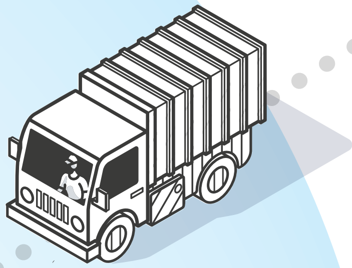
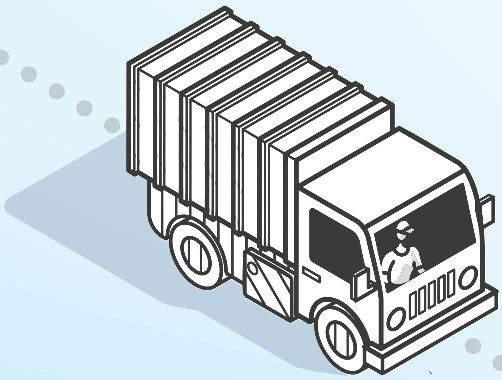
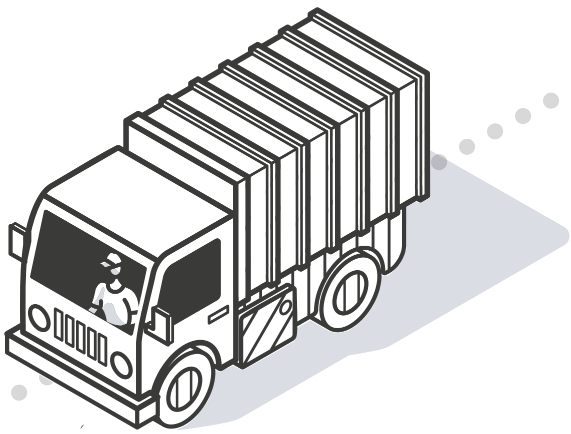


Letting Digital Twins Run the Show:

Exploring Possibilities of Letting Vehicles Plan and Organise Transportation Themselves





whitepaper

TNO

Letting Digital Twins Run the Show:

Exploring Possibilities of Letting Vehicles Plan and Organise Transportation Themselves

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Abstract: In this paper we present a way to organize logistics entirely by decentral decision-making. This is achieved by implementing a degree of intelligence in the digital twins of a fleet of trucks and subsequently fully yielding autonomy from planners to the fleet.

1 Introduction

In the last decennia logistics has changed tremendously. Supply chains have gotten more efficient to meet an increase in transportation demand within the capacity constraints of the global logistics network.[1] Recent developments in information technology play a key role, but technology is also a source of concern. We have witnessed the rise of global track and trace systems, but widespread integration between supply chain partners is still hampered by security threads and privacy issues.[2]

In this paper we propose an alternative way of organizing the operational planning of a logistics system. We will start with a history lesson explaining the reasons why distribution systems are designed the way they are, and why this might be problematic in an integrated supply chain.

We will then propose a decentralized version of such a system. This means that we are smartening up individual assets, such as trucks and containers, and let them make the decisions instead of humans. We will discuss the technology driving this approach and exemply it with a feasibility study. There are many application areas to which such systems may be applied and those are shortly discussed in the last section.

Enjoy the read!

1 *UNCTAD (2019). Review of Maritime Transport. Retrieved from https://unctad.org/en/PublicationsLibrary/rmt2019_en.pdf*

2 *Clausen, U., De Bock, J. & Lu, M. (2016) Logistics Trends, Challenges, and Needs for Further Research and Innovation. In: Lu, M. & De Bock J. (Eds.) Sustainable Logistics and Supply Chains (pp.1-13). Contributions to Management Science. Springer, Cham*

2 A HISTORY LESSON IN THE DESIGN OF DISTRIBUTION SYSTEMS

Distribution of cargo by a single logistics service provider is typically a centralized affair. This means that the decision making is done by a central entity. An example of this is displayed in Figure 1. A planner receives a riddle as input, performs some thinking and produces a planning which he records in a software system and then communicates to the truck drivers and possibly his customers.

It should be noted that this is a very simplified example. A container might have hazardous cargo and a close cut-off date, a truck might have an emission label which restricts its drivable area, and a driver might not like to stay overnight.

It should also be noted that many capabilities reside in the planner. The planner is able to receive information, process this information, make an informed decision, act upon it, and memorize large parts of this process (or in the very least record this in a transport management system).

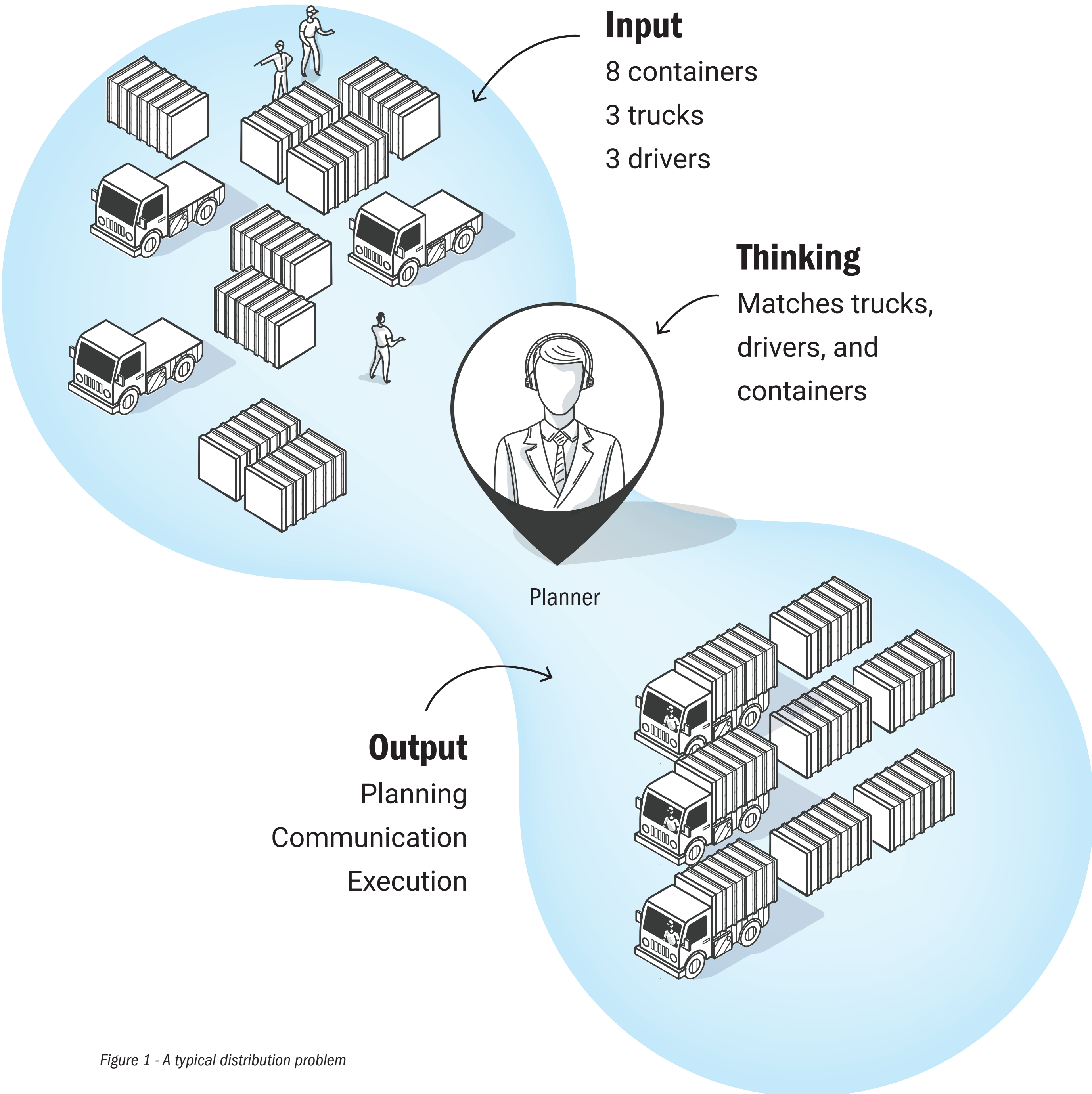


Figure 1 - A typical distribution problem

This pattern of organization can be encountered pretty much everywhere in logistics. The reason for this makes sense historically. The tasks performed by humans in the example above can currently not be done by objects such as trucks or containers. Even before the introduction of software, human planners managed this process with pen and paper. Software was introduced to serve as a long-lasting memory, to make communication faster and more efficient and to support human decision making in an increasingly complex world.

The continuous drive for cost reduction demanded more efficient processes.Synchronisation of internal and external processes requires the sharing of data and track and tracing systems for cargo. Increased digitization provides the required visibility and thus so-called control towers were introduced. However, the decentralized nature of a supply chain makes the degree of visibility dependent on external partners.

Up to today many logistics service providers are aspiring the situation depicted in Figure 2. If one has full supply chain visibility than one is able to plan and execute its processes in the most efficient manner. However, only in very exceptional cases, a single company will be able to control a complete supply chain from front to end. Even situations where companies collaborate, monitor and control through some entity on a higher level in a limited part of the supply chain are rare.

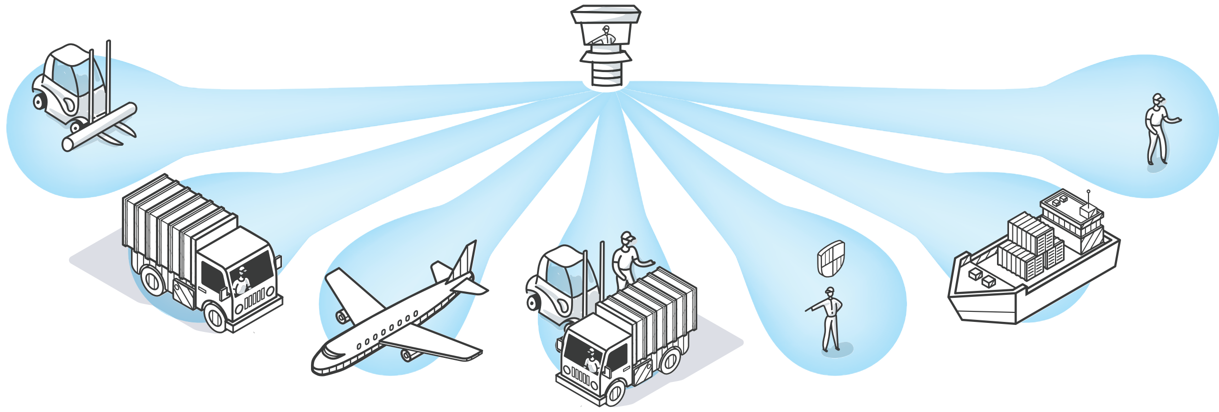


Figure 2 - Aspiring situation

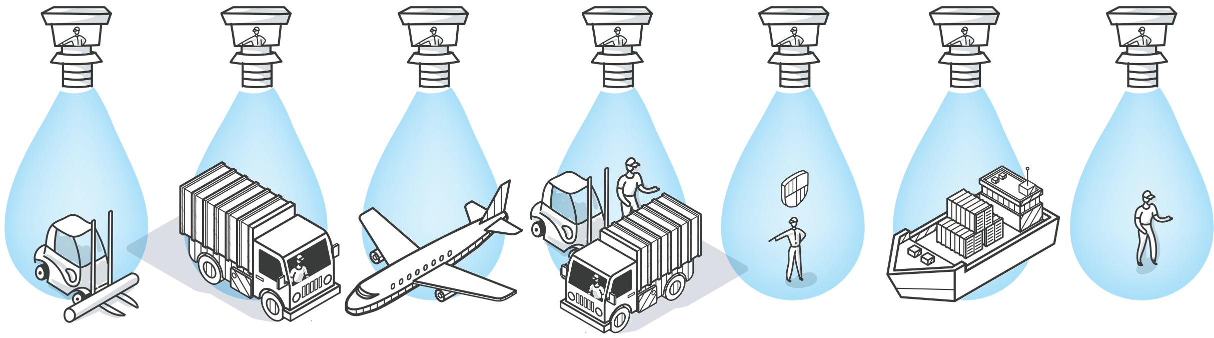


Figure 3 - Situation in practice

What happens in practice looks a lot more like Figure 3. Each player in the supply chain is individually gathering as much information as possible to efficiently (and effectively) optimise its own processes. Wherever these processes depend on other players data is shared through phone calls, emails, documents, and API connections.

The problem with this is that information resides in many places. The status of goods is known somewhere by someone, but when these goods are not under your control you have no way of knowing that the status reported in your control tower is correct at a given point in time.[3]

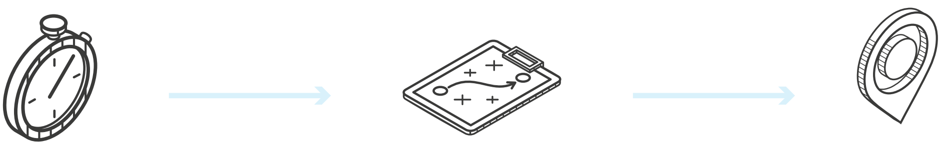
3 Dalmolen, S. (2013, August 12). Connectivity key voor ketensamenwerking. Retrieved from https://www.logistiek.nl/supply-chain/blog/2013/08/connectivity-key-voor-ketensamenwerking-101130649

This problem is enlarged because companies tend to develop ERPs (Enterprise Resource Planning systems) and TMSs (Transport Management Systems) with the goal of managing all information. The complexity of such a system naturally enforces standardisation. Standardisation then inevitably leads to work-around processes, because your customer demands might not match the standard process. Now information resides in the heads of people and is no longer in the system that manages all information.

Given this lack of visibility, planners across the chain can only decide between options that are limited by what they think they know.

3 Extreme Decentralization as Viable Alternative?

When looking at human mobility, one will discover a remarkably different system of distribution. The personal decision process of the same planner of Figure 1 might look a lot like what is depicted in Figure 4. What is remarkable is that every single planner, individually, goes through a similar process: with slightly different inputs, a slightly different manner of thinking, which leads to slightly different outputs. These outputs in most cases will lead to a result that is satisfactory for the planner who initiated the action.



Input:
- Leaving work at 5pm
- Trains are delayed
- Pickup kids before 6pm
- F1 is on at 6pm

Thinking:
If I take a taxi, I can pick up the kids and be on time for F1

Output:
- Order taxi
- Inform partner that I'll pick up the kids

Figure 4 - Each planner individually plans his own transportation

The reason this differs so much from logistics is that a human planner has the capability to communicate, to think, to decide, to act, to memorize this process and to learn from it. Vehicles and cargo typically lack these (human) functions. State of the art technology, however, allows us to create digital twins of supply chain assets that do possess many of these functions, with the exception of physically acting.

Is it is sensible to yield these (human) capabilities to a virtual representation of a physical object?

Under the assumption of complete data and complete control we think decentralizing logistics planning is not the ideal solution. In a controlled environment, say a stack of reefer containers, it makes sense to monitor temperature in a central unit, adjust where needed, and sound an alarm if anything goes wrong. This, however, is an example of a very unique case within a supply chain. Typically, there are many dependencies, each shipment has slightly different characteristics, each shipper has slightly different preferences, incidents and disruptions might occur and there is no single central command center to react to these incidents, instruct supply chain players and take care of cargo characteristics and wishes of the end customer.

A decentralized logistics system where digital twins run the show may be compared with our human mobility systems. There is a need for ground rules: stop in front of red sign, give right of way, drive no faster than 100 km/h, but within the bandwidth of these rules each human decides for himself how fast to drive and where to go. The role of a planner in the logistics analogy then changes from commander to a teacher who sets the rules for his pupils, monitors progression, and adjust thinking where needed in order to meet some specific goal.

The state of equilibrium that results from the behaviour of individuals in a traffic system is known as a Wardrop equilibrium. In a Wardrop equilibrium each individual chooses the best route from alternatives because of congestion. Note that this is different from Wardop's second principle, the system optimal, where all users cooperate in choosing their routes to create a situation where the system is used as efficiently as possible.[4]

This same concept can be applied to digital twins in a decentralized logistics system. Each twin is choosing the best option from alternatives, but should in some way cooperate to avoid system congestion as much as possible.

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4 Wardrop, J.G. & Whitehead, J.I. (1952). Some Theoretical Aspects of Road Traffic Research. Proceedings of the Institution of Civil Engineers.

4 The Anatomy of a Digital Twin

A digital twin is defined as the replica of a living or non-living physical entity. This means that it is entirely possible to create a digital twin of a human planner or of an entire terminal, or even a supply chain. At TNO, we apply the concept of a digital twin to assets utilized in a supply chain. Examples of these are mobile assets, such as vehicles, vessels, cranes, and conveyor belts, and immobile assets, such as containers, pallets, and boxes. We then use the characteristics of these assets as the base of its virtual representation and add some extra features.

These extra features include:

1. A database: We like our digital twin to memorize its characteristics and decisions
2. A means of communication: Our twins need to be able to interact with other (human) agents
3. Intelligence: When information can be communicated, and decision can be made, we'd like to have our twins make intelligent decisions

When comparing these to the characteristics of human planners discussed in the previous chapter, we only lack the ability to act.
For immobile assets this will forever be a limitation. However, with

autonomous driving on the horizon this is a capability that could be added to mobile assets in the foreseeable future.

Of these three features, intelligence, is by far the most challenging aspect. Some ground rules may be programmed in with simple business logic, but in logistics a degree of coordination between assets is required to achieve high efficiency.

The environment in which these assets operate is dynamic, arguably agents need to be able to react to these changing environments. Ideally they should even be able to adjust their logic by learning how to react to a new reality.

Is it possible to replace central planning and command with smart agents that take care of planning and transportation themselves? Or to make it more concrete: Can the trucks of Van Berkel Logistics organize themselves?

5 FEASABILITY STUDY WITH VAN BERKEL LOGISTICS

Van Berkel Logistics is a logistics service provider located in Veghel, the Netherlands. They operate two inland-terminals, several barges and a fleet of trucks. The network looks roughly as displayed in Figure 5. There are three types of container transports: on terminal, region, and port.

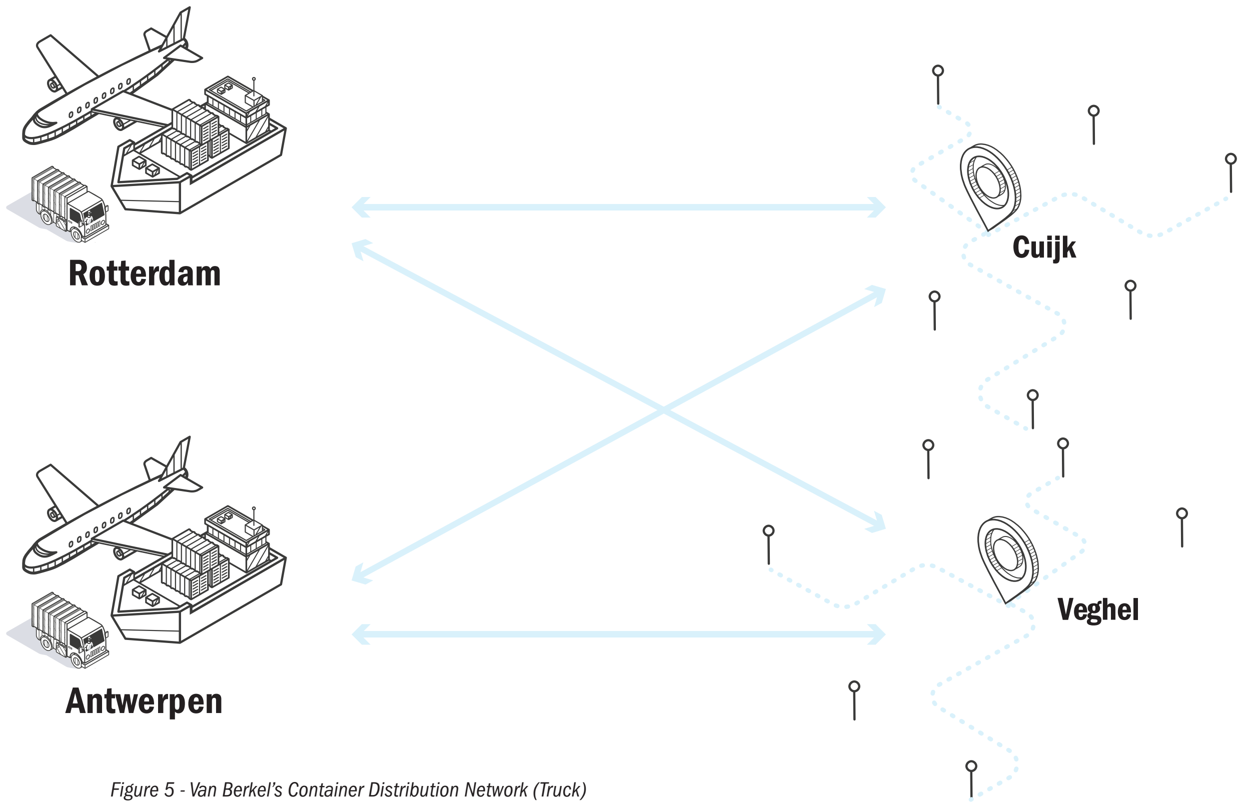

Figure 5 - Van Berkel's Container Distribution Network (Truck)

Orders are coming in through a booking desk and typically consists of both an import (terminal to customer) and export (customer to terminal) order. At the end of each day a team of planners collects all bookings and assigns them to trucks and drivers. During the day execution is monitored and bookings are re-assigned when required.

Our aim was to develop a completely decentralized method for running this logistics operation. To limit the scope we decided to only look at trucked container bookings (single loads). The architecture displayed in Figure 6 was created. The core components are the simulation manager, message broker, agent generator and the agents itself. The simulation manager serves as a replacement for the booking desk. Based on historical data we random sample bookings from a dataset provide by Van Berkel. These bookings are then published on the message broker. This is a piece of software based on Apache Kafka. It works much like a group Whatsapp. A topic (group) is created and other systems may subscribe and publish on this topic. The message broker, thus, is the center of communication in this distribution network. When a simulation is started the simulation manager also publishes some commands to initiate agents. These commands are picked up by the agent generator who then initiates our agents (digital twins of physical trucks) with the characteristics contained in the command.

These characteristics define for a large part what a truck is. The main characteristics include driver, max load, emission category, number of axles, sleeping cabin, and home base. Next to characteristics the truck agents are programmed to organize and schedule transports in a decentralized manner.

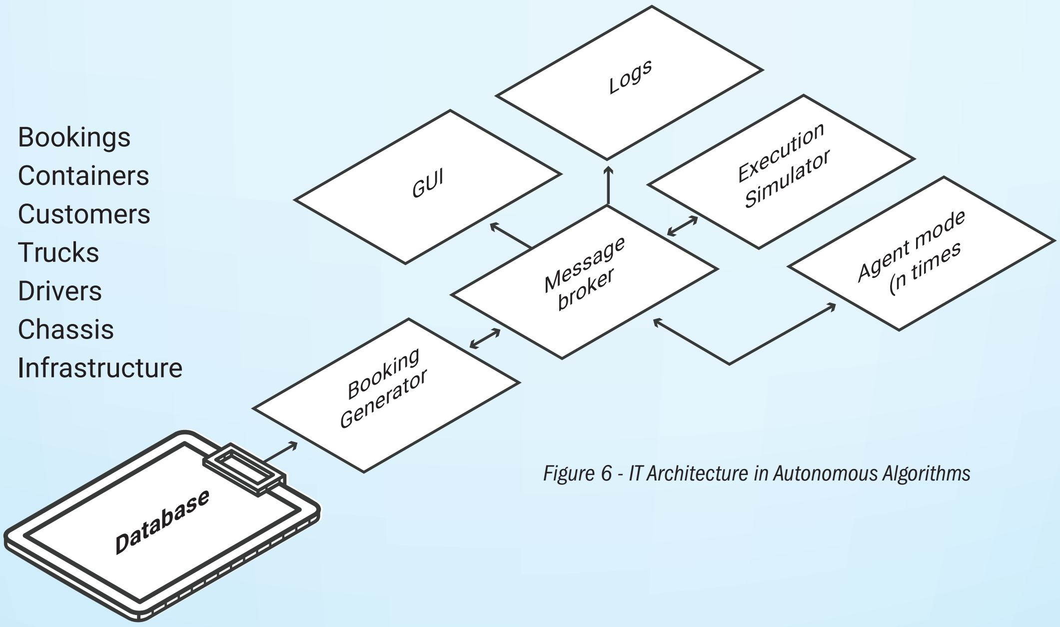

Figure 6 - IT Architecture in Autonomous Algorithms

Once an agent is initiated it will start listening for incoming orders. When finding an order on the message bus each agent goes through a decision tree to evaluate the order on a set of criteria. An example of this is the requirement that the truck meets the European emission standard Euro 6 if the origin or destination of the order is a terminal in Rotterdam. If a truck does not meet the criterium it will ignore the order.

For the orders that meet the truck's criteria costs are calculated. A cost function typically looks like this:

cost_function.py loss_message.json

```python
cost = ((total_distance_km * agent_info['distance_km_costs'])
        + (total_time_h * agent_info['time_h_costs'])
        + late_delivery_costs)
        * truck_type_penalty
```

It consist of four components that calculate the costs for a given transport based on the distance, the expected duration, a penalty for a late delivery, and a penalty for the truck type (it is prefered Euro 6 trucks to do transportations to sea terminals rather than region work).

After calculating the costs for several orders each agent will sort the orders and start publishing messages. A typical message might look like this:

loss_message.json cost_function.py

```json
{
    "event": "new_loss_message",
    "loss_message": {
        "truck_id": "V1",
        "booking_id": 1,
        "costs": 25,
        "loss": 25,
        "rank": 1
    }
}
```

What truck V1 is essentially saying here is: “My first preference (rank) is to transport booking 1 for costs 25 (costs). If I someone else executes this booking I will lose 25 (loss) because the costs of my second preference are 50 (loss + costs). All other active trucks will publish similar messages.

This scheme is designed for the situation depicted in Figure 7 where prefer to transport the same booking. In situations like this the agents are programmed to assign the task to the truck with the greatest loss (truck V2). This problem of decentral assignment is known as Decentral Constraint Optimisation Problem (DCOP) and further described in.[5]

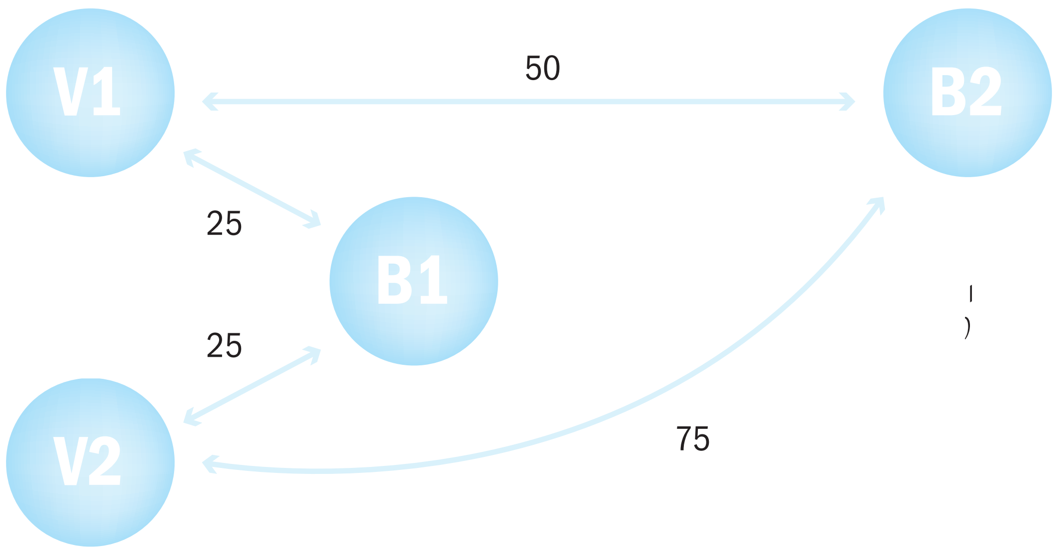

Figure 7 - Managing conflicts of interest between trucks

5 Leeuwen, C.J. van & Pawelczak, P. (2017). CoCoA: a Non-iterative Approach to a Local Search (A)DCOP Solver. Association for the Advancement of Artificial Intelligence.

6 EXPLORING FUTURE POSSIBILITIES

Logistics by definition is decentralized, or else all goods would be in one place. Yet we organize logistics in a very centralized manner.

In the project discussed in this whitepaper we proved that it is possible to smarten up a fleet of trucks and let them organize the planning and distribution of containers in a decentral manner. This requires quite a shift in the way processes are engineered at logistics service providers.

We have not yet piloted this in real life, so that is an important next step. Looking further ahead, what is there to expect? How will decentralized organisation impact logistics?

On an operations level, the decentralized organisation of logistics requires a role-shift of planners from task distribution towards monitoring. Whenever unwanted and unforeseen situations occur the rules the system or the internal logic of agents should be adjusted. The way these processes should work in practice need to be studied. The monitoring and incident resolving function of planners might remain, but assignment of orders and the facilitation of collaboration might move to a digital entity. New roles in rule setting and internal logic (or intelligence) development of twins and their environment will surface.

From a technical perspective there is no need to stop at self-organizing fleets. Opportunities lie in cross-fleet collaboration, where a truck, barge, and crane of different owners may collaborate in solving a single transport order. So far, we have viewed this transport order as a static, but a shipment too, may be controlled by a digital twin that chooses among transport providers. Shipments may also bundle into higher entity twins and unbundle when arriving at a crossdock in its journey towards its destination. The technical challenges of this lie in the facilitation of communication, the preservation of privacy, the lifecycle management of digital twins, the interaction with transport management systems, and the internal intelligence of digital twins.

From a business perspective one could ask whether this is value proposition that puts a price tag on a timely delivery or whether decentral organisation is a new push towards further cost reduction. It also might create entirely new business models, digital allow for far more flexible schemes of collaboration in contrast current long-term contracts and service level agreements that dominate the industry. Value is created by finding the most efficient routes, but if digital twins themselves engage in path finding it questionable if this will still remain the main source of value creation. Last but not least, one might ask whether asset manufacturers will still be willing to sell vehicles when they can function autonomously.

On a higher level there is a need to consider the societal impacts of decentralized supply chains. Do these decentralized supply chains create a more robust network for good deliveries? What is the impact on the environment? Do we have sufficient control mechanism to manage a crisis? How will these changes affect the workforce, asset owners and service providers throughout the industry? How do we ensure that logistics remains a sector where fair competition and entrepreneurship thrive?

The opportunities for multi-agent digital twin systems in logistics are many, research questions are abundant, but an important first step is to validate whether the promises of such a system hold true in real live!

Want to know more about self-organisation or participate in a pilot?
Visit https://tno.nl/sol.