A Framework on Centralised to Decentralised Logistics Control Structures Applied in Two Case Studies

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Abstract. Developments on digitalisation and automation in transport and logistics create new possibilities in the organisation of supply chains. New technologies can disrupt existing control structures, establish new forms of control and improve the efficiency and flexibility of operations. This paper provides a framework to analyse the trade-offs and conditions that best apply to each control structure from centralised to decentralised. A centralised control structure is characterised by one party (control tower) that collects and analyses data to come to optimal operational decisions on a system level. In opposition, a decentralised control structure is characterised by each unit in the logistics chain taking independent decisions (self-organisation) based on local intelligence and autonomy. A 2×2 control structure matrix is created, with each corner defining a different type of logistics control structure. The framework is then applied in two practical case studies in which simulation models are developed to show the impact of different logistics control structures. Results show the effects of different control structures in one supply chain and under which circumstances and for which type of logistics chain, each logistics control structure is most suitable.

Keywords: Centralised or decentralised organisation · Container logistics · Multi-agent simulation · Self-organising logistics (SOL) · Supply chain management

1 Introduction

The increasing technological development on digitalisation and automation in transport and logistics creates new possibilities in the organisation of supply chains. Real-time connectivity and improved data sharing enables innovative methods of decision making which can change the control structure of logistics operations. More (autonomous) data driven decision making can be applied in different control structures, ranging from central coordination (control tower approach) to decentral coordination (self-organising approach). On one hand, a central control structure is characterised by one party (control tower) that collects and analyses data to come to optimal operational decisions, which are then communicated to various parties in the logistics chain. Consequently, decisions are made globally based on globally-available information. This control tower approach

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offers potential for optimisation of efficiency at system level. In this way, the interests of the chain can be placed above individual interests, and standardised communication takes place via one system.

In opposition, a decentral control structure is characterised by each unit in the logistics chain (e.g. a parcel, a container, a vehicle or a hub) taking independent decisions (self-organisation) based on local intelligence and autonomy, aiming for more flexible operations. A mixed approach between centralised and decentralised control, could combine the advantages of both forms, aiming at improving efficiency for the operations that require a central organisation and providing flexibility for the operations that can be performed at a local level.

In a centralised control structure, the advantages of a centralised system are reduced communication errors within the chain, and a large degree of predictability and accountability. However, a lot of responsibility rests within one party, which makes this control mode sensitive due to a single point of failure. Questions whether logistics parties can develop a feasible control tower or whether data can be exchanged, processed, optimised and returned fast enough, are still open.

Self-organising logistics (SOL) comes into scope when operators and carriers make decentral decisions to organise their logistics operations and no longer require control towers or other centralised forms of decision making. Less communication and fast direct local response to unexpected events can be identified as organisational advantages, along with not having the requirement of developing, operating and maintaining a central control infrastructure. There are however questions on how supply chains can become more self-organising, what the impact is on performance and what properties are essential for successful implementation.

Building on a previous publication on the implementation of self-organising logistics from Quak [1], in this contribution we develop a framework to define different logistics control structures ranging from central to decentral. The aim is to analyse the trade-offs and conditions that best apply to each control structure, by applying this framework into two practical case studies. To do so, a two-step methodology was followed. First, a set of interviews and brainstorming sessions were conducted to answer the following research question: "What are the factors that affect the type of logistics control structure and what are their possible development directions?" Subsequently, two use cases were analysed with simulation models in order to answer the following research question: "What is the effect of different control structures and under which circumstances and for which type of logistics chain, is each logistics control structure most suitable?".

This paper is based on the research conducted for the SOLPort project (Self Organising Logistics in the Port), carried out by a consortium of the following partners: TNO, SmartPort, Port of Rotterdam, University of Twente, Pharox, Distribute, NPRC, Intel and Ab Ovo. The project was partly financed by TKI Dinalog (Dutch Top Sector Logistics).

2 Background

The term self-organisation refers to a dynamic process in which an overall order is achieved through local interactions between parts of an initially disordered system [2]. In the logistics sector, self-organisation can be found in hybrid forms in which elements from a centralised control structure and a decentralised control structure are combined using automated processes and real-time system information. Self-organising logistics (SOL) systems can be seen as a network of nodes of different nature: nodes can be locations operated by humans and supported by IT systems (e.g., seaports, container terminals and warehouses) but also intelligent moving objects that are capable of automated decisions (e.g., trucks and barges) [3]. These nodes should have access only to the data that is relevant to accomplish their tasks and should communicate with other nodes in the network to optimise the logistics chain. To achieve that, SOL-systems should ensure secure and efficient communication, extended sensors monitoring and adequate robustness [4].

Most studies on SOL systems focus on fully decentralised approaches. For example, Wycisk [5] describes how self-organisation can improve the performance of a logistics chain, allowing for more autonomy at a decentral and local level. However, as already explored in Pan [6], it is important that, although defined as decentralised systems, self-organising logistics should also be able to work towards a common goal and thus should be able to oversee the whole logistics chain. Moreover, recent studies started to take central coordination into account when exploring the possibilities of self-organising logistics. In Feng [7], a decentral agent decision-making framework with central coordination is developed, showing how including a vertical and horizontal collaboration can improve the system performances.

Linked to the work of Feng [7], this research explores decentral structures with a central escalation channel. This central escalation channel is activated when decentral agents deviate from the system boundaries (e.g., when key performance indicators are exceeded) to intervene and bring the system back to its standard values. While previous studies focused on SOL-systems as a decentralised control structure or on the combination of decentralised and centralised control, this research examines the differences between centralised and decentralised control and tests them on two case studies, to gain practical knowledge on the impacts that different control structures could have on a logistics chain.

3 Methodology and Research Setup

In the previous study from Quak [1], the possibilities of self-organising logistics were discussed through serious gaming sessions and living labs (i.e. real-life experiments). In this contribution, we broadened the scope and created a framework for analysing different logistics control structures, ranging from completely centralised (control tower approach) to fully decentralised (self-organising approach), considering also in-between approaches. Subsequently, we applied this framework to two case studies, to quantitatively assess the different control structures with simulation models.

The research was structured in two phases. First, interviews and brainstorming sessions were conducted to define the framework. Consequently, the framework was tested through the simulation modelling of two case studies.

3.1 Interviews and Brainstorming Sessions

To define the important aspects and development directions of logistics control structures, four interviews and brainstorming sessions were conducted between August and December 2018 with experts in the logistics field. The aim was to enrich the existing definitions of centralised and decentralised control structures. As a result, the first research question is answered: "What are the factors that affect the type of logistics control structure and what are their possible development directions?".

The interviews started with defining the concepts of centralised and decentralised control structures. The discussions then moved towards the aspects of new mixed control structures, which led to the creation of a control structure matrix with two axes, and the definition of four logistics control structures. During the interviews and the follow-up brainstorming sessions, each control structure was analysed, to understand the preconditions and the perspectives that should be taken into account. Current practical examples of control structures were put in perspective with respect to the control structure matrix, so to understand how logistics chains are currently organised and how they could be improved in the future.

3.2 Case Studies and Simulation Models

In the SOLport project, two case studies (i.e. practical experiments) were performed, in which different control structures (from centralised to decentralised) were compared with each other. The first case study concerns dry bulk inland shipping, whereas the second case study deals with container hinterland transport by road. In the elaboration of these experiments, a link was made with the control structures previously formulated in the framework, which makes them extensive examples of an application of different logistics control structures.

To analyse the case studies, simulation models were used. The simulation models were developed and calibrated based on real data. To gain insight into the effects of the different control structures applied to different logistics chains, multiple scenarios were run for each case study. The results of the simulation models provide an answer to the second research question: "What is the effect of different control structures and under which circumstances and for which type of logistics chain, is each logistics control structure most suitable?".

Set Up Case Study 1 – Dry Bulk Inland Shipping. The first case study was performed by the inland shipping cooperative NPRC and the research institute TNO, and pertains the inland waterway transport of bulk goods from one production facility to three different consumption locations, which is fully executed by barges. The consumption locations have limited stock capacities and the barge fleet has to guarantee the receiver a security of supply, i.e. a minimal amount of available stock.

The current logistics control structure consists of a central planner that oversees the process and allocates load to barges, while ensuring sufficient stock at the consumption locations. Each barge in the fleet is an individual enterprise with their own interests and preferences. This gives the skippers the urge to have a role in the decision making process of the operations they have to execute. The details on the physical and organisational flows were provided by barge cooperation NPRC and the receiver in this supply chain. For the details regarding the planning and execution processes, the logistics manager at NPRC and one of the barge skippers had been interviewed. Based on the information collected in the interviews, as well as real-world data, scheduling heuristics have been designed and integrated into a newly developed simulation model.

Description of the Simulation Model. An agent based model was developed to simulate this case study. Agents are the barges, the production facility and the three consumption locations. Agents simulate both the physical processes of sailing, berthing and (un)loading and the organisational processes of shipment and (un)load slot allocation. The model provides an aggregate representation of the essential physical processes as this research focusses on the organisational aspects of logistics control structures. Three different scenarios were analysed: one with a centralised control structure and two with a decentralised control structure. The first scenario is a representation of the current practice with a central planner. The decision heuristic of the central planner was implemented by assigning barges to the unload location with the earliest expected stock depletion. The second and third scenarios represent two forms of self-organising logistics where barges decide for themselves to which location and at which unload slot they will go, based on their own specific preferences. The difference between the second scenario ('standard decentral') and the third ('flexible decentral') scenario is the time at which the unloading decision is made by each individual barge. In the standard decentralised scenario the choice is made at the same time as in the centralised scenario: both the load and the unload slots are immediately scheduled as soon as the barge is empty and leaves the consumption location to sail back to the production facility. In the flexible decentralised scenario, decisions about the unload slot are made by the barge only a few hours before it reaches the unload location. In this way, more accurate information on delays and stock levels can be taken into account.

To prevent undesired outcomes in the two SOL scenarios, an escalation method was implemented. In the case that an unload location foresees critical low stock levels, it can claim priority for a barge visit and therewith overrule the preferred location decision of the barge. Implementing this heuristic prevents unwanted stock depletion, but also reduces decision autonomy of the barge skippers. In the case that multiple locations use this priority claim simultaneously, then the central scheduling rule of the earliest stock depletion is used.

Set Up Case Study 2 – Container Hinterland Transport by Road. The second case study is performed by Distribute and Combi Terminal Twente (CTT) and concerns self-organising logistics for the last-mile container transport from a hinterland container terminal by a fleet of trucks [8]. Each container has its own specifications, such as client location, and pick-up and delivery windows. The challenge is to assign containers to trucks such that all containers are transported in an efficient manner.

The current logistics control structure consists of human planners that manually assign containers to trucks with a centralised decision-making process. The assignment is based on a list of attributes, which can change and can be updated by each party during the process.

Description of the Simulation Model. To simulate different control structures (from central to decentral) a multi-agent simulation system was developed, in which containers and trucks are represented as agents. The simulation model explores seven scenarios with their own control strategy with different levels of self-organising logistics. These decentralised decision-making processes enable the agents to autonomously schedule their activities following a local sealed-bid auction mechanism. The auction mechanism is based on the Vickrey auction from Mes [9], in which agents only have information from their neighbours (decentralised approach) using sensors and local communication protocols. When a container reaches the terminal, it opens an auction and each truck can place a bid expressed by price, expected departure time and expected arrival time. Once the bid is accepted, the container communicates the decision to the winning truck, creating a new schedule. In some of the scenarios, a scanning mechanism is triggered after a fixed amount of time (threshold), in which a human planner or the SOL-system re-evaluates or confirms the decisions.

4 Framework for Logistics Control Structures

During the first phase of the research, as described in Sect. 3.1, interviews and brainstorming sessions were conducted to define the framework for logistics control structures as described in Hopman [10]. Gathering the information provided by the experts during the interviews, it was possible to identify two important criteria for defining the type of control – decision level and information – and their two possible directions – global or local. As a result, a control structure matrix is created, with four logistics control structures (Fig. 1).

Decisions can be made on a local or global level. In the case of global-level decisions, there is a (third) party who oversees (a part of) the logistics chain and makes operational decisions for different agents (e.g. logistics parties or vehicles). In the case of local-level decisions, every logistics party in the chain is responsible for its own operational choices.

Information can be exchanged on a global or local level. In the case of global-level information, all the necessary data is available and exchanged through the entire logistics chain. In the case of local-level information, data is known only within a specific party and it is shared in a very limited way. This limitation concerns the number of parties (e.g., data is only shared with the previous and the next parties in the logistics chain), but also the content of the shared data (e.g., only aggregates or specific data that are required for the logistics process are shared).

4.1 Control Structure Matrix

Based on which level decisions are made and information is exchanged, a 2×2 matrix is created (Fig. 1), with each corner defining a different type of control structure. The figure presents four possible controle structures along the two axis, level of information exchange and level of decision making.

The top left corner defines a central logistics organisation with one large control tower. Decisions are made on a global/central level based on information that is available

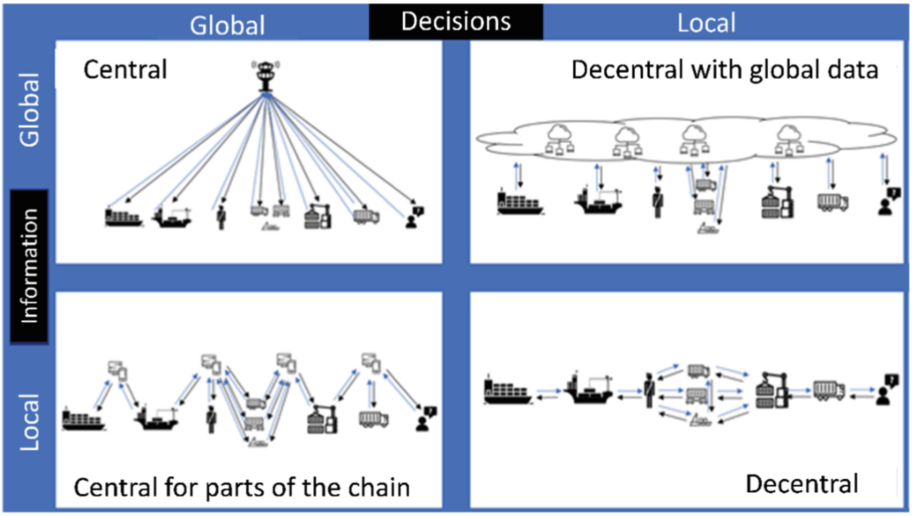

Fig. 1. The 2 × 2 matrix with four different control structures.

on a global/central level. The advantage of this control structure is that the control tower has the overview of all processes and can optimise decisions on a system level. Some of the disadvantages include having a single point of failure, a high chance of mistrust from companies, low willingness to share data with the control tower, the complexity of collecting and processing lots of data (possibly in a standardised way), and optimise processes and communicate actions with all stakeholders in a short period of time. It is possible to invest in and maintain back-up facilities to improve uptime of a central control tower, but this does not take away the reliability of the supply chain on the presence of a control tower. This structure is especially relevant for situations where the system perspective is very important and for situations that are rather predictable.

In complete opposition, the bottom right corner defines a decentral logistics organisation, also called self-organising logistics. In this control structure, agents in the logistics chain can make their own (local) decisions based on the information they have directly available. Advantages are that only a limited amount of data has to be shared and that agents can optimise their own decisions in a responsive and flexible way without dependency on a central organisation, which creates high autonomy. A disadvantage is that there is no optimization at system level which might lead to unwanted results at system level. Escalation levels should be introduced to avoid this. This structure is most relevant in situations that are very dynamic, where fast and flexible decisions are required often and in situations where autonomy of agents is important.

The top right corner combines local-level decisions with globally-shared information in a decentral logistics organisation with global data. Information on logistics processes and possible disturbances is sent to a global data infrastructure with a standardised way of communication and information is available for all the parties involved in the logistics chain to make operational decisions based on individual performance indicators. This control structure can potentially allow for a better utilisation of assets and less delay in the logistics chain, using as much as possible real-time information. On the other hand, since different parties are involved in the logistics chain, it might be a challenge to properly coordinate all operational processes. Moreover, the lack of predictability (due to the local-level decisions) can be harmful for long-term investments. The application of a decentralised logistics organisation with global data is suitable when coordination and data exchange between different parties are crucial for making individual decisions in dynamic circumstances.

Lastly, the bottom left corner combines global-level decisions with locally-shared information in a central logistics organisation with several smaller control towers. Each of the smaller control towers (e.g. an organisation or a digital platform) oversees and manages a specific part of the logistics chain by collecting locally-shared information and by making operational decisions. To realise this control structure it is important that the control towers are jointly accepted by the parties involved and that they are able to efficiently collect and process data. Compared to central operations, the smaller control towers can better cope with dynamic conditions, while the system perspective is taken into account and clarity about the motivations behind decisions is provided.

An overview of the characteristics and trade-offs for each control structure is shown in Fig. 2.

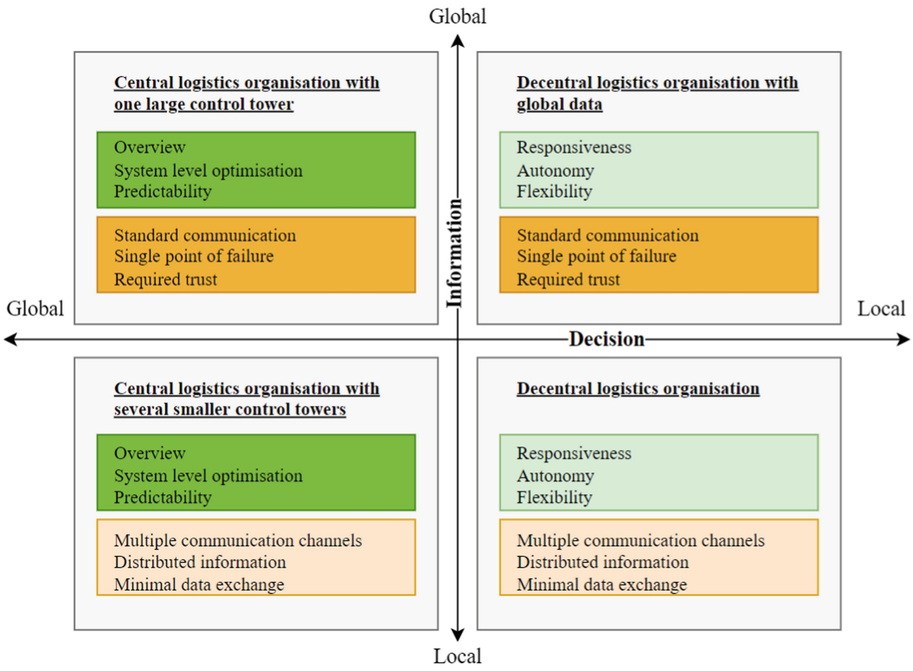

Fig. 2. Control structure matrix with characteristics for global (dark green) and local (light green) decisions and for global (dark orange) and local (light orange) information (Color figure online).

5 Application of the Framework in Two Case Studies

The second phase of the research includes the application of the logistics control structure framework in two case studies: dry bulk inland shipping and container hinterland transport by road. Different logistics control structures were simulated for each case study. All results can be found in Fransen [11] and De Bruin [8] and are summarised below.

5.1 Dry Bulk Inland Shipping

The developed simulation model represents real world operations and performances in the case of a centralised control structure (current practice) and was used to compare three different logistics control structures (*centralised*, *standard decentralised* and *flexible decentralised*). The main difference between the scenarios is how barges are assigned to the unload slots and locations.

Results show that both a centralised and decentralised approach are able to supply the requested annual volume of dry bulk to the consumption locations. The variation in turnover per ship is much bigger in the decentralised scenarios, since in this control structure, skippers choose their unload location based on individual preferences, which has a clear effect on the distribution of ships across the different locations, hence on the turnover.

For what concerns the stock levels, results show that different control structures lead to different stock levels per unload location. In the centralised control scenario, there is less variation and thus more stability and certainty regarding the stock levels. In contrast, both self-organising logistics structures (decentralised scenarios) have a much greater variation in stock levels, which is caused by the individual unload preferences of the different barges. To ensure the security of supply for the receiver, an escalation method was implemented in the decentralised scenarios, but the simulation model still shows that decentral organisation can lead to sub-optimal performance from a system perspective.

Another aspect that differs between centralised and decentralised control structures is the priority claim by consumption locations. In case of self-organising logistics, a priority claim is often needed to ensure security of supply while dealing with the higher variation in stock level. Location preferences by skippers play an important role in the priority claim that is required for (other) consumption locations and therefore the preferences of skippers have a high influence on the outcome.

For the shipper, security of supply and a stable stock level are extremely important. To guarantee this, a central control structure is more suitable. On the other hand, the interests of a skipper are better represented in the case of a decentralised control structure, in which they have more flexibility and autonomy. As an inland shipping cooperation, NPRC is the connecting factor between skippers and shippers and, when choosing a logistics control structure, a trade-off has to be made between different interests of these parties. It is a balancing act with the freedom of choice for skippers on one hand and the security of supply for shippers on the other hand, which variation can be assessed by setting different system rules. Based on the results of the simulation and the characteristics of the case study (e.g. a predictable flow of goods and a well-organised supply chain), a centralised control structure is most suitable. In case that a decentralised control structure is chosen, it is important to create system rules in such a way that skippers only have freedom of choice within the limits necessary to meet system requirements. When the system rules are more strict, there is less freedom of choice for the skippers and the situation will be more similar to a centralised control structure.

5.2 Container Hinterland Transport by Road

The developed simulation model represents real world operations for the container hinterland transport by road at CTT, and was used for comparing seven different scenarios, with each scenario having an increased level of self-organisation.

Results show that increasing the level of self-organisation does not lead to substantial changes in meeting the established deadlines. The differences in the on-time deliveries are less than 1% and thus considered neglectable. Furthermore, increased levels of self-organisation do not bring many changes in the loading and unloading turnaround times. However, these average turnaround times are significantly lower in the two scenarios in which overruling of the system is not allowed.

The simulation of scenarios with a different level of self-organisation, leads to interesting results on the efficiency of last-mile container transport. For configuring a self-organising fleet of trucks, trade-offs should be made on different performance aspects for the container terminal and its clients. A positive aspect of a more self-organised control structure is the opportunity of continuously scanning for better options, which allows for merged trips (i.e. one trip in which the delivery of a container to one client is combined with the pick-up of a container at another client). Having more merged trips leads to higher efficiency in transporting a container. Therefore, within a SOL-system agents can increase the percentage of loaded driving time and consequently decrease the total driving distance. The simulation model shows that the self-organising scenarios have a better performance on driving time and driven kilometres. However, this also leads to a more dynamic system with spontaneous overruling and merging trips, which requires more communication between trucks and thus more connectivity and flexibility from the truck drivers.

Based on the results of the simulation, a decentralised form of control should be preferred for the container hinterland transport at CTT. Introducing a SOL-system drastically reduced the dependence on manual planning and increased operational performance, which in turn leads to reduced costs. The optimal degree of self-organisation should be evaluated for each specific case study and preferences with respect to the different performance indicators using simulation.

6 Conclusions and Further Research

This research defines a framework to analyse different logistics control structures and tests this framework by applying it in two case studies.

The first part concerns the creation of the framework and aims to answer the following research question: “What are the factors that affect the type of control and what are their possible development directions?”.

Based on a set of interviews and brainstorming sessions, it was possible to identify the trade-offs that should be made between a completely centralised control structure and a completely decentralised one. Consequently, a 2 × 2 matrix was created, with the axes decision-level and information-level and with the two possible directions of global and local (as shown in Fig. 2). The results are four logistics control structures, each corresponding to one quarter of the matrix: central logistics organisation with one large control tower, central logistics organisation with several smaller control towers, decentral logistics organisation with global data and decentral logistics organisation with local data.

The second part concerns the simulation analysis of two case studies, to test the framework and to answer the following research question: "What is the effect of different control structures and under which circumstances and for which type of logistics chain, is each logistics control structure most suitable?".

Simulation models were developed for the case of dry bulk inland shipping for NPRC and the case of container hinterland transport for CTT. For the case study of dry bulk inland shipping, three different scenarios were simulated, one with a centralised control structure and two with a decentralised control structure. For the case study of container hinterland transport, seven scenarios were simulated, each with an increased level of self-organisation. By comparing the performance indicators of each scenario and taking into account the real world characteristics of the case studies it was possible to identify the most suitable control structure for each of the case studies and therefore answer the second research question.

Both case studies show that self-organisation can be successfully implemented for the logistics operations in the simulation models. Applying self-organisation in real world dynamics requires an approach that can handle undesired outcomes at system level (e.g. an escalation mechanism). In current centrally-organised logistics, this is generally resolved by human flexibility.

The case study of dry bulk inland shipping has a stable and predictable flow of goods, it is well organised and there is the need for a high security of supply at the consumption locations. Simulation results show that a decentral organisation leads to a decrease on performance levels, such as the stability of stock levels. Consequently, a central control structure is more suitable. With respect to the matrix in Fig. 2, this case study should be positioned in the top-left section, with global-level decisions and globally shared information. A self-organising logistics control structure is advised only in the case that the benefits outbalance the decrease in system performances, or when a control tower approach with globally-available information is not achievable.

The case study of container hinterland transport by road is defined by a flexible chain, in which minimal data is exchanged and a high responsiveness is required due to the dynamic circumstances. Simulation results show that performances can be improved if a self-organising control structure is introduced. The main benefit lies in the possibility of decision overruling, which represents a very flexible way of planning. For these reasons, a decentralised control structure is more suitable. With respect to the matrices in Fig. 1 and Fig. 2, this case study should be positioned in the bottom-right section, within local-level decisions and locally shared information.

Choosing a feasible logistics control structure is not a choice between two extremes (central and decentral), but rather identifying a point on the scale between central and decentral such that a specific control structure best suits the different interests and needs of the parties involved. In this context, more research is needed to find the balance between a centralised and decentralised control structure. On a general term, more practical use cases are required to study the effects of different control structures on the performances of a logistics chain, and to understand how to implement a new control structure in practice.

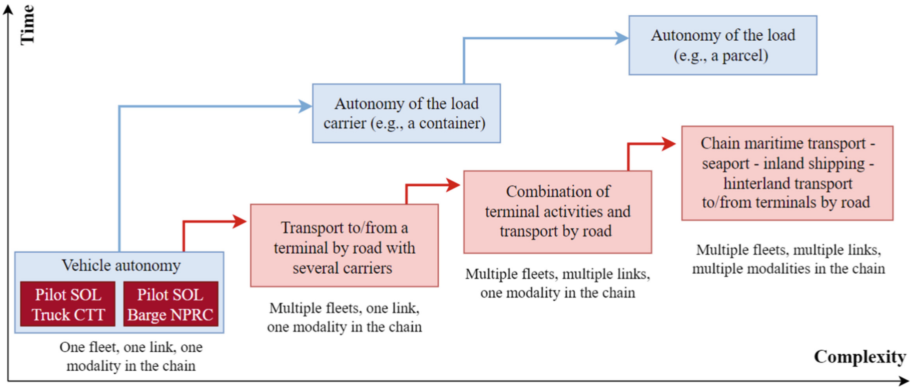

Fig. 3. Vision for further research on self-organisation.

The current research can be enriched in two ways, as displayed in Fig. 3. On one hand, future studies should focus on placing higher intelligence in a lower level of the chain (blue development in Fig. 3), such as assigning autonomy at a load carrier level (e.g., a container) or even at a load level (e.g., a parcel). On the other hand, the focus should be on extending the scope of the logistics chain (red development in Fig. 3), going from a configuration with one fleet, one link in the logistics chain and one modality (like in the NPRC and CTT case studies), to a configuration with multiple fleets, links and modalities in the logistics chain.

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