# HOLONIC ORDER MANAGEMENT FOR LARGE-SCALE AUTOMATED LOGISTIC SYSTEMS

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## ABSTRACT

Automation of resources for transport, transshipment, and storage of freight is an important development in modern logistics. Some automated logistic systems are already operational, like automated container terminals. These systems use only small numbers of logistic resources, transport distances are short, and human intervention still plays an important role. In other cases, such as automated factories, the flexibility of the system is very low, i.e. all degrees of freedom have been reduced in the design of the system. We study large-scale fully automated logistic systems. For such systems neither hierarchical control nor heterarchical control is suitable. In this research we advocate a holonic approach that combines both hierarchical and heterarchical control paradigms. Two different types of holons were developed. The first type controls logistic resources, and is called the LogisticResourceHolon. The second type is responsible for dealing with customer orders, and is called the LogisticOrderHolon. The first preliminary results showed that the holonic control proved to be safe, efficient, reliable, and able to deal with several types of disturbances. Further research will focus on how holonic control can deal with several types of disturbances, like AGV breakdowns.

## INTRODUCTION

Control systems for logistic and transport systems are among the most complex control systems that are in existence (Pyle et al. 1993). Control systems from the field of logistics and transportation have to control many concurrent processes, have to react to input within strict time windows, have a distributed nature, and have to work with large sets of heterogeneous data.

Traditionally, hierarchy has been the most important paradigm in logistic control systems. In hierarchical systems, the complex logistic decisions are divided into a number of smaller sub-decisions with less complexity (Simon 1969). A number of disadvantages of hierarchical structures can be found in literature and practice (Wyns 1999, Bongaerts 1998). Hierarchical systems are rigid and static; modifications are costly and hard to incorporate, and hierarchical systems cannot cope effectively with disturbances. These drawbacks of hierarchical control have led to a paradigm shift towards heterarchical control structures. Heterarchical control is a flat control structure composed of independent agents, without centralized or explicit direct control. Agent-based systems can naturally cope with disturbances, and are easier to change or extent by replacing or adding agents. The disadvantage of using agents is the large number of interactions between the agents. This leads again to a complex system and behavior that is difficult to understand, control, predict, and scale. For controlling large-scale automated logistic systems we advocate a holonic approach, in which both hierarchical and heterchical control are combined.

After this introduction the term holons will be discussed. After this discussion an architecture for holonic order management will be introduced. The holonic order management was implemented for the Underground Logistic System Schiphol, a large-scale automated logistic system. Within the Underground Logistic System Schiphol holons were used to control Automatic Guided Vehicles and material handling stations. Furthermore, the holons scheduled the order they received from customers. The holonic order management was implemented in simulation models, some preliminary results from these models are given. The paper ends with a number of conclusions and ideas for further research on holonic control.

## HOLONS

Holons were introduced by Koeslter (1967). The word holon is a combination of the Greek words *holos* (meaning whole) and the suffix *on* (indicating particle or part). The word holon suggests a combination of a whole system and individual parts. Holons are autonomous and self-reliant units. They can make decisions on their own without consulting 'higher' levels of control. Simultaneously, holons are subject to higher levels of control. This combination makes a holon a stable form that survives disturbances, can act in the absence of data, and still functions for the functionality of the bigger whole.

Holonic control has been successfully applied in several logistic areas. Wyns (1999) and Bongaerts (1998) introduce a reference architecture for Holonic Manufacturing Systems. This architecture consists of three different holons; resource-, product-, and order holon. The three types of individual holons have to cooperate to carry out a customer order. Bürckert et al. (1997) model basic physical logistic objects, like trucks, drivers, trailers, and containers, as individual agents. To execute customer orders the individual agents that are needed to transport cargo join themselves in holons. Each holon has a head that represents the holon to other holons and agents. The competencies of the heads range from pure administrative tasks to the authority to issue directive to other agents (Bürckert et al. 1997).

An important question that needs to be answered is why we should use holonic control for large-scale automated logistic systems. First, large-scale logistic systems use large sets of heterogeneous automated resources, like AGVs and material handling stations. Each set has its own control systems that largely differ from other control systems. Each set can be controlled by a different holon. However, to execute a customer order, the individual holons have to cooperate. This structure of autonomy and cooperation is closely represented within a holonic structure. Secondly, large-scale automated systems cover large geographical distances. The control over these geographical areas will be distributed, each area having its own control systems (Verbraeck & Versteegt 2001). The control will be distributed, but still have a strong hierarchical setting. A number of smaller areas belong to a larger area. This distributed hierarchical setting is naturally represented in holons. A holon can have a number of hierarchical control components, while the physical parts are distributed. Finally, holons are stable systems that can deal well with disturbances. The technology that will be used within large-scale automated logistic systems, is new and will show high levels of failures during the start-up phases.

## HOLONIC ORDER MANAGEMENT

A logistic holon is:

'*An autonomous and cooperative control system for scheduling and controlling the execution of logistic activities.*'

Logistic holons have the following characteristics:

- *Autonomy*. Holons can create their own plans and control the execution of these plans.
- *Cooperation*. Holons can cooperate with other holons to perform logistic services that they cannot perform on their own. Holons can exchange and develop mutual acceptable plans with each other.
- *Goal-oriented*. A goal is a state to be achieved; sub-goals are the result of the decomposition of goals (Meystel & Albus 2001). Each holon works towards achieving its own goal. The goals of the individual holons are sub-goals of the goal of the entire logistic system.
- *Control components and representation of physical components*. A holon consist of control components and representations of the physical components, like logistic resources.

Two types of logistic holons are distinguished. A LogisticResourceHolon, abbreviated to LRH, is responsible for controlling and scheduling sets of logistic resources. The term resource is a broad term, logistic resources range from AGVs and material handling stations to infrastructure elements. Two different LRHs were implemented, one for controlling transshipment facilities and one for controlling AGVs. The resource holons consist of control components, information components, and a representation of the logistic resources. The resource holons do not contain the actual physical resources. The LRHs are responsible for scheduling and controlling the execution of customer orders. The scheduling takes place when customer orders arrive at the logistic systems. The control activities are aimed at controlling the logistic activities that have to be performed. The second type of holon, the LogisticOrderHolon, abbreviated to LOH, is responsible for dealing with customer orders. It has to decide what types of resource holons are needed to execute a customer order. The LOH contacts several LRHs to coordinate the scheduling of customer orders. In a holonic architecture implementation this is done in a co-operative manner; the LOH cannot force any LRH to carry out a customer order, but when a LRH agrees to carry out an order, the LOH can count on the execution of the agreed 'contract'. The customer is also implemented as a holon, but lies outside the logistic control system.

Customers initiate the entire process of order management by generating customer orders, as can be seen in Figure 1. After an order has been generated the customer sends the order to the LogisticOrderHolon. More precisely, the order is placed in the mailbox of the LOH. When the LOH has checked the mailbox and found a customer order, it checks whether or not the customer order is correct. If the LOH finds any errors in the order the customer is contacted.

System internally the LOH can be seen as a 'client' and the LRH provide logistic services to this 'client'. The LOH divides the orders into a number of suborders. This is a functional decomposition. The LOH has knowledge on what kind of logistic services the LRHs can perform. The customer order is divided into parts that the individual LRHs can schedule and execute. For example, in most automated logistic systems two material handling stations are needed for transshipment (one at the origin and one at the destination), and one Automatic Guided Vehicle is needed for the transport. Each of these different types of logistic resources is controlled by its own LogisticResourceHolon. The LOH sends the suborders to the LRH that are needed to carry out the customer order. These suborders can be seen as requests. Since we operate in a holonic setting, the LRH do not have to cooperate with the LOH. They will cooperate when this is advantageous for them or the entire system. Based on these suborders the individual LRH *may* create one or more sub-offers. The LRH send the sub-offers to the LOH. The LOH joins the best sub-offers into one offer and this offer is send to the customer.
Each LRH tries to optimize its own planning. Each holon has its own goal, that is a sub-goal of the entire system. The LOH receives all the sub-offers and combines the sub-offers into one or more offers for the customer. The LOH tries to join those sub-offers as optimal as possible for the entire system. Each individual LRH tries to reach its own goals that are sub-goals of the entire system. The LOH tries to reach or guard the goal of the overall system. All the sub-offers that are made by the LRH are temporary claims on logistic resources. These temporary claims can become fixed when the customer and the LOH agree with the offer, or they can be deleted when the customer or LOH do not agree. Each temporary claim and offer to the customer have short life spans. Customers and LOH have to react to quickly to offers or sub-offers. When the there is no reaction within this life span, the temporary claim is automatically deleted. We use short life spans of temporary claims. When the life span is too long, it is difficult for each LRH to schedule activities optimally. The number of temporary claims that can be made is also important. When too little temporary claims are made the LOH has difficulties to combine the sub-offers into a good offer for the customer. When too many temporary claims are made the planning, the LRHs have difficulties in optimizing its schedules.
The customer checks the offer of the LOH. The customer can accept an offer or decline an offer. When the customer accepts an offer, the customer order is finally planned in the system. The temporary claims that belong to the offer and sub-offer are changed into fixed claims and all other temporary claims are deleted. When the customer does not accept the offer, all temporary claims are deleted.

Based on the acceptance or rejection of the offer the LRHs update their planning.

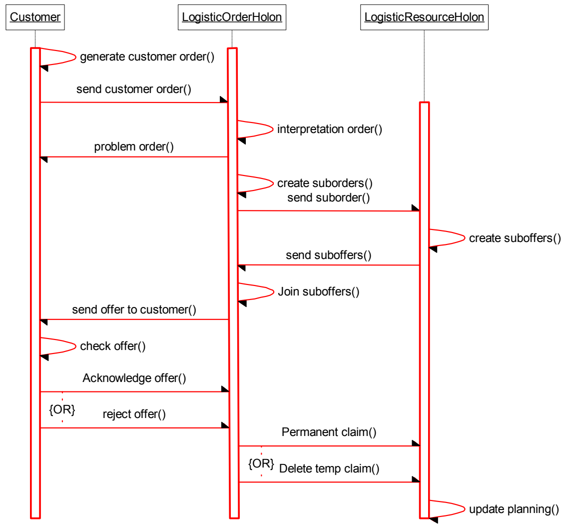


Figure 1: Scheduling of a Customer Order

All communication between holons, customers, and logistic resources is asynchronous (Ben-Ari 1990). This way processes or activities can continue to operate without having to wait for other processes to be ready for information exchange. For example, the customers place their messages in the mailbox of the LOH. Every time unit, e.g. every second, the LOH check if there are any messages in the mailbox. When the customer has placed a message in the mailbox, the customer can continue to operate normally.
The holons contain world models. A world model is a model of the state of the world (Meystel & Albus 2002). The world model can contain information on the internal state of the system or the external world. Holons use world models to make decisions for which they cannot timely collect all information. The world model then tries to provide this information. For example, the resource holons do not contain the actual physical resources. They have representations, or world models, of the physical resources.
The world models have to contain up-to-date information on the world. To keep the world models up-to-date a publish/subscribe mechanism was implemented (Versteegt & Verbraeck 2001). The holons subscribe themselves to information services that are provided by another holons or logistic resource.

## UNDERGROUND LOGISTIC SYSTEM SCHIPHOL

The roads near Amsterdam Airport Schiphol and the Flower Auction Aalsmeer are heavily congested. This leads to long throughput times and unreliable delivery rates of the transport of time-critical and

expensive airfreight, e.g. flowers, computer parts, and newspapers, between Amsterdam Airport Schiphol, logistics centers at the airport, the Flower Auction Aalsmeer, and a future Rail Terminal near Schiphol. To solve these problems an underground logistic system called the Underground Logistic Systems Schiphol, abbreviated to OLS Schiphol, has been proposed for the transport of expensive and time-critical air-cargo. The OLS Schiphol connects Amsterdam Airport Schiphol, Flower Auction Aalsmeer, and rail terminal near Hoofddorp, as can be seen in Figure 2.
OLS Schiphol is an underground logistic system that will be separated from other traffic allowing congestion-free freight transport. OLS Schiphol should ensure a seamless connection between different transport modes and stimulate inter-modal transport and transshipments of goods between inter-continental planes and high-speed freight trains.

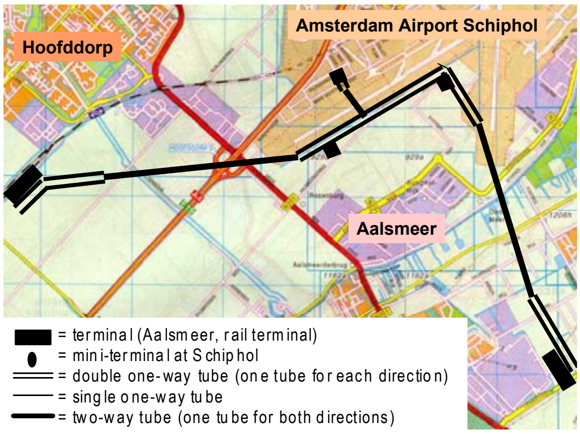


Figure 2: Underground Logistic System Schiphol

The OLS Schiphol is a large-scale automated logistic system. The transport distances are large and large numbers of logistic resources will be used. The tunnels, located 60 feet below are up to 5.000 meters long, which results in driving times of 15 minutes. The tunnels connect large freight terminals at Hoofdorp and Aalsmeer and smaller freight terminals at Schiphol Airport. OLS Schiphol is highly automated and will use up to 400 Automatic Guided Vehicles, and 30 fully automated material handling stations.

## IMPLEMENTATION

This section provides an overview of the evaluation of the holonic order management, which is currently being carried out. The holonic approach was implemented in EM-Plant version 4.6. At this moment a number of experiments have been carried out to test the feasibility of the holonic control.
The expected flows for the year 2020 were used as input into the for the order management. It should be noted, however, that such predictions have large margins of error. This is mainly because there are large uncertainties surrounding the future growth of transport, especially when looking at a longer time horizon. Furthermore, customers have little insight in how they can use the OLS Schiphol. The traffic flow predictions can, therefore, only be used as starting point for evaluating the holonic order management. The prognoses of the transport flows are given in Table 1. The flows differ largely, most cargo units will be transported between the flower auction and rail terminal. These are mainly flower and related products that will be transport by high-speed train towards the rest of Europe. The flow between airport and rail terminal consists mainly of heavy main deck air-pallets that are used to transport high-value and time-critical airfreight.

Table 1: Prognosis of Transport Flows in Thousands of Cargo Units per Year in 2020

| To ⇒<br>From ⇓ | Airport Schiphol | Rail terminal | Flower auction |
|---|---|---|---|
| Airport Schiphol | - | 122 | 67 |
| Rail terminal | 182 | - | 197 |
| Flower auction | 10 | 414 | - |

The first preliminary experiments provided some insight in the performances of the holonic order management.
The overall utilization of the logistic resources, both AGVs and material handling stations is low. The average utilization lies between 30% and 40%. This is mainly because the capacity of the OLS Schiphol is based on peek-demands. The peek demands during the year are just before Christmas and Valentines Day. During the day the peek demand lies in the morning just after the auction process has been finished. During the rest of the day and year there is a surplus of AGVs and material handling stations. The surplus capacity can be used for maintenance on AGVs and material handling stations and provides good flexibility for scheduling.
The number of temporary claims that are made by each LogisticResourcesHolon does not significantly influence the logistic performance of the OLS Schiphol. This can be explained by the short life span of temporary claims, and the low overall utilization of the logistic resources. Experiments with different numbers of temporary claims (3, 5, and 10) did not show any significant differences in logistic performance. When the overall utilization of the system is high, around 80%, the number of temporary claims has to be lowered. Otherwise the system shows nervous behavior.

## CONCLUSIONS AND FURTHER RESEARCH

Not all experiments have yet been carried out to fully evaluate the holonic order management for the OLS Schiphol. In this section a number of preliminary conclusions is drawn based on the first experiments that have been carried out.

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The OLS Schiphol is a fully automated system, it uses new technology for the AGVs and material handling stations. Such technology is not yet proven. Both AGVs and material handling stations will show large number of disturbances during the early operational phases. Further research will focus on how holonic order management can deal with different types of disturbances, like AGV breakdowns, no-shows of cargo units, delays of cargo units. The holonic order management has to be able to quickly recover from such disturbances and limit the negative consequences.

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