanced operating concept, traditional train operations in accordance with ETCS level 3 can be combined with operations using "virtual train formations" on the same network. Trains equipped for the advanced concept benefit from their advantages, while trains that are not equipped can still use the network.

5 Simulation Experiments

The previously outlined concepts where implemented as an agent based system prototype in an experimental platform for simulation purposes [23]. In the following section, the basic simulation concept and setup as well as initial simulation results are described.

5.1 Simulation Concept and Setup

In order to gain maximum flexibility for the sender, a (semi-)continuous planning mechanism is regarded, allowing senders to place transport orders for an operational time window without a deadline. For simulation experiments, one time slice is extracted from the continuous planning process, focussing a distinct operational time window. Figure 3 schematically sketches the time slice in continuous planning for the operational time window $T_1...T_2$, which includes re-planning stimuli caused by incidents during operation.

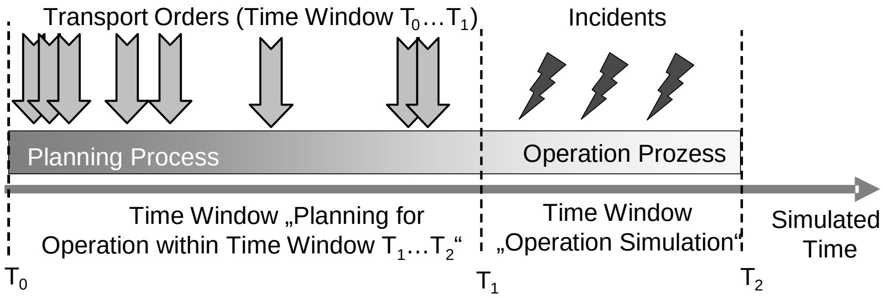

Figure 3: Basic simulation concept: one time slice for a planning process without deadline

Figure 4 sketches the setup of the simulated system by a stylized component diagram. Each component represents a distinct agent type, participating in the process indicated as an interface. The association to a process with a drawn line shows that the agent acts as a service provider, whereas the association using a dotted line announces the agent participates as a service user. The basic system partioning and agent allocation to the locally distributed sub systems (sender, electronic marketplace, fleet, transport units, infrastructure sections) are indicated by dotted blocks, showing that a major amount of functionality is placed in mobile transport units, i.e. train-side.

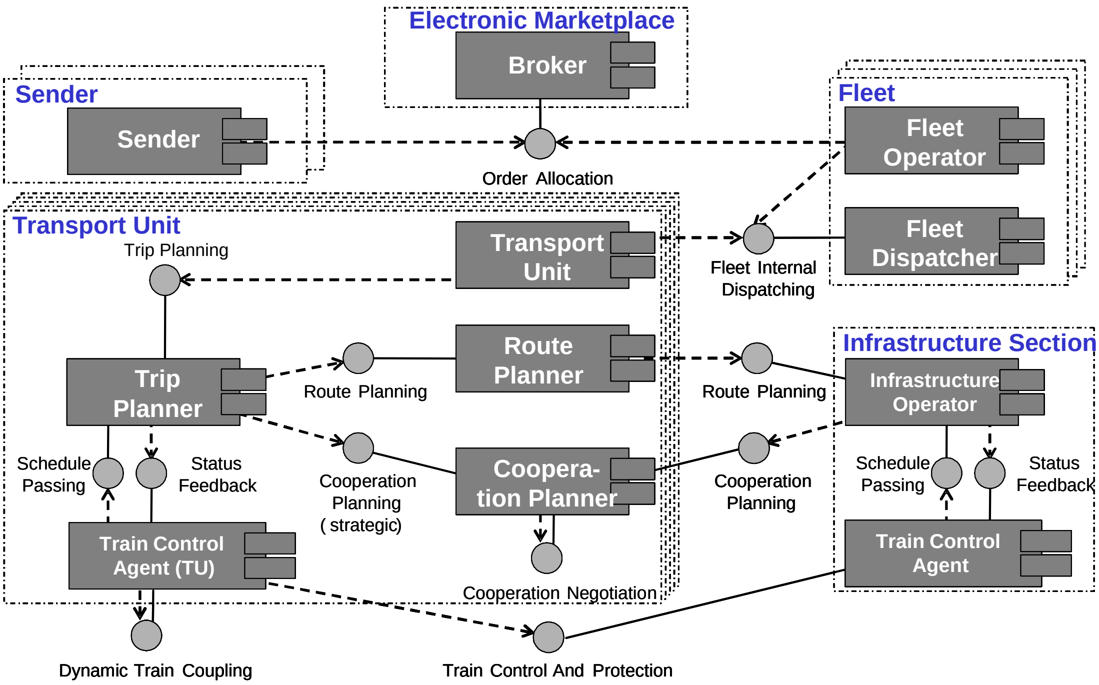

Figure 4: Setup of the simulated DOGMA system

5.2 Initial Results

In order to examine the DOGMA concept and prove basic operability, initial simulations have been carried out based upon the described setup. As an example, the following simulation results give an idea on fundamental effects arising from the interaction of agents following different individual strategies.

In a basic scenario, two parties of senders where regarded, either showing a short or a long termed demand behaviour. For distinct fleets, the acquisition strategies of the contained transport units where differentiated in terms of taking a high respectively a low financial risk in calculating bids for transport orders. Moreover, the effects of train coupling according to the advanced operation concept where examined by introducing a competition among cooperative and non cooperative transport units.

Figure 5 gives a qualitative overview on the effects arising from this scenario. It turns out that in general, due to the rise of operational capacity by introducing the advanced operation concept and because of the integrated planning mechanisms, short termed transport demand can be fulfilled properly, especially in case appropriate willingness to pay exists.

Moreover, it can be observed that fleets taking a high risk (e.g. fleet F.0 in figure 4) in order acquisition cause a large amount of fleet internal (in a first stage) and inter fleet trading activities (in a second stage) of transport orders which cannot be fulfilled profitably by the transport unit which once acquired the order. This however leads to a successive optimization of order allocation. The effectiveness of the different order acquisition strategies depends on boundary conditions to be defined, as e.g. penalties for re-sale of orders.

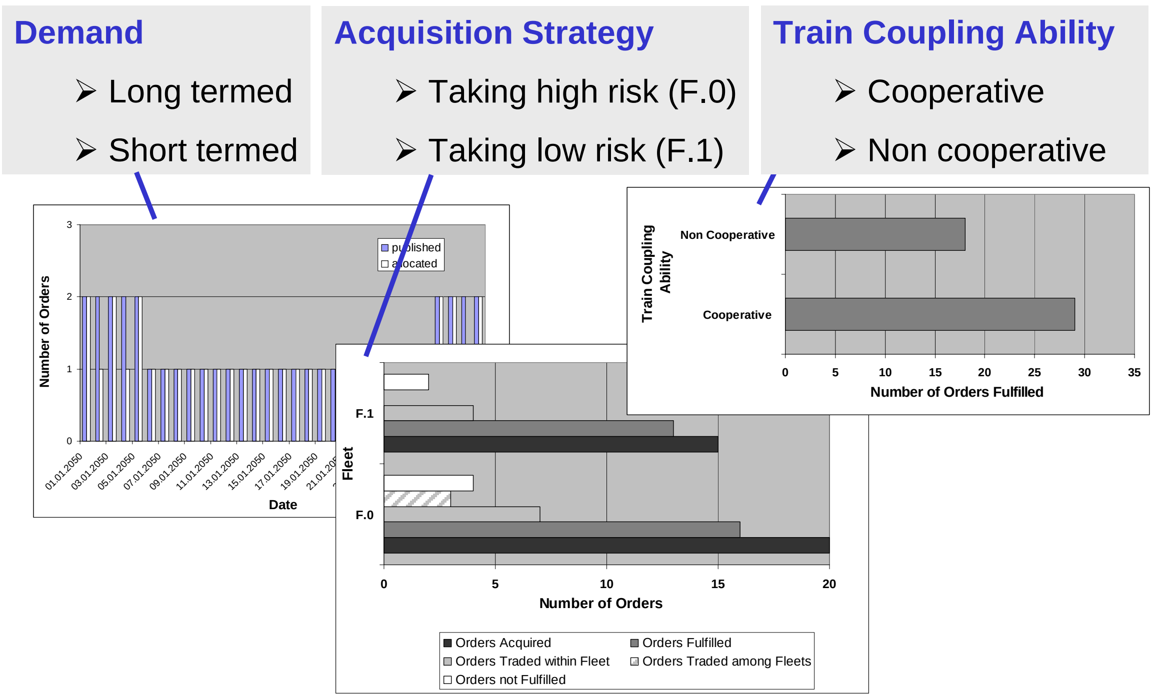

Figure 5: Simulation results for variations of basic strategies of senders, fleets and transport units

6 Conclusion

The solution presented and its implementation in the concept for operations and organisation, DOGMA, aim to provide a market-focused system for operations and organisation of rail freight transport, which integrates logistics structures that are suited to railway operations, and uses modified operating concepts. Given the system's high level of dynamism, flexibility and complexity, an agent based approach is useful. Basic customer demands for providing both flexibility and the ability to schedule are accommodated by interlinking the planning processes for a fleet's internal contract allocation with transport planning (route and cooperative planning) in a multi agent system, and extending planning times to include operations. This allows the use of very similar methods to accommodate long-term contracts, contracts awarded at short notice, and contract changes. Most of the individual planning methods and algorithms used are also agent based solutions.

The interlinking of planning and organisation mechanisms combined with the use of customized transport units and traditional trains, and a new operating concept for rail transport adds a component to the range of rail services, thus offering an alternative option to road haulage. Designing the operating concept as a downward compatible extension of the future European ETCS standard contributes fundamentally to increasing the acceptance and migrability of such an operating concept. However, given the European railway industry's conservative attitude towards innovations, the future implementation and introduction of such a system face great obstacles of a structural, technical, economic, administrative, and legal nature (see also [23]). Fundamental changes and political backing will be required in the coming years, for far-reaching innovations to help create a more attractive rail-based transport system.

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