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TR 43 64 S'

Stellingen

Behorende bij het proefschrift

Holonic Control For Large Scale Automated Logistic Systems

Cornelis Versteegt
15 december 2004

I

Holonische besturingssystemen zijn beter in staat tot het effectief en efficiënt besturen van grootschalige geautomatiseerde transportsystemen dan volledig centrale dan wel volledig decentrale besturingssystemen.

II

Gangbare definities van efficiëntie in transportsystemen nemen ten onrechte verschuivingen in de vraag naar transportdiensten niet mee.

III

Pogingen om een simulatiebenadering en een emulatiebenadering in elkaar te verenigen lopen vast op een fundamenteel verschil in de uitgangspunten. Simulatie is gebaseerd op het reduceren van de werkelijkheid, emulatie is gebaseerd op het volledig weergeven van de werkelijkheid.

IV

De toegevoegde waarde van fysieke prototypes van Automatisch Geleide Voertuigen ligt meer in de bevrediging van de kinderlijke genoegens van onderzoekers dan in het behalen van verbeteringen in het ontwerp.

V

De term intelligent in Intelligente Transport Systemen (ITS) zegt meer over de intelligentie van de toegepaste technologie dan over het intelligent gebruik van het systeem.

VI

De afkorting OLS stond oorspronkelijk voor *ondergronds* logistiek systeem. Dit werd snel veranderd in *ongehinderd* logistiek systeem. De trage besluitvormingsprocessen rondom ondergrondse logistieke systemen indiceren dat de betekenis beter kan worden aangepast tot *ongewenst* logistiek systeem.

VII

ICT moet niet worden gebruikt om de logistiek te managen. Logistiek moet worden gebruikt om ICT te managen.

VIII

Animaties gekoppeld aan simulatiemodellen verbergen meer dan dat zij laten zien.

IX

Gezien het veelvuldig aanduiden van internetpagina's (URL's) in kranten, boeken en tijdschriften moeten de regels omtrent afbreektokens worden heroverwogen.

X

Promoveren is uit het leven gegrepen. Aan het einde kijkt men terug, weet men alles beter en als men alles opnieuw zou moeten doen, zou men alles anders aanpakken.

T12 4364 S¹

Propositions pertaining to the dissertation

Holonic Control For Large Scale Automated Logistic Systems

Cornelis Versteegt
15 December 2004

I

Holonic control systems can control large scale automated logistic systems more effectively and efficiently than fully centralised systems and fully decentralised systems.

II

Regular definitions of efficiency of logistic systems fail to take into account shifts in the demand to the systems' functions.

III

Attempts to join the fields of simulation and emulation are futile. Simulation is based on the reduction of reality; emulation is based on keeping reality as it is.

IV

The added value of using physical prototypes of Automated Guided Vehicles has more to do with satisfying the childish feelings of the researchers than achieving improvements in the design of the system.

V

The word intelligent in Intelligent Transport Systems tells us more about the intelligence of the technology that is used, than intelligent use of the system.

VI

The abbreviation ULS originally stood for *underground* logistic system. This quickly changed to *undisturbed* logistic system. Given the protracted nature of the decision making processes surrounding underground logistic systems ULS should now be used to denote an *unwanted* logistic system.

VII

ICT should not be used to manage logistics. Logistics should be used to manage ICT.

VIII

Animation linked to simulation models hides more than it shows.

IX

The rules regarding the use of punctuation marks need to be reconsidered to accommodate the frequent use of references to internet pages (URL) in newspapers, books and magazines.

X

Getting a PhD is like life itself. At the end you look back, you now know almost everything better, and with 20/20 hindsight would have chosen a different approach.

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Holonic Control For Large Scale Automated Logistic Systems

Cornelis Versteegt

Holonic Control For Large Scale Automated Logistic Systems

PROEFSCHRIFT

*ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof.dr.ir. J.T. Fokkema,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op woensdag 15 december 2004 om 15:30 uur
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Cornelis VERSTEEGT

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Prof.dr. H.G. Sol

Samenstelling promotiecommissie:

Rector Magnificus	Voorzitter
Prof.dr. H.G. Sol	Technische Universiteit Delft, promotor
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Prof.dr.ir. G. Lodewijks	Technische Universiteit Delft
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Contents

PREFACE AND ACKNOWLEDGEMENTS

LIST OF ABBREVIATIONS

1	DESIGNING CONTROL FOR AUTOMATED LOGISTIC SYSTEMS	1
1.1	INTRODUCTION OF PROBLEM AREA	1
1.2	LARGE SCALE AUTOMATED LOGISTIC SYSTEMS	2
1.2.1	SEPARATION OF INFRASTRUCTURE.....	2
1.2.2	INTELLIGENT TRANSPORTATIONS SYSTEMS.....	4
1.2.3	ISSUES ON LARGE SCALE AUTOMATED LOGISTIC SYSTEMS.....	5
1.3	RESEARCH OBJECTIVE AND QUESTIONS.....	6
1.4	RESEARCH APPROACH.....	8
1.4.1	RESEARCH PHILOSOPHY	8
1.4.2	RESEARCH STRATEGY	9
1.4.3	RESEARCH INSTRUMENTS.....	10
1.5	RESEARCH OUTLINE	11
2	A DESIGN APPROACH FOR LOGISTIC CONTROL	13
2.1	WAY OF THINKING.....	14
2.2	WAY OF MODELLING	17
2.2.1	UNIFIED MODELING LANGUAGE	18
2.2.2	DISCRETE-EVENT SIMULATION	19
2.3	WAY OF WORKING.....	20
3	THEORIES ON LOGISTIC CONTROL	23
3.1	CONTROL THEORY.....	23
3.1.1	CONTROL SYSTEMS	23
3.1.2	OPEN AND CLOSED LOOP SYSTEMS.....	25
3.2	LOGISTIC CONTROL.....	26
3.2.1	HIERARCHICAL LOGISTIC CONTROL.....	27
3.2.2	HETERARCHICAL LOGISTIC CONTROL.....	28
3.2.3	COMBINED HIERARCHICAL AND HETERARCHICAL LOGISTIC CONTROL	29

4	TILBURG UNDERGROUND CITY DISTRIBUTION SYSTEM.....	31
4.1	SYSTEM DESCRIPTION	31
4.1.1	INFRASTRUCTURE	33
4.1.2	LOGISTIC RESOURCES.....	34
4.2	CONCEPTUAL MODELS	35
4.2.1	LOGISTIC CONTROL CONCEPT	36
4.3	EMPIRICAL MODELS	38
4.3.1	QUANTIFICATION OF LOGISTIC RESOURCES AND LOGISTIC PERFORMANCE	39
4.3.2	DETAILED INSIGHT INTO THE DYNAMIC BEHAVIOUR	41
4.4	LEARNING MOMENTS	43
4.4.1	LEARNING MOMENTS ON AUTOMATED LOGISTIC SYSTEMS	43
4.4.2	LEARNING MOMENTS ON LOGISTIC CONTROL	44
4.4.3	LEARNING MOMENTS ON MODELLING AUTOMATED LOGISTIC AND CONTROL SYSTEMS	44
4.5	TOWARDS A SUPPORT ENVIRONMENT.....	45
5	SUPPORT ENVIRONMENT FOR DESIGNING LOGISTIC CONTROL.....	47
5.1	INTRODUCTION.....	47
5.2	REQUIREMENTS FOR LOGISTIC CONTROL SYSTEMS	49
5.3	SUPPORT ENVIRONMENT PART ONE: GENERIC STRUCTURE OF LOGISTIC CONTROL.....	51
5.3.1	HOLONIC LOGISTIC CONTROL	51
5.3.2	LOGISTIC HOLONS	51
5.4	SUPPORT ENVIRONMENT PART TWO: DESIGN GUIDELINES FOR LOGISTIC CONTROL.....	53
5.4.1	HIERARCHICAL LAYERED CONTROL	53
5.4.2	DISTRIBUTED CONTROL.....	55
5.4.3	SCHEDULING AND REAL-TIME CONTROL.....	56
5.4.4	RESOURCE REPRESENTATIONS AND AUTONOMOUS LOGISTIC RESOURCES	60
5.4.5	ASYNCHRONOUS COMMUNICATION	61
5.4.6	COMMAND/EVENT BASED COMMUNICATION	62
5.4.7	COMMUNICATION THROUGH INFORMATION SERVICES.....	63
5.5	SUPPORT ENVIRONMENT PART THREE: EVALUATION OF LOGISTIC CONTROL SYSTEMS	64
5.5.1	COMBINATION ONE: SIMULATION OF RESOURCE HOLONS AND LOGISTIC RESOURCES	66
5.5.2	COMBINATION TWO: EMULATION OF LOGISTIC RESOURCES.....	67
5.5.3	COMBINATION THREE: PROTOTYPE LOGISTIC RESOURCES	67
5.6	EVALUATION OF THE SUPPORT ENVIRONMENT.....	68

6	EMPIRICAL TESTING OF THE RESOURCE HOLONS	69
6.1	UNDERGROUND LOGISTIC SYSTEM SCHIPHOL	69
6.1.1	OVERVIEW LOGISTIC SYSTEM	69
6.1.2	LOGISTIC RESOURCES OF THE ULS SCHIPHOL	71
6.1.3	CHALLENGES IN DESIGNING LOGISTIC CONTROL FOR THE ULS SCHIPHOL	74
6.2	LOGISTIC RESOURCES AT THE TESTSITE.....	75
6.3	RESOURCE HOLONS AT THE TESTSITE.....	77
6.3.1	AGV HOLON.....	78
6.3.2	DOCK HOLON.....	82
6.4	SAFEGUARDING THE CONCURRENT USE OF INFRASTRUCTURE	86
6.4.1	IMPLEMENTATION OF TRACES IN THE AGV HOLON	86
6.4.2	SAFEGUARDING SIMPLE INFRASTRUCTURE ELEMENTS	88
6.4.3	SAFEGUARDING COMPLEX INFRASTRUCTURE ELEMENTS	90
6.4.4	SAFEGUARDING OTHER INFRASTRUCTURE ELEMENTS	91
6.5	EVALUATION OF THE AGV HOLON AND DOCK HOLON.....	92
6.5.1	SIMULATION MODELS.....	92
6.5.2	EMULATION MODELS	93
6.5.3	PROTOTYPES	93
6.5.4	SYNCHRONISATION OF TIME AND PLACE	94
6.6	LEARNING MOMENTS	95
7	EMPIRICAL TESTING OF THE ORDER HOLON	99
7.1	INTRODUCTION.....	99
7.2	STRUCTURE OF THE HOLONIC ORDER MANAGEMENT SYSTEM.....	100
7.2.1	ORDER HOLON	101
7.2.2	RESOURCE HOLONS	102
7.3	HOLONIC SCHEDULING PROCESS	104
7.3.1	PART ONE: SCHEDULING OF CUSTOMER ORDERS	104
7.3.2	PART TWO: SCHEDULING OF MAINTENANCE	105
7.4	SPECIFICATION OF THE HOMS.....	107
7.4.1	OBJECT ORIENTED STRUCTURE.....	107
7.4.2	COMMUNICATION IN THE HOMS	108
7.4.3	MAINTENANCE FOR THE LOGISTIC RESOURCES	109
7.4.4	PERFORMANCE INDICATORS	109
7.4.5	INITIAL TREATMENT	110
7.4.6	VERIFICATION AND VALIDATION	111
7.5	EXPERIMENTS WITH THE HOLONIC ORDER MANAGEMENT SYSTEM.....	112
7.5.1	TRANSPORTATION FLOWS PROGNOSIS	112
7.5.2	EXPERIMENTS	113
7.6	EVALUATION OF HOLONIC ORDER MANAGEMENT SYSTEM.....	120

8	GROUP EVALUATION SESSION.....	123
8.1	INTRODUCTION.....	123
8.2	STRUCTURE OF THE GROUP EVALUATION SESSION	123
8.3	EVALUATION OF THE HOLONIC STRUCTURE	124
8.4	EVALUATION OF THE CASE STUDIES	128
8.5	ENHANCEMENTS FOR THE SUPPORT ENVIRONMENT	129
9	EPILOGUE	131
9.1	RESEARCH FINDINGS	131
9.1.1	RESEARCH QUESTION ONE	131
9.1.2	RESEARCH QUESTION TWO	132
9.1.3	RESEARCH QUESTION THREE	133
9.1.4	RESEARCH QUESTION FOUR	133
9.1.5	HOLONIC STRUCTURE OF CONTROL SYSTEMS	134
9.1.6	MODELLING OF LARGE SCALE AUTOMATED LOGISTIC SYSTEMS	136
9.2	RESEARCH	137
9.2.1	RESEARCH AREA	137
9.2.2	RESEARCH APPROACH.....	138
9.3	FURTHER RESEARCH	138
	REFERENCES.....	141
	SUMMARY.....	153
	SAMENVATTING.....	161
	APPENDIX. PARTICIPANTS OF THE GROUP EVALUATION SESSION.....	169
	CURRICULUM VITAE.....	171

Preface and Acknowledgements

Freight transport and goods distribution are an essential and inevitable component of economic activities and development. The volume of goods that is transported is growing constantly. This growth is not without negative consequences. A great challenge lies in balancing the positive and the negative impacts of the growth of freight transport. Sustainable solutions for goods distribution are needed, solutions that are environmentally sound and economically efficient. We focus on a solution in this research that is expected to be sustainable; large scale automated logistic systems.

The control systems for large scale automated logistic systems are among the most complex control systems to be found in practice. The control systems have to control many concurrent processes, have to react to inputs within strict time windows, have to operate in a distributed setting, have to work with large sets of heterogeneous data and have to control large numbers of heterogeneous logistic resources. We want to support designers in the complex engineering process of control systems for automated logistic systems with our research.

We support the engineering process by developing a support environment. The support environment provides a generic structure for control systems, design guidelines and recommends support facilities for the design of control systems for automated logistic systems. The developed support environment is applied to design control systems for a future large scale automated logistic system; the Underground Logistic System Schiphol.

This research is part of the Delft University of Technology research program on Freight Transport Automation and Multimodality (FTAM) and is supported by the Netherlands Research School TRAIL.

Logistics is the topic of this book and logistics lies at the basis of this book. Many people have helped in the logistic process of writing it. First of all, I would like to thank Henk Sol. He provided me with the freedom I needed in my research and made many valuable comments on my research. Second, many thanks to Alexander Verbraeck. We had lengthy discussions and provided each other with valuable inputs for our research. We made a lot of joint publications, which offered me possibilities to present my research all over the world, e.g. Japan, USA, Australia, Germany, Belgium and the UK. I would like to thank the people involved in the research project on the Underground Logistic Systems Schiphol; Yvo Saanen, Edwin Valentin, Ben-Jaap Pielage, Jos van der Putte and Jan Katgerman. I received a lot of support from Connekt, especially from Dick Buitenhek and Frank Melcherts.

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Corné Versteegt
Delft, November 2004

List of Abbreviations

AAS	Amsterdam Airport Schiphol
AGV	Automated Guided Vehicle
CDS	City distribution system
CORBA	Common Object Request Broker Architecture
CTA	Container Terminal Altenwerder
CU	Cargo Unit
DCOM	Distributed Components Object Model
DDE	Dynamic Data Exchange
DLL	Dynamic Link Library
DTM	Delft Tunnel Mover
ECT	Europe Container Terminals
FMEA	Failure Mode and Effect Analysis
FTAM	Freight Transport Automation and Multimodality
GLO	Global Logistic Object
GPS	Global Positioning System
HMS	Holonic Manufacturing System
HOMS	Holonic Order Management System
IP	Internet Protocol
IPOT	Interdepartementale Projectorganisatie Ondergronds Transport
ITS	Intelligent Transportation System
OPC	Object Linked Embedding for Process Control
PROSA	Product Resource Order Staff Architecture
RTH	Rail Terminal Hoofddorp
TCP	Transfer Control Protocol
Tilburg CDS	Tilburg city distribution system
TRACES	TRAnsport Control Engineering System
ULS	Underground Logistic System
ULS Schiphol	Underground Logistic System Schiphol
UML	Unified Modeling Language
VBA	Verenigde Bloemenveiling Aalsmeer (flower auction Aalsmeer)
#	Number

Successful problem solving requires finding the right solution to the right problem. We fail more often because we solve the wrong problem than because we get the wrong solution to the right problem.

R.L. Ackoff

1 Designing Control for Automated Logistic Systems

Automation of equipment for transport, transshipment and storage is one of the most important developments in modern logistic systems. Logistic resources, like vehicles and material handling stations, are increasingly being automated (FTAM 1997). Some automated logistic systems are already operational, commonly such systems consist of a small number of logistic resources, short transport distances, with human intervention still playing an important role (Hammond 1986, Müller 1983). The logistic systems studied for this research are large scale automated logistic systems. Large scale automated logistic systems use a large number of automated logistic resources, such as Automated Guided Vehicles¹ and automated material handling stations. The transport distances and transported volumes of freight are large and the control over large scale automated logistic systems is highly automated (Kusters 2000, Rijsenbrij et al. 2000). The demands on automated logistic systems, in terms of throughput times and volumes, are high and these will increase strongly in the near future (Rijsenbrij 1999).

The performance of logistic systems is highly sensitive to the accuracy of the control systems (Ryan 1998). Logistic systems show little throughput and great imbalances when adequate control systems are not available (Jing et al. 1998). Experiments where one logistic system is controlled by several different control systems show that control systems strongly determine the performance of the logistic system (Roderique 1999, Bongaerts 1998). The high levels of automation ask for a new approach to controlling logistic systems, and it is this that forms the focal point of the research discussed here.

1.1 Introduction of Problem Area

Freight transport and goods distribution are an essential and inevitable component of economic activity and development. The volume of transported goods is growing constantly, but this growth is not without negative consequences. A great challenge lies in balancing the positive and negative impacts of this growth in freight transport, especially in highly populated urban areas.

¹ Abbreviated to AGV. We use the term Automated Guided Vehicles. The term Automatic Guided Vehicles can also be found in the literature.

Currently, road vehicles account for almost the entire transported volume of goods in highly populated, urban areas (CBS 2001). Road vehicles, like lorries and vans², can be used to transport goods where a high frequency of delivery, high flexibility and the ability to reach many locations are required to transport a wide variety of goods (Binsbergen & Visser 2001, D'Este 2000). Road vehicles, however, have large negative impacts on the local environment and society, like air pollution, noise pollution, vibration problems and accidents. These negative impacts of goods distribution in urban areas can be found globally and do not only have consequences for the efficiency of goods distribution; they affect the future economic development and the structure of urban areas (Taniguchi et al. 2001).

Several initiatives have been taken to reduce the negative impacts of goods distribution in urban areas, e.g. restricted time windows to enter inner cities, cooperation between carriers and restricted vehicle sizes. Most of these initiatives concentrate on the current way of distributing goods. Although these initiatives are helping to guide the growth of freight transport in good directions; there are limits to the level to which the current way of distributing goods can be improved or optimised. A sustainable solution is needed, one that is environmentally sound and economically efficient (Binsbergen & Visser 2001). The focus is on a new way to distribute goods in this research. A way that is expected to be sustainable; large scale automated logistic systems. Although automated logistic systems are seen as promising alternatives for traditional road transport, little is known about such systems.

1.2 Large Scale Automated Logistic Systems

Automated logistic systems can play an important role in facilitating the growth of goods distribution. Although large scale automated systems have several advantages over traditional human based logistic systems, there are only a few real world implementations available. A number of obstacles hinder the implementation of large scale automated logistic systems.

1.2.1 Separation of Infrastructure

Automated logistic systems are *separated* from other traffic. The logistic operations can be performed undisturbed and free of congestion. The interactions between logistic systems and other traffic are often unpredictable, which makes the operations difficult to automate. In separated systems some of the environmental variables are reduced, which makes the operations easier to automate. The separation has safety benefits, no collisions occur with other traffic. High transport capacities are possible due to the separation from other traffic and weather conditions.

Separation can be achieved in several ways, e.g. underground infrastructure or elevated infrastructure. One way, that has received much attention in the last couple of years, is to use an underground infrastructure (IPOT 1998). Within underground transportation a distinction is made between pipeline transport and tube transport (CBS 2001). Pipelines are used to transport fluids and gasses, like oil-related products, natural gasses and water. Tube transport systems use vehicles to transport cargo units, e.g. pallets or containers. The volume transported in pipelines is at present much larger than the volume of goods transported by tube systems (CBS 2001). The volume of goods transported by tube systems is small and has not been measured accurately. Here the focus is on tube systems that use vehicles to transport cargo units.

² Vans have a maximum weight of 3.5 tonnes. Lorries weigh between 3.5 and 7.5 tonnes.

Underground logistic systems also have other advantages. Underground logistic systems have little impact on the local environment and society (Binsbergen & Visser 2001, IPOT 1998). The negative impacts of the logistic activities are not noticeable at the surface. Underground systems will use environmental friendly vehicles with electric propulsion systems so the fumes of traditional combustion engines do not have to be cleared out of the tunnels. The surface area can be used for other purposes, e.g. offices, housing or shopping centres. In highly populated urban areas where it is difficult, or even impossible, to extend current infrastructure, underground logistic systems can be easier to realise than extending current infrastructure or constructing new infrastructure at surface level.

Automated underground logistic systems are not a new concept. A number of major cities have underground metro systems for passenger transport. The number of underground freight transport systems is small. The British Royal Mail started operating an underground logistic system in London, called Mailrail in 1927 (Bliss 2000). The Mailrail transports mail between mail sorting offices and railway stations in inner city London and uses driverless trains. The (un)loading of trains and traffic control are not automated. Mailrail is a small scale system; a small number of locations is connected through a simple network and the number of vehicles is small. The system was built because of problems with limited space available for expansion, congestion and excessive noise caused by goods distribution in the inner city London (Bliss 2000). In the mid 1990's underground logistic systems began to receive more attention (IPOT 2000, 1998). Several initiatives were taken to construct underground logistic systems in highly populated, urban areas all over the world, e.g. Tokyo (Taniguchi et al. 2000), the 'Ruhrgebiet' in Germany (Stein & Schoesser 2000) and Texas (Roop & Bierling 2000). It must be noted, however, that all these initiatives are still in their conceptual phases; construction had not started at the time of writing.

Within the Netherlands two major application areas can be found for automated underground logistic systems; urban areas and main-ports. Urban areas and main-ports face similar problems in attempting to facilitate the growth of freight transport. It is difficult, unwanted or even impossible to expand the current way of transporting freight. Several larger cities in the Netherlands are studying the possibility of underground logistic systems, i.e. underground city distribution systems, e.g. Tilburg (DHV 2000), Utrecht (Boerkamps 2001), Arnhem/Nijmegen and Leiden (IPOT 2000, 1998). It is expected that such systems will consist of distribution centres at the edges of the city and an underground network of tunnels that will connect the distribution centres with the inner city (Binsbergen & Visser 2001, Venemans 1994). The goods will be transported to the distribution centres by lorries, trains or barges, where they will be transhipped onto Automated Guided Vehicles and transported to various delivery points through tunnels. In future an integrated national underground logistic system could be feasible with local underground logistic systems in industrial and urban areas, with the various underground systems connected by traditional surface level transport systems (Iding & Heijden 2000). Automated logistic systems can also be used at main-ports. A main-port is a location where various transport modes are interconnected and can be seen as a decoupling point between intercontinental transport flows and national or European oriented transport flows. The Netherlands has two large main-ports; Amsterdam Airport Schiphol and the port of Rotterdam.

1.2.2 Intelligent Transportations Systems

An important range of developments in logistic and transport systems can be summarised in the term '*Intelligent Transportation Systems*'. Intelligent Transportation Systems, abbreviated to ITS, refer to the application of Information and Communication Technologies to the planning and operation of transport systems (McQueen & McQueen 1999). Designers of ITS have several goals, i.e. to make transport systems more efficient, less congested, safer and less polluting (Drane & Rizos 1998). Until recently most developments in ITS have focused on passenger transport and providing information to human drivers (Carsten & Nilsson 2001). Current and future developments are focused on automation of transport systems, especially on the automation of drivers' activities both for passenger and freight transport (Vlacic et al. 2001).

Within AGVs many or all of the drivers' activities are automated. An AGV based system is an advanced material handling system that involves driverless vehicles controlled by computers (Hammond 1986). AGV based systems generally consist of the following components (Cameron & Probert 1994, Hammond 1986, Müller 1983).

1. *Automated Guided Vehicles* which are the driverless vehicles used to transport freight.
2. *Material handling stations* which are the interfaces between vehicle system, storage system and production system. AGVs pick up and deliver cargo units at material handling stations. A typical material handling station uses conveyors to tranship and move cargo units.
3. *Transportation networks* which consist of the infrastructure elements that connect the material handling stations.
4. *Control systems* which are responsible for controlling the AGVs, the material handling stations and the transportation network. Common control activities for the AGVs are scheduling, routing, dispatching and collision avoidance (Versteegt & Verbraeck 2002a, Meer 2000). A common control activity for the material handling stations is the scheduling of transshipment activities (Versteegt & Verbraeck 2002b). Although transportation networks cannot perform activities, a certain amount of control is needed, such as access control to single lane bi-directional tunnels (Ebben 2001).

AGVs were introduced in the 1950s and the number of applications has grown strongly ever since (Müller 1983). AGV based systems have a number of advantages over vehicle systems operated by human drivers (Cameron & Probert 1994, Hammond 1986, Müller 1983). AGV based systems can be used to enlarge capacities of logistic systems, while simultaneously reducing labour forces. The relation between logistic performance and labour costs is very efficient within AGV based systems. This is an important aspect in Western countries where labour costs are high. AGV based systems can improve the quality of logistic services. AGVs operate with high levels of precision, especially when performing complicated driving manoeuvres, e.g. docking operations. AGVs need less space than human operated vehicles for their operations. This is an advantage in systems where the available space is limited, like underground systems and systems in factories. Finally, there is less chance for human errors in AGV based systems, which improves the reliability and the efficiency of the logistic system.

Since their introduction AGVs have been used for internal logistic systems in production plants and warehouses (Hammond 1986). In such systems speeds are low, a limited number of AGVs is used, the transport distances are short, and the number of (un)loading points is limited (Müller 1983). The focus of this research is large scale automated logistic systems. Large scale automated logistic systems will use large numbers of AGVs driving at higher speeds; the AGVs have to travel large distances (Kusters 2000). The logistic equipment is intelligent in the sense that many of the drivers' activities are automated (Vlasic et al. 2001). At the moment of this research no large scale automated logistic systems had been implemented. The ECT terminal at the port of Rotterdam and container terminal CTA in Hamburg are examples of automated logistic system that are close to the type of systems we study. The current control systems of the ECT terminal have a number of bottlenecks which makes them not suitable to control large scale automated logistic systems (Bierhuizen et al. 2001). The control systems of the ECT terminal have difficulties in dealing with uncertainties, dealing with large numbers of AGVs and the integration between control systems is problematic. The control systems at the ECT terminal are not scalable, because of the complex control algorithms and centralised structure.

1.2.3 Issues on Large Scale Automated Logistic Systems

A number of issues hinder the implementation of large scale automated logistic systems. These issues have to be solved, before actors are willing to make decisions to invest in such systems.

A number of *economic issues* has to be studied before actors are willing to invest in large scale automated logistic systems. The investments needed for automated logistic systems are high. Automated logistic equipment is expensive (Hammond 1986). Underground logistic systems are even more expensive, since underground infrastructure is costly to construct. A major paradigm shift has taken place regarding who should invest in infrastructure projects in the Netherlands (IPOT 2000). The national government, i.e. the Ministry of Transportation, was traditionally responsible for investing in large scale infrastructure projects. The national government has, at this moment, no money for the construction of large scale automated logistic systems. Another factor that reduces the willingness of the national government to invest is that automated logistic systems solve problems at a local level. The environment, society and accessibility of a small geographical area are improved. This makes the impacts of automated logistic systems small compared to problems at a national level. Local governments are more willing to invest in such systems, but often lack funds. Completely private financing of large scale automated logistic systems is not feasible, as the risks are high and the return-on-investment is uncertain. Several ideas on public/private partnerships have been studied (Ham & Koppenjan 2002, IPOT 2000).

There are *organisational issues* to be dealt with. Large scale automated logistic systems cross traditional organisational borders. Several organisations are involved, e.g. customers, shippers, authorities, banks, insurance companies and distribution centres. Each organisation has its own goals and means. This creates a complex inter-organisational setting in which decisions on the design and operational aspects have to be taken (Dunn 1981). When automated logistic systems are applied to urban areas large numbers of actors are involved, mostly small parties with little power to influence policy-makers, e.g. shop owners. In more point-to-point systems fewer actors are involved with high levels of power in the decision making process. In both cases actors need to cooperate, leading to difficult negotiation processes.

Issues on safety mainly concern collision avoidance and the transport of dangerous goods. Large numbers of AGVs drive at high speeds in automated logistic systems. This leads to complex interactions between the AGVs, especially in places where AGVs have to drive closely together. Failsafe control systems are needed that offer high levels of logistic performance and safe concurrent use of infrastructure (Lindeijer 2003). The separation of the infrastructure of large scale automated logistic systems has safety benefits; no collisions can occur with other types of traffic. The separation, however, increases the complexity in emergencies, e.g. AGVs in tunnels are difficult to reach in case of a fire.

A number of *legal issues* has to be dealt with. Presently there is no usable legal framework for automated logistic systems. The current legal framework for transport only covers traditional human operated logistic systems. An important aspect that has to be solved is liability in cases of accidents or damage to cargo units.

A lot of *technological issues* obstruct implementation of large scale automated logistic systems. New technologies for AGVs and material handling stations will be used (Pielage 2001, Rijsenbrij et al. 2000). The technologies have not been fully tested or in some cases had not even been developed at the moment of writing. These technologies range from new types of vehicles and sensors to communication equipment. AGV systems are technically more complex than other types of logistic systems and more prone to equipment failure (Hammond 1986). A number of technological issues regarding AGVs still has to be studied, e.g. guiding AGVs that drive at higher speeds, merging and splitting of platoons, reduction of inter vehicle lead times and automated handling of cargo (Kusters 2000). Finally, the flexibility of automated logistic equipment needs to be studied. Human operated systems offer high flexibility and can react well to unforeseen circumstances and disturbances (Hammond 1986). The possibilities for automated logistic systems to offer similar flexibility in the face of disturbances still have to be studied.

Not much is known about *controlling* large scale automated systems. Not only the physical activities will be automated; the control activities will also be automated. Control systems for logistic systems are among the most complex control systems to be found (Pyle et al. 1993). Such control systems have to control many concurrent processes, have to react to inputs within strict time windows, have to operate in a distributed setting and have to work with large sets of heterogeneous data. The control systems have to be able to control large numbers of heterogeneous logistic resources, since many logistic resources are used.

The issues mentioned here form obstacles that hinder the implementation of large scale automated logistic systems. The aim of this research is to deal with a number of issues on the technology and a number of issues on controlling large scale automated logistic systems. The implementation of large scale automated logistic system should become easier once these issues have been dealt with.

1.3 Research Objective and Questions

The central belief of this research is that a support environment for designing control systems for large scale automated logistic systems can be used to deal with a number of the issues on the technology and control mentioned in section 1.2. Control systems for automated logistic systems are among the most complex control systems in existence (Pyle et al. 1993). Designing control systems for large scale automated logistic systems is a complex activity. The technology used is new and sophisticated, many actors are involved, many alternatives need to be studied and designers of different disciplines have to

cooperate during the design process (Veeke 2003, Bongaerts 1998). We want to support designers in the complex engineering process of control systems for automated logistic systems. The central research objective is formulated as:

'Develop a support environment that helps designers in developing control systems for large scale automated logistic systems.'

The *social relevance* of our research becomes clear when looking at the role that automated logistic systems can play in facilitating the sustainable growth of freight transport. The social contribution is aimed at helping to solve issues involving the technology and the control of automated logistic systems. These issues hinder the further development and implementation of large scale automated logistic systems. Actors are reluctant to invest in such systems while so many of these issues remain. The *scientific contribution* is aimed at creating theory on controlling large scale automated logistic systems. Most efforts to date in research on automated logistic systems have been focused on infrastructure and on technological developments of logistic resources (FTAM 1997). Large scale automated logistic systems consist of more than just collections of advanced automated technologies. Control systems strongly determine the performance of logistic systems (Kia et al. 2000, Evers et al. 2000). The scientific contribution consists of a methodical approach to design control systems for automated logistic systems and provides a basis for the further implementation of such systems.

A number of research questions is formulated that need to be answered to reach the research objective. A detailed understanding of the components of automated logistic systems is needed before we can begin designing control systems and develop our support environment. The subject of the first research question is identifying the characteristics of automated logistic systems.

Research question 1

What are the generic characteristics of large scale automated logistic systems? What types of logistic resources are used and what services do they provide?

This first research question is answered partially in this first chapter and is further elaborated in chapters four and six. An inductive case study on the Tilburg city distribution system was carried out to gain detailed insight into automated logistic systems, see chapter four. The logistic resources of a future large scale automated logistic system, the Underground Logistic System Schiphol, are described in chapter six. The characteristics of automated logistic systems and automated logistic resources provide an input for the second research question. The subject of our second research question is to identify promising concepts for the control of logistic systems.

Research question 2

What concepts can be used for controlling large scale automated logistic systems?

This question is answered by studying literature on control systems and conducting an inductive case study (chapters three and four). The answer to the second research question provides input for the third research question. Designing control systems for large scale automated logistic systems is a complex activity. The objective of our research is to develop a support environment to support the design of control systems for large scale automated logistic systems.

Research question 3

What should a support environment for designing control systems for large scale automated logistic systems look like?

This research question is dealt with in chapter five, in which such a support environment is developed. The answer to this research question provides inputs for the last research question. The designed controls need to be evaluated before they can be implemented. The support environment should, therefore, support the evaluation of control systems. The subject of our fourth research question is the evaluation of logistic systems and control systems.

Research question 4

How can large scale automated logistic systems and their control systems be evaluated before implementation?

This research question is answered in chapters five and six. The idea behind this research question is to solve as many of the issues regarding technology and control before the implementation of the logistic system starts. Answering these four research questions should lead to a support environment for designing control systems for large scale automated logistic systems.

1.4 Research Approach

The *research approach* defines the strategy that is followed within a piece of research, in which a set of research instruments is employed to collect and analyse data on the phenomenon studied, guided by a research philosophy. The research philosophy is the guideline by which the research is conducted, it is used to guide us and teaches us how to observe the world and how to gather and analyse data. The research strategy is the plan that is carried out to conduct the research. Research instruments are used to address research questions and pursue research objectives.

1.4.1 Research Philosophy

The *research philosophy* underlines the way in which data on the phenomenon studied is collected and analysed, it determines what kind of knowledge can be obtained and what the limits to that knowledge are (Orlikowski & Baroudi 1991). For research on information systems two dominant schools of philosophy can be distinguished (Hirschheim 1992, Galliers 1991, Orlikowski & Baroudi 1991).

- *Positivism*. According to this school of philosophy reality can be observed and described objectively without interfering with the phenomenon being studied. The phenomena are isolated and repeatable observations are made. Most of the studies carried out according to this philosophy are aimed at theory testing and make use of deductive reasoning and quantitative research instruments.
- *Interpretivism*. This tradition, also called anti-positivism, states that reality can only be understood by subjectively interpreting observations of reality; multiple interpretations of reality are possible. Most of the studies carried out according to this philosophy are aimed at building or designing theory and make use of inductive reasoning and qualitative research instruments.

Each school has preferences for research instruments; each instrument having its own strengths and weaknesses. Positivists advocate the use of 'hard' research instruments like laboratory experiments, field experiments and surveys. Interpretivists advocate the use of 'soft' instruments like action research, gaming and reviews. Several authors (Leeuw 1990, Yin 1994) advocate a more '*pluralistic*' philosophy on science, which advocates the idea that research should not necessarily embrace one of the two mentioned philosophies. We follow this pluralistic view and use a combination of instruments drawn from both philosophies, to counterbalance the weaknesses and the strengths of each instrument.

1.4.2 Research Strategy

A *research strategy* provides an outline of the plan, which must be carried out to meet the research objectives. The choice for a research strategy is based on the nature of the research problem and on the status of theory development in the research field. The research strategy we followed is the inductive-hypothetic research strategy (Sol 1982, Bosman 1977). This strategy is based on Singerian inquiring systems, which advocate expansion of scientific knowledge by adapting it endlessly and inductively in a multidisciplinary manner based on new observations (Churchman 1971). The inductive-hypothetic research strategy is used for the following reasons (Sol 1982).

- It emphasises the activities of conceptualisation and problem specification, underlining specification and testing of premises in an inductive way.
- It opens up possibilities for multidisciplinary research.
- It enables the generation of various solutions, starting if possible with an analysis of the existing situation.
- It permits feedback and learning and enables evaluation of ideas.
- It is very useful when there is a lack of usable theory or methodological support.

This makes the inductive-hypothetic research strategy very applicable for emerging research fields such as designing control systems for large scale automated logistic systems. First of all, automated logistic systems consist of more than just sets of automated logistic technologies. Organisational, economical, legal and technical aspects play an equally important role; this asks for a multidisciplinary research approach. Second, designing control for large scale automated logistic systems is an emerging research field with little accepted theory. It is hard, or even impossible, to design logistic control in a deductive way. An inductive research strategy seems to be most appropriate. Finally, it is not likely that the creation of a single solution will eliminate the issues that were observed in section 1.2; a set of possible solutions is needed.

The inductive-hypothetic strategy consists of five steps in which four different types of models are constructed, as depicted in Figure 1-1 (Sol 1982).

1. A number of *initial theories* is identified in the first step. Using these theories empirical situations are investigated. This step ends with the construction of descriptive empirical models. Each model describes the perceived situation of a specific area of interest. The first step is primarily used to get a detailed insight into, and a better understanding of, the problem area.

2. An *abstraction* is made of the essential parts of the descriptive empirical models in the second step. Perceived problem situations are translated into a descriptive conceptual model. The descriptive conceptual model is used to represent the essential and generic elements of the problem area under investigation and gives indications for possible solutions.
3. A *theory* is constructed to solve some of the observed problems in the third step. Theory is used in a broad sense and indicates an explicit and elaborated set of solutions for the original problem. Theories can range from a set of concepts and the relationships between them (Wierda 1991), to a modelling approach (Bots 1989), to a support environment (Janssen 2001). The theory is presented in a prescriptive conceptual model. This model is still an abstraction of the specific areas of interests, but explicitly defines how to address the perceived problems.
4. The prescriptive conceptual model is *implemented* in a number of practical situations in the fourth step. The result of this step is a set of alternatives that provide solutions for the originally identified problems and is presented in prescriptive empirical models.
5. The developed theory is *evaluated* by comparing the descriptive empirical models to the prescriptive empirical models in the fifth step. Based on this evaluation the prescriptive conceptual models can be improved. The inductively expanded theory can be used as initial theory in empirical situations to start a new cycle.

Figure 1-1: Inductive-hypothetic research strategy

1.4.3 Research Instruments

Research instruments are needed to collect and analyse data on the research area and are used to answer the research questions. The actual choice of research instruments depends on three conditions: the type of research questions, the control over the actual behaviour of the phenomenon and the time focus (Yin 1994). A pluralistic view is chosen in this research, making it possible to choose the most appropriate instruments of both research philosophies.

Case study research and action research are suitable instruments for the inductive-hypothetic research strategy (Sol 1982). Case studies are very useful in emerging research areas, the investigator has little control over events and the focus is on a contemporary phenomenon within some real life context (Yin 1994). Case studies are a research instrument that focuses on understanding dynamic aspects present in single settings (Meinsma 1997). Action research focuses on intervention and designing the processes in the situation studied. The main difference between case study research and action research is the level of participation of researchers (Yin 1994). In case studies the researcher is an observer who conducts exploratory, explanatory or descriptive research. In action research the researcher is an active participant who conducts intervening research. Where case studies are more focused on answering "how and why" questions, action research additionally focuses on "how to" questions.

Selecting appropriate cases is often more based on opportunism than on rational grounds (Yin 1994). Some considerations should be given on selecting appropriate cases.

- The cases should involve organisations that are willing to introduce new technologies on the automation of logistic resources and Information and Communication Technology.
- The cases should involve design processes of automated logistic systems that cross traditional organisational boundaries and involve different independent organisations.
- The cases should allow action based research (Yin 1984) and involve design processes of automated logistic systems that are in still in their conceptual phases (Sage & Armstrong 2000). This leaves many possibilities open to influence the design processes.

1.5 Research Outline

The background, social and scientific relevance of our research were discussed in this chapter. The research objective, approach, philosophy and questions were stated to demarcate our research area. The outline of this dissertation is shown in Figure 1-2, the chapter numbers are depicted between brackets. The steps taken in the inductive-hypothetic research strategy are depicted in *italics*, on the right side of Figure 1-2.

The methodology we follow in our research is described in chapter two. The theoretical background of the research is described in chapter three. An inductive case study on an automated logistic system is described in chapter four. Relevant issues are derived from the inductive case study on controlling automated logistic systems. These issues form starting points for developing the support environment in chapter five. The support environment was evaluated by applying it in two case studies and presenting it to a group of experts during an evaluation session. The support environment was applied to design control systems for a future large scale automated logistic system in the case studies. The first case study, described in chapter six, was used to test the technical feasibility of the support environment. The second evaluating case study, described in chapter seven, tested the functional usability of the support environment. The final evaluation was carried out in a group evaluation session, described in chapter eight. A group of experts on automated logistic systems and control systems was invited to evaluate the developed support environment and the application of the support environment. Some general conclusions, a reflection on the research and recommendations for further research are discussed in the final chapter.

Figure 1-2: Outline of dissertation

The limits of my language mean the limits of my world.

Ludwig Wittgenstein

2 A Design Approach for Logistic Control

We follow Sol's analytical framework (1990) to create an understanding of modelling approaches for designing control for automated logistic systems. Traditionally this framework has been used for the analysis of methodologies for developing information systems (Wijers 1991). Sol's framework has also been applied for gaining insight into methodologies in other application areas. The framework has successfully been used to analyse methodologies in design oriented studies in the field of logistics and transportation (Bockstael-Blok 2001, Janssen 2001, Hengst 1999, Babeliowsky 1997, Jong 1992). In Sol's analytical framework, depicted in Figure 2-1, a methodology is assessed using a way of thinking, a way of working, a way of modelling and a way of controlling.

Figure 2-1: Framework for analysing design methodologies

The way of thinking concerns the philosophy behind a methodology. It delineates how an application domain is observed and the way in which the elements of a problem situation are interpreted. The way of modelling describes the different types of models that are constructed when following a methodology.

The way of working consists of the tasks or activities that have to be performed when following a methodology. The way of controlling deals with the managerial aspects of a methodology. The way of thinking strongly determines the principles followed in the way of working, modelling and controlling. The focus of this chapter lies on the way of thinking, the way of modelling and the way of working. The way of controlling is not taken into account.

2.1 Way of Thinking

The way of thinking encompasses our *Weltanschauung*, which delineates how we observe a problem area under investigation. A *Weltanschauung* is a particular, non-absolute world image that we take for granted and through which we interpret reality (Checkland 1981, Churchman 1971).

A distinction is made between *control systems* and *systems-being-controlled*. A control system is the total of formal and informal rules of behaviour, information systems and physical expedients used to control a system-being-controlled (Aken 1978). Control systems promote the preferred behaviour of systems-being-controlled. Control systems influence the systems-being-controlled; they do not completely determine the behaviour of the systems-being-controlled (Leeuw 1990). In our research the systems-being-controlled are large scale automated logistic systems that consist of automated logistic resources, e.g. Automated Guided Vehicles and automated material handling stations.

The focus of our research lies on *design*, not analysis. Analysis aims at determining why things are as they are and how they work (Simon 1969). Design involves how artificial things with desired properties should be made and/or should be achieved (Checkland 1981). Design is thinking behaviour, which conceptually selects the alternative among a set of alternatives that leads to the desired goal (Churchman 1971). Three aspects have to be taken in consideration in design processes (Cross 2000, Churchman 1971). First, design attempts to distinguish different sets of behaviour patterns. Second, design attempts to estimate how well each alternative set of behaviour patterns will serve a specified set of goals. Third, part of design is the communication of thoughts to other minds.

Modelling control and logistic systems plays a significant role in designing control for large scale automated logistic systems. The logistic systems-being-controlled that form our research area are at the moment of the research not available in reality. Models are used as a replacement of the logistic systems. The modelling techniques used to construct models are discussed in section 2.2. *Simulation* is the process of designing a model of a system and conducting experiments using this model to understand the behaviour of the system and to evaluate various strategies for the operation of the system (Shannon 1975). Simulation is part of our way of thinking rather than just a modelling technique. We use simulation as an inquiry approach to get insight into and knowledge of the systems we design (Sol 1982, Churchman 1971).

We look at designing control for large scale automated logistic systems from a *problem solving perspective*. A problem exists if the following conditions are met (Sol 1982).

- A problem owner is in doubt as to which course of actions is best to remove his dissatisfaction with his present state, or possible future state. A problem owner does not have to be an individual person; a problem owner can be an organisation or a group of problem owners.
- Several solutions, or possible courses of action, can be identified that are unequally efficient and effective to improve the problem situation.

- The environment of the problem situation contains factors that affect the solutions or the possible courses of action. These environmental factors cannot, or only with great difficulty, be influenced.

Decision makers and stakeholders are confronted with practical limits to human rationality when solving problems. It is hard, or even impossible, to find an optimal solution when solving problems within this vision of *bounded rationality* (Simon 1969). We follow a process that will not yield optimal solutions but satisfactory solutions that satisfy the various actors involved.

Sol classifies problems on a scale ranging from well-structured to ill-structured problems. A well-structured problem meets the following criteria (Sol 1982).

- The set of possible courses of action, or solutions, is finite and identifiable.
- The possible courses of action are consistently derived from models that show a good correspondence with the problem situation.
- The effectiveness and/or the efficiency of the possible courses of action can be evaluated numerically.

Ill-structured problems do not meet one or more of these criteria (Sol 1982). Dunn (1981) provides an overview of the characteristics of the two types of problems, shown in Table 2-1.

Table 2-1: Characteristics of well- and ill-structured problems

	Structure of the problem	
	Well-structured	Ill-structured
<i>Decision maker(s)</i>	One or few	Many
<i>Alternatives</i>	Limited	Unlimited
<i>Utilities (values)</i>	Consensus	Conflict
<i>Outcomes</i>	Certainty or risk	Unknown
<i>Probabilities</i>	Calculable	Incalculable

A complete intransitive decision problem is an example of an ill-structured problem, one where it is impossible to select a single alternative that is preferred to all others (Dunn 1981). Designing logistic control systems for large scale automated logistic systems is a complex activity that can be seen as solving ill-structured problems. Many actors are involved, i.e. problem owners and stakeholders. The problem owners are organisations that want to implement large scale automated logistic systems and range from city councils of medium sized to large cities to large transport organisations. Besides the problem owners many other stakeholders are involved that influence the problem owner, e.g. customers, transport organisations, political parties and environmental groups. Each actor has its own goals and objectives in the design process, which are often conflicting. Besides the rational behaviour of actors

other factors also influence their behaviour, like political and social ones. Many possible alternatives exist within designing automated logistic systems and control systems and the effectiveness and the efficiency of each alternative cannot be evaluated by only using numerical data. Alternatives on the logistic and control systems differ on the layout of infrastructure, the technology used, the services that are offered and the control concepts. The outcomes, or effects, of each alternative are not fully known in advance. High levels of uncertainty surround the technology, economic uncertainties exist regarding the profitability and uncertainties arise to the social impacts the alternatives will have.

Several *problem-solving cycles* can be used to address ill-structured problems (Ackoff 1978, Bosman 1977, Simon 1973). Sol (1982) states that the inductive-hypothetic research strategy, described in chapter one, is very useful when dealing with ill-structured problems. Mitroff et al. (1974) introduce a whole systems view of science. A whole systems view implies that there is no such thing as a 'component' that exists independent of other components and independent of the whole system (Ackoff & Emery 1972, Sagasti & Mitroff 1973, Churchman 1971). This holistic view of science can be applied to problem solving. Problem solving consists of six activities and four elements, as can be seen in Figure 2-2.

Figure 2-2: Whole systems view of problem solving (Mitroff et al. 1974)

The problem solving cycle starts with the conceptualisation of the problem situation. The result of this activity is a conceptual model that provides the problem solver with a vocabulary to describe the problem situation. The second activity is specification of the problem situation. The result is a detailed descriptive empirical model of the problem situation. The specification activity results in an empirical model of an 'as-is' nature. During the third activity, solution finding, the problem situation is analysed and solutions are designed. The solution finding activity leads to empirical models of a 'to-be' nature. The 'to-be' models are then compared and one solution is chosen. The fourth activity is implementation of the chosen solution in the problem area. A consistency check, activity number five, is carried out to make sure that the chosen solution can be expressed in terms of a previously formulated conceptual

model. A correspondence check, activity number six, is aimed at validation of the descriptive empirical model. The empirical model must closely resemble the problem area. Re-conceptualisation, re-specification of the problem situation, or redesign of the solutions are needed if inconsistencies are found during the consistency check or the correspondence check.

The activities, sketched in Figure 2-2, do not have to be followed in any specific order (Mitroff et al. 1974). There are some specific loops that have been used frequently. Mitroff et al. (1974) and Bosman (1977) map different modes of scientific inquiry to this general schema. Loops located in the left of Figure 2-2 concentrate on the origin of ideas or the 'context of discovery', while loops located in the right half of Figure 2-2 cover testing of ideas or the 'context of verification' (Reichenbach 1968, Popper 1965).

Large scale automated logistic systems consist of subsystems, e.g. Automated Guided Vehicles, material handling stations, transportation network and control systems, as stated in chapter one. Each subsystem is designed by designers from a different discipline. For example, mechanical engineers design the AGVs, civil engineers design the transportation network, and electrical and software engineers develop the control systems. Other non-technical disciplines are also involved, e.g. economists are needed to study the economic feasibility and legal experts are needed to develop legal frameworks. The designs of the subsystems interact in the design of the entire large scale automated logistic system. A *multidisciplinary approach* is needed for designing control for large scale automated logistic systems (Cross 2000). Several studies on control of automated logistic systems support this multidisciplinary view (Veeke 2003, Lindeijer 2003, Wyns 1999, Pyle et al. 1993).

2.2 Way of Modelling

The way of modelling describes the *modelling techniques* used to construct models in the methodology we follow. Models are an essential part of designing control for large scale automated logistic systems. As such systems do not yet exist models are used as substitutions. Models are abstractions of systems and are used to reduce the complexity of a problem situation and to communicate knowledge on a problem situation. A model is an artificial, mental, symbolic or physical system which is substantially simpler than the system of interest, yet it gives an opportunity to reason about, or simulate the processes in, the system of interest with sufficient accuracy for decision making (Meystel & Albus 2002).

Several modelling techniques are used within the field of logistics. Many of them have a quantitative nature, like the widely used Operations Research techniques, e.g. shortest route calculations and inventory models (Kasilingam 1998, Hillier & Lieberman 1995). We argue that these more mathematically oriented modelling techniques are not very suitable for dealing with situations that are characterised by many actors, complex technology and bounded rationality. The Operations Research techniques can still be used to solve smaller problems in the subsystems of the entire design of automated logistic systems.

A distinction is made between *conceptual* and *empirical* models. Conceptual models set out the definition of a particular problem situation in broad terms (Mitroff et al. 1974, Sagasti & Mitroff 1973). Conceptual models of a problem situation are characterised by high levels of abstraction and fuzziness and structure perception, representation and reasoning regarding a problem situation (Sol 1982). Conceptual models can be used as a vocabulary or a vehicle of communication (Bots 1989). A conceptual model should be drawn with little or no regard to the software implementation and has to be

considered language independent (Fowler & Scott 2000). Empirical models result from a specification phase and enable analysis and diagnosis of a problem situation and possible solutions. Empirical models capture more details and time ordered dynamics of interdependent activities and are formalised representations of reality (Sagasti & Mitroff 1973).

We only use a small set of the immense collection of available modelling techniques. The following selection criteria are used to choose appropriate modelling techniques (Sol 1982).

- The modelling techniques have to show a high degree of qualitative and quantitative correspondence with the problem situation.
- The modelling techniques have to capture static and dynamic aspects of logistic systems. The techniques have to explicitly model time aspects of the problem situation (Streng 1993).
- The modelling techniques have to offer facilities for experimentation (Bots 1989).
- The modelling techniques have to be able to deal with different perspectives of various actors, show the different points of view of the various stakeholders and allow for different levels of abstraction (Bockstael-Blok 2001, Cross 2000, Wyns 1999).
- It should be possible to communicate the models easily to involved actors (Cross 2000). The constructed models have to be easy to communicate to actors with little training in reading diagrams (Vreede & Verbraeck 1996). Not all actors involved in the design of automated logistic systems have experience in reading and understanding models.

These criteria are independent of the cases studied during our research. More criteria can be added that are case dependent. As there is no single approach that meets all the criteria mentioned above, we choose two; Unified Modeling Language and discrete-event simulation.

2.2.1 Unified Modeling Language

The *Unified Modeling Language*³, abbreviated to UML, is an object oriented modelling approach. UML is a standard graphical oriented representation technique widely used in software engineering. The UML was put through a standardisation process by the Object Management Group⁴, and is now an OMG standard (Fowler & Scott 2000). UML tries to capture static and dynamic aspects of systems and focuses on the interactions between objects rather than studying single objects. UML consists of a number of different modelling techniques of which a subset is used in this research (Fowler & Scott 2000, Rumbaugh et al. 1999).

- *Class diagrams*, or object models, are used to describe the types of objects in a system and the various relationships among them. Class diagrams describe the static aspects of a system and are used to increase insight into a system. Class diagrams are used as a communication tool or vocabulary to express the problem situation to actors (Bots 1989). Object modelling is a very intuitive modelling technique and easily understandable for people who have little or no training in reading models. Objects and classes are described by attributes and operations. Attributes describe the state of an object and operations represent the possible behaviour of an object.

³ Note that we use the American term 'modeling', instead of the English 'modelling'. UML was developed mainly in the USA. We do not use UML as a modeling approach; we only use a number of the modeling techniques from UML.

⁴ www.OMG.com

A distinction is made between active objects, which show behaviour, and passive objects, which show no behaviour (Streng 1993, Sol 1982). Passive objects are for example cargo units that are transported and messages that are sent between active objects.

- *Sequence diagrams*, a type of interaction diagram, are used to describe how groups of objects collaborate. Sequence diagrams model dynamic aspects of a system and put an emphasis on the sequence, or order, in which activities occur. The order in which activities take place, or time aspect, is modelled on the vertical axis of a sequence diagram. The communication between objects is explicitly modelled in sequence diagrams.
- *Activity diagrams*, a type of interaction diagram, are used to describe the sequence of activities. The core symbol is the activity, a state of doing something. The activity can be a physical activity, a control activity or a communication activity.

2.2.2 Discrete-Event Simulation

We use discrete-event simulation to model control systems and systems-being-controlled. Banks (1998) states that simulation is the imitation of a real world system over time, and includes the generation of an artificial history of the system, and observing that history to draw inferences concerning the operational characteristics of the system-being-modelled. Simulation is widely used within the field of logistics (Ebben 2001, Meer 2000, Rohrer 1998) and transportation (Janssen 2001, Manivannan 1998, Babeliowsky 1997, Streng 1993).

Banks (1998) and Law & Kelton (1991) offer an overview of the benefits of using simulation as a research approach. We refer to simulation because the systems studied do not yet exist and simulation is a powerful tool for studying systems that are not available in practice. Automated logistic systems are complex systems that consist of several subsystems. The activities that are executed in the subsystems and the interactions between subsystems are difficult, or even impossible, to translate into more mathematically oriented models (Pidd 1992). Simulation offers possibilities to model complex systems without having to make too many assumptions on the behaviour of the system.

In animation key elements of a simulation model are represented on the screen by icons that dynamically change position, colour and shape as the simulation evolves through time (Law & Kelton 1991). Animation is a standard feature of most simulation packages and can show both static and dynamic aspects of a simulation model (Vreede & Verbraeck 1996). Animation can be useful for a number of purposes (Law & Kelton 1991). Animation can be used to support the communication between actors. Animations are easy to understand for all actors and can be used to achieve a better understanding of systems. Animation can be used to view the simulation model from different perspectives in a recognisable way for both non-simulation experts and non-domain experts (Streng 1993). Animation can also be used for the verification and the validation of simulation models.

Choosing simulation software is an important aspect of simulation studies. In practice many different simulation software packages exist that can be used to construct simulation models (Swain 1999). Nikoukaran et al. (1999) provide a comprehensive list of criteria for the selection of suitable simulation packages. Law & Kelton (1991) provide a list of desirable features that simulation software needs to offer. The criteria offered by Nikoukaran et al. (1999) and Law & Kelton (1991) are general criteria for selecting simulation software. When choosing simulation software case specific criteria play an equal important role.

2.3 Way of Working

The way of working consists of the steps that need to be taken when following a methodology. Our way of working uses several approaches for conducting simulation studies as starting point (Banks 1998, Law & Kelton 1991, Sol 1982). Our way of working is sketched in Figure 2-3 and consists of the following steps.

1. *Problem identification.* The problem formulation is the first demarcation of the problem situation under investigation. The problem formulation has to be communicated with problem owners and actors. All have to understand and agree to the problem formulation. We speak of a problem situation, although the real system does not yet exist. In our definition of a problem we stated that a problem can also concern dissatisfaction of a problem owner with a possible future state.
2. *Conceptual model construction.* Conceptual models of the problem situation are constructed in this phase. The goal of these models is to provide a general overview of the problem situation. The conceptual models are constructed in a number of iterative steps. The first models have high levels of abstraction, more details are added as greater understanding of the problem situation is obtained. It is important that the conceptual models are not unduly complex, this will add to the time needed to complete model construction without increasing the quality of the conceptual models (Banks 1998).
3. *Data collection.* Data on the problem situation under investigation is collected in this phase. Data can be collected in several ways, e.g. retrieving data from management information systems, interviews or studying analogous systems. The data collection determines what is modelled and the level of abstraction.
4. *Empirical model construction.* The conceptual models are translated into empirical models. We use discrete-event simulation software to construct empirical models in our research.
5. *Treatment.* Simulation experiments embody a number of simulation runs under the same treatment (Sol 1982). A treatment consists of the specification of the input data, specification of initialisation conditions, specification of run control conditions and specification of the output data (Ören & Zeigler 1979). The initialisation conditions and run control conditions are decided by the system under investigation. As we see large scale automated logistic systems as non-terminating systems, the length of the simulation run, the number of runs and start-up time need to be defined (Sol 1982). Start-up time is the time that the model needs to reach a steady state (Banks 1998). The start-up time can be estimated by plotting the throughput times of objects against the number of arrived objects. During the start-up time no statistics are collected from the model. The run-length of a replication can heuristically be defined to be at least equal to three times the largest cycle time (Sol 1982). The number of replications depends on the amount of variability in the output (Banks 1998, Law & Kelton 1991). The higher the variability, the more replications are needed. The number of replications is determined by first performing a number of initial replications. The number of additional replications is calculated based on the outcomes of the initial replications (Law & Kelton 1991).

6. *Model verification.* During verification checks are made to see whether the empirical models behave as the modeller intends (Law & Kelton 1991, Shannon 1975). Verification is a continuous process that starts directly from the beginning of empirical model construction (Balci 1998). We chose not to wait until the entire model is finished, this way we can verify relative small and easy to understand parts of models, instead of large complex models that are difficult to understand.
7. *Model validation.* The modeller should ensure that empirical models are adequate and appropriate for the task for which they are intended (Pidd 1992). The correspondence of the model with the real system is checked in the validation process⁵ (Balci 1998). Two types of validation can be distinguished; structural and replicative (Sol 1982). Within replicative validation the output data of the empirical model is compared to corresponding sample data from real systems, this is preferably carried out by statistical testing. The second type of validation is structural validation, also called face validation (Law & Kelton 1991, Shannon 1975). Experts that are familiar with or knowledgeable about automated logistic systems are asked whether the model and its behaviour appear to be reasonable. Animation and structured walk throughs of the model can be used as supporting tools during validation. During a walk through the activities that are performed and the sequence in which they are performed are checked.
8. *Experimental design.* The experiments used to study the logistic systems are defined in this step. The experiments represent possible 'to-be' situations of the automated logistic systems. The experiments are often defined in cooperation with experts on the system under investigation.
9. *Conducting experiments.* The experiments defined during the experimental design are carried out using the empirical models. Different outputs of the models are recorded, such as statistical data and animations.
10. *Reporting.* The results of the experiments are documented. The constructed models have to be documented in detail, this is important when reusability of models is an important aspect (Banks 1998).

Although the way of working is described as a linear process of sequential steps, in practice several iterations are made and steps are carried out in parallel.

⁵ Balci (1998) states that verification deals with building the model right, validation deals with building the right model.

Figure 2-3: Framework for simulation

*Anyone wishing to see what is to be must consider what has been:
all the things of this world in every era have their counterparts in ancient times.*

Machiavelli

3 Theories on Logistic Control

Important concepts drawn from literature on control systems, and logistic control systems in particular, are discussed in this chapter. The initial theories described in chapter one and the literature described in this chapter form the starting point for our inductive case study, which is presented in chapter four.

General theory on control systems is introduced in section one. Theory on logistic control is discussed in section two. Traditionally, hierarchical structures have been used in logistic control systems. The shortcomings of hierarchical control structures are discussed. Heterarchical control structures have been developed to overcome the drawbacks of hierarchical control. Heterarchical control, however, has its own shortcomings. Finally, a holonic structure, in which the advantages of hierarchical and heterarchical control are combined is presented.

3.1 Control Theory

3.1.1 Control Systems

We use the following definition of control (Leeuw 1990, Aken 1978, Ackoff & Emery 1972):

‘Control is the use of control actions by a control system to promote the preferred behaviour of a system-being-controlled.’

A distinction is made between control systems and systems-being-controlled. A control system is the total of formal and informal rules of behaviour, information systems and physical expedients used to control a system-being-controlled (Aken 1978). *Control actions* are the efforts control systems use to influence the state of systems-being-controlled. For control actions the plural form is used to indicate that control is considered as being a continuous process, rather than a single action. The control system promotes the preferred behaviour of the system-being-controlled. This does not mean that the control system completely determines the behaviour of the system-being-controlled. The control system influences the system-being-controlled, but the control actions do not have to be successful (Leeuw 1990, Aken 1978).

Figure 3-1: Control system and system-being-controlled

A control system has two kinds of output, both information flows, as sketched in Figure 3-1 (Leeuw 1974).

- *Control actions* are the efforts of a control system to influence the state of a system-being-controlled. A control action is a request to a system-being-controlled to perform a certain activity at a certain moment in time.
- *Coordination actions* are the efforts of a control system to influence other control systems. Control systems rarely work on their own; they have to cooperate with other control systems. These other control systems can be control systems that control other parts of the system-being-controlled, i.e. system internally, or control systems in the environment, i.e. system externally. A coordination action is a specification of a dependency between multiple control systems at a certain moment in time.

The inputs of a control system are twofold. First, a control system receives information on the state of the system-being-controlled. Second, a control system receives coordination actions from other control systems.

Control within complex systems consists of *a mix of self-control and coordination* (Aken 1978). Within self-control the responsibilities for controlling the execution of activities is assigned to the system itself. Within coordination the execution of activities is controlled by control systems in a coordinating position. It is impossible to obtain sufficient controllability within a complex system without a certain level of self-control (Aken 1978). Control systems have cognitive like limitations (Simon 1969). Not all information needed to make decisions is available for, or can be used by, central coordinating control systems. A certain amount of self-control is needed that uses locally available information. Self-control, however, cannot guarantee satisfactory overall behaviour and has to be supplemented by an overall mode of control, i.e. coordination.

A *system* is a set of interrelated objects, of which each object is related directly or indirectly to every other object, and no subset is unrelated to any other subset (Ackoff & Emery 1972). A system has a number of properties or attributes that represent the characteristics of the system. Systems can perform activities or operations and have a transformation function; input is changed into output. Inputs and outputs are the relations between a system and its environment.

The *environment* of a system consists of the systems and the objects that are not part of the system itself, but influence the system or are influenced by the system (Leeuw 1990). The *world* is defined as the combination of a system and its environment (Albus & Meystel 2001).

An *object* is the smallest entity that is considered in a system. Although an object may be divisible it is treated as an opaque and indivisible unit. An object has a number of attributes and shows behaviour. *Attributes* are the characteristics or properties of an object. *Operations* are the activities that an object can perform. The *state* of an object or system is the collection of the values of all the attributes of that object or system at a certain moment in time (Ackoff & Emery 1972). Objects and systems show behaviour, their state changes in time. An *event* is a change in the state of an object or of a system.

Parts of systems can be studied to reduce the complexity (Leeuw 1990, 1974). A *subsystem* of a system is a subset of objects with all the attributes, operations and relations of the objects unchanged. Within an *aspect-system* of a system we study the entire set of objects, but only a subset of the attributes, operations and relations. In a *phase-system* all the objects with all the attributes, operations and relations are studied, but only at certain moments in time. Various combinations of subsystem, aspect-system and phase-system are possible.

3.1.2 Open and Closed Loop Systems

Within control theory two control paradigms are distinguished, open loop and closed loop control (Dorf & Bishop 2001, Leeuw 1990). An *open loop control* system utilises an actuating device to control a system-being-controlled directly without using feedback (Dorf & Bishop 2001). In open loop systems a control system simply assumes that control actions and coordination actions are effective. Open loop systems are only stable if there are no interferences into or within the system-being-controlled (Aken 1978). Open loop control systems are not very usable in complex logistic systems in which many disturbances occur (Euwe 1999). *Closed loop control* systems measure systems-being-controlled and compare the actual measurements with desired values (Dorf & Bishop 2001). The loop is called closed, because it is repeated continuously. Two basic types of closed loop control systems exist, feedback and feed-forward.

In *feedback control* systems measurements of the system-being-controlled are compared with desired values. Control actions are taken when the deviation between the measurements and the desired values exceeds a certain level (Leeuw 1990). Feedback control produces reactive control (Albus & Meystel 2001). The main disadvantage of feedback control is the tendency to have a persistent error; the actual state tends to lag behind the desired state. It is important that feedback systems can react in good time to differences between measurements and desired values, but there is always a time delay. Time delays can have several causes, e.g. the time it takes before an event is sensed and the time it takes before control actions are effective. When the time delays are too large the system can become unstable. A stable system is defined as a system with a bounded systems response when the system is subjected to a bounded input or disturbance (Dorf & Bishop 2001).

In *feed-forward control* the system-being-controlled also uses measurements. The measurements are used to predict what control actions need to be taken to prevent a difference between the measurements and desired values in the future (Leeuw 1990). Feed-forward control produces pro-active, or anticipatory control, and takes control actions before differences between the desired state and actual state arise (Albus & Meystel 2001). The disadvantage of feed-forward control is that it is very difficult to predict exactly how complex systems will react to control actions.

Feedback and feed-forward control are not just used for controlling technical systems; they can also be used to control organisations or parts of society (Leeuw 1990, Aken 1978, Simon 1969). It should be noted that, feedback and feed-forward control are conceptual schemes. The literature from which they originate mainly studies small and theoretic control systems and systems-being-controlled, e.g. a thermostat that controls a central heating system (Dorf & Bishop 2001). By studying small problem situations the control paradigms seem very clear, transparent and sequential (Leeuw 1990, Aken 1978).

3.2 Logistic Control

We define logistic control as:

'The coherent set of activities used to decide the control actions and the coordination actions needed to promote the preferred behaviour of a logistic system-being-controlled.'

A logistic system has three primary functions, see Figure 3-2.

1. *Transport function.* This process is a transformation in position and time. This function can be represented by $f(x, y, z, t)$. The z-component of the position is not always important. When goods are transported from city A to city B, we are only interested in x, y, t-components.
2. *Transfer function.* This function represents a change of modality, position and time. This function can be represented by $f(x, y, z, t, \text{modality})$. An example of a transfer is freight being unloaded from a lorry and moved into a warehouse.
3. *Storage function.* This is a transformation in time. The change of the position of the goods is not important. This function can be represented by $f(t)$. An example of storage is freight that is temporarily stored in a warehouse.

Control systems for automated logistic systems have to control all three primary functions. Besides the primary functions secondary functions can be identified, like maintenance, accounting and battery management. We study mainly the primary functions; the secondary functions are only discussed when needed.

Figure 3-2: Primary functions of a logistic system (FAMAS 2002)

3.2.1 Hierarchical Logistic Control

Simon (1969) introduces hierarchy as a fundamental characteristic of complex systems. A hierarchical system is a system of which the subsystems are systems and the subsystems may in their turn also be hierarchical systems, until some lowest form of elementary subsystems is reached. Hierarchical control has a tree shaped structure and the coherence within the subsystems is stronger than the coherence between the subsystems. Simon (1969) uses his Watchmakers' parable to illustrate that hierarchical structures are essential to tackle complexity. In the Watchmakers' parable three reasons are provided for why complex systems generally are modelled as hierarchical structures. First, the mechanisms of natural selection will produce hierarchical systems more rapidly than non-hierarchical systems of comparable size, because the components of hierarchies are stable systems. Second, among systems of a given size and complexity, hierarchical systems require less information transmission among their parts than other types of systems. Third, within hierarchical structures the complexity of a system, as viewed from any particular position within the system, becomes independent of the total size.

Traditionally, logistic control systems consist of a number of hierarchical layers (Evers et al. 2000, Euwe 1999, Bertrand et al. 1990). A hierarchical structure makes it possible to reduce the complexity of control and decision making. Complex systems are divided into a number of smaller well-ordered subsystems. Control over the smaller subsystems is easier than control over entire complex systems. Hierarchy divides the power of decision among layers. The top layers have the highest level of power; the lower layers have less power. The higher layers provide constraints or boundaries between which lower layers can operate. The activities at lower layers are coordinated in such a way that the entire structure of the system is in pursuit of the high level goals (Albus & Meystel 2001).

Dividing control systems into a number of independent layers allows designers to work simultaneously on different independent layers. This is not only important during the design of the system, but also during the operational phases of logistic systems. Changes made to one independent layer do not affect other layers, which improves the maintainability of the control systems.

Important questions within hierarchical control systems are how many layers are used and what decisions have to be taken in each layer. Several classifications can be found in literature. Simon pictures an organisation as a three-layered cake (1977). The bottom layer carries out the basic work processes. The middle layer is responsible for the programmed decision making processes that govern day-to-day operations. The top layer takes care of the non-programmed decision making processes. Other classifications are based on the time horizon of the decisions that have to be taken. The higher layers are responsible for taking decisions on a longer time horizon, while lower layers are responsible for taking decisions on a short time horizon (Bowersox & Closs 1996).

Hierarchical control systems have a number of drawbacks. Hierarchical systems have a rigid structure and modifications are hard and costly to implement (Wyns 1999, Fischer 1998, Ulrich & Düring 1995). Hierarchical control is static and cannot cope efficiently with disturbances (Bongaerts 1998). Hierarchical control operates following a top-down approach in which higher levels introduce constraints to lower layers. Activities at lower levels are triggered by control actions or coordination actions from higher levels. In practice, however, the lower levels often trigger higher levels to take control actions. Disturbances occur at the lowest level, e.g. machine breakdowns, and the disturbances trigger higher levels of control to take the control actions required to solve the disturbances (Albus & Meystel 2001).

3.2.2 Heterarchical Logistic Control

Heterarchical control structures have been introduced to overcome the disadvantages of hierarchical control structures. Heterarchical control is a distributed form of control and can be seen as the opposite of hierarchical control. Heterarchical control is a flat control structure composed of independent agents, without centralised or explicit direct control (Bradshaw 1997). An *agent* is an encapsulated computer system situated in an environment and capable of flexible autonomous actions in that environment to meet its design objectives (Jennings 2000). The term agent is used for computer applications varying from simple spreadsheets to special programs designed to perform activities autonomously on behalf of their users (Janssen 2001). Agents have the following characteristics (Jennings 2000, Bradshaw 1997, O'Hare & Jennings 1996, Wooldridge 1992).

- *Autonomy*. Agents have the ability to create and control the execution of their own plans and strategies. Agents can operate without direct intervention of higher levels of control.
- *Goal driven*. Agents can work towards a goal by taking initiatives and by responding to events from their environment.
- *Communication*. Agents can communicate, or exchange messages, with other agents and perform activities with other agents to reach a common goal. The possibility of agents to communicate is called their social ability. Agents communicate using communication protocols, like the widely spread Contract Net Protocol (Smith 1980).
- *Reactive*. Agents can react to events they perceive from their environment or messages from other agents.
- *Adaptability*. Agents can learn and improve their behaviour with experience.

Heterarchical control originates from biological systems and market economies, such systems consist of simple subsystems and have a natural reactive-ness to disturbances (Bongaerts 1998). Agent based systems are fault tolerant and have a natural tendency to cope with disturbances (Russ & Gerber 2001). For example, when a logistic resource breaks down the representing agent does not communicate with other agents for new tasks. It should be noted, however, that agents only can deal with disturbances in situations where homogenous resources are used (Wyns 1999).

Heterarchical control systems have a number of drawbacks. Although agent based systems consist of relative simple agents, the behaviour of agent based systems can be very complex. First, the large number of interactions between the agents results in complex behaviour that is difficult to understand, control, predict and scale (Bongaerts 1998). Second, heterarchical structures are inefficient and unwieldy when applied to large systems (Albus & Meystel 2001). Third, agent based systems cannot guarantee system optimisations, since all forms of hierarchy are banned (Bongaerts 1998). Finally, agent based systems lack real world implementations and most research on agents is carried out within simulated environments (Janssen 2001). The simulated environments have a tendency to be less detailed and more homogenous than real world settings (Wyns 1999).

3.2.3 Combined Hierarchical and Heterarchical Logistic Control

Koestler (1967) introduces holons to overcome the drawbacks of hierarchical and heterarchical control systems. The word *holon* is a combination of the Greek word *holos* (= whole) and the suffix *-on* (= particle or part). Holons suggest combinations of individual parts and whole systems. Complex real life systems are composed of multi-layered hierarchical stable subsystems (Simon 1969). The stable autonomous subsystems cannot exist on their own; they only have a purpose in the entire whole. Koestler (1967) uses holons to describe this hybrid structure of real life systems, e.g. organs in the human body are evolutionary holons and nations are social holons⁶. A holon is an identifiable part of a system that has a unique identity made up of sub-ordinate parts and is itself part of a larger whole (Fischer 1998).

A holon has a dual tendency to preserve its individuality as a quasi-autonomous whole and to function as an integrated part of a larger whole (Koestler 1967). Holons make decisions on their own without consulting higher levels of control; simultaneously holons are subject to higher levels of control. The combination of hierarchical and heterarchical control, makes holons stable forms that survive disturbances and are still able to function for the functionality of the bigger whole (Wyns 1999, Bongaerts 1998). The strength of holons lies in the fact that complex structures can be made that are nonetheless efficient, highly resilient to disturbances, flexible, agile and adaptable (Bussmann & Sieverding 2001, Fletcher et al. 2000, Fischer 1998).

A structure of a several holons cooperating together is called a *holorachy* (Russ & Gerber 2001). Koestler (1967) describes that the members of holorachies represent 'Janus', the Roman god with two faces looking in opposite directions. One face is looking to the subordinate levels; this face is the master of the lower levels. The other face is turned towards the higher levels on which it is dependent. Holorachies are flexible; holons can enter or leave the holorachy at any time. Holons have a recursive structure; one holon can be part of another holon.

⁶ Checkland (1988) discusses the original work of Koestler (1967) and states that 'are' should be replaced by 'may be regarded as'. Organs *may be regarded as* evolutionary holons, instead of organs *are* evolutionary holons.

Holonic control systems have been applied in manufacturing environments (Bussman & Sieverding 2001, Giebels et al. 2001, Salaheddine 2001, Fischer 1998). Brussel et al. (1998) introduce a reference architecture for Holonic Manufacturing Systems called PROSA, an abbreviation of *Product Resource Order Staff Architecture*. The PROSA architecture consists of three different holons (Wyns 1999, Bongaerts 1998).

- A *resource holon* is an abstraction of a production resource such as a factory, machine, conveyor, employee or floor space. A resource holon contains physical parts, e.g. production resources and information processing parts, e.g. control systems. Resource holons contain knowledge on the state of resources and on how to use resources in the production process. Resource holons provide production functionality to surrounding holons.
- A *product holon* contains product knowledge and process knowledge needed to manufacture products, e.g. information on user-requirements, product designs and bills of material. Product holons provide information services to other holons.
- An *order holon* contains the customer orders that have to be carried out by the resource holons. Order holons are responsible for guaranteeing that the assigned work is performed correctly and on time.

The developments in Holonic Manufacturing Systems are mainly focused on controlling activities at the shop floor (Bussman & Sieverding 2001). Holonic control systems have also been applied in the field of transportation (Liu et al. 2000). Bürckert et al. (1997) developed a holonic fleet management system for trucks, called TeleTruck. In TeleTruck basic physical objects, e.g. trucks, drivers, trailers and containers, are modelled as agents. The different agents form a holon to perform transport activities in order to execute customer orders.

The paradigm shift from hierarchical to heterarchical control systems was sketched in the last section. The most recent development is the combination of hierarchical and heterarchical control structures into a holonic control structure. Holons try to combine the advantages of hierarchical and heterarchical control, while disregarding any disadvantages. It should be noted that although agents and holons are different, they also have similar characteristics (Odell 2002). First, agents and holons differ in size. Agents are small entities, while holons often consist of a number of agents (Bussmann & Sieverding 2001, Bürckert et al. 1997). Second, holons can contain physical components. The holons in Holonic Manufacturing Systems contain the actual physical resources, like machines. Agents do not have physical components, they are software based (Bradshaw 1997).

A journey of a thousand miles must begin with a single step.

Chinese proverb

4 Tilburg Underground City Distribution System

An inductive case study, described in this chapter, was designed to explore the research area in line with the inductive-hypothetic research strategy. The idea behind the inductive case study is to identify issues that influence the control of automated logistic systems. These issues form starting points for the development of our support environment, described in chapter five.

The design of logistic control for the future Tilburg city distribution system, abbreviated to Tilburg CDS, was selected as our inductive case study. The Tilburg CDS was chosen based on the consideration for selecting cases mentioned in chapter one. The Tilburg CDS will use automated logistic resources, like Automated Guided Vehicles. Many heterogeneous actors are involved in the design process, like the city council of Tilburg, local shop owners, shoppers and transport organisations. Implementation of the Tilburg CDS has not yet begun. The design process is still at the conceptual phase. The design activities are focused on the logical design and architecting (Sage & Armstrong 2000). This leaves many possibilities open to influence the design of the Tilburg CDS. The Tilburg CDS is a small scale automated logistic system. A limited number of logistic resources is used and the infrastructure has a small scale. This makes the Tilburg CDS well suited for our inductive case study; the problems met in designing automated logistic systems can be studied on a small scale.

4.1 System Description

Tilburg is a middle sized city located in the southern part of the Netherlands. The supply of goods to shops in the inner city of Tilburg is problematic, especially near the main shopping street, the Heuvelstraat. The streets are narrow and lorries that are being unloaded block the progress of other traffic. This leads to increased transportation times and high logistic costs for transport companies. These high logistic costs are paid for by the shop owners and ultimately by the customers. The lorries cause inconveniences for customers and people living in the direct neighbourhood, like noise, vibrations and exhaust gasses. These inconveniences and high logistic costs are causing the inner city of Tilburg to lose its attraction for customers and are reducing the quality of life of local inhabitants. This is endangering the long term economic and social welfare of the inner city of Tilburg.

The city council of Tilburg wants to attract more shoppers and inhabitants to the inner city and has decided to build a new shopping centre at the Pieter Vreede plein in the inner city. The supply of goods to this new shopping centre will have further negative effects on the quality of life in the inner city. The city council of Tilburg, which can be seen as the problem owner, decided to study the possibilities of an automated underground city distribution system to minimise the negative effects of goods distribution. The goal of the Tilburg CDS is to supply the shops at the Pieter Vreede plein and at the Heuvelstraat in a cost effective manner, while minimizing disturbances for the local environment.

The case study described in this chapter formed part of the preliminary design for the Tilburg CDS (DHV 2000). The objective of this case study was:

'To design logistic control concepts for the Tilburg CDS. Construct models to quantify the number of logistic resources, measure the logistic performance and provide detailed insight into the logistic system.'

The design process of the Tilburg CDS is characterised by a large design space; many degrees of freedom exist and many actors are involved (Cross 2000). Within the design process of the Tilburg CDS researchers from several disciplines have to cooperate. Automated underground logistic systems consist of a number of subsystems, like Automated Guided Vehicles, transportation network, material handling stations and control systems. Each subsystem is developed by designers from different disciplines. The AGVs and material handling stations are designed by mechanical engineers, the transportation network by civil engineers and the control systems by logistic experts. These subsystems interact within the integral design of the entire system. Designers of different disciplines have to cooperate to achieve an integral design (Bongaerts 1998). Choices made in one subsystem of the Tilburg CDS influence the design of other subsystems. Many actors are involved in the design process, like the city council, political parties, shop owners, transport companies and city residents. Each actor has its own objectives and means. This creates a complex multi-actor setting in which decisions on the design have to be taken (Dunn 1981).

Within the design of the Tilburg CDS many degrees of freedom exist. Different subsystems have to be designed and each subsystem has its own degrees of freedom. Examples of the degrees of freedom are specifications of the AGVs, layout of the transportation network, design of the terminal and the types of cargo units that are transported. The degrees of freedom make the design process difficult; many factors have to be taken into account (Cross 2000). In order to reduce the complexity of the design process the number of degrees of freedom was limited at the beginning of our case study. Several degrees of freedom were taken away by explicitly making choices within the subsystems, especially in the physical systems. A small number of different layouts of the transportation network and certain characteristics of the logistic resources were chosen and did not change within our case study. The degrees of freedom within the control systems still exist, e.g. routing AGVs through infrastructure and scheduling of transport orders.

The multi-actor, multi-disciplinary setting and the large number of degrees of freedom put extra constraints on the modelling techniques used to construct models of the logistic processes. The models had to be able to answer the questions of actors from different disciplines and be able to deal with the large number of degrees of freedom. The models needed to be easy to communicate to the various actors involved. Not all actors had experience in reading and understanding models. UML-diagrams were used to construct conceptual models of the Tilburg CDS; simulation was used for the empirical models of the Tilburg CDS.

4.1.1 Infrastructure

City distribution systems consist of one or more distribution centres at places that are easily reached by lorries, trains or barges; and are mostly located at the edges of a city. Freight is transported to the distribution centres and transferred onto smaller vehicles that can easily enter the city (Venemans 1994). This way larger vehicles, that cause a lot of disturbances to the local environment, are kept out of cities. A number of cities in the Netherlands have studied the possibilities of CDSs, e.g. Leiden, Amsterdam, and Utrecht (Binsbergen & Visser 2001). The Tilburg CDS expands the concept of a city distribution system to encompass an automated underground distribution system. The Tilburg CDS, sketched in Figure 4-1, connects three areas in and near the inner city.

- A future *terminal*, or *distribution centre*, located near the railway station at the edge of the inner city. Unloading of lorries and trains takes place at the terminal and has to be carried out quickly to reduce the time lorries and trains spend at the terminal. The Tilburg CDS can use a Just-In-Time strategy to supply stores (Vollmann et al. 1997, Bowersox & Closs 1996, Ballou 1992). Within this Just-In-Time strategy cargo units are stored at the terminal and not at the shops. When a shop actually needs a cargo unit, the cargo unit is retrieved from storage and transported to the shop. This seems a very promising strategy, since shops commonly have only limited space available for storage. Shops can use their limited floor area more effectively for sales instead of storage by using a Just-In-Time strategy.
- A future *shopping centre* at the Pieter Vreede plein. The shopping centre will be constructed at (level 0 and 1) and below (level -1 and -2) surface level. A number of offices, houses and entertainment centres will also be located at the Pieter Vreede plein.
- The existing *shops* in the Heuvelstraat and its adjacent streets. These are the main shopping streets in the inner city of Tilburg.

Figure 4-1: Tilburg city distribution system (Versteegt et al. 2001)

The investments needed for the Tilburg CDS are high and there are a number of technological issues regarding the logistic resources that still have to be solved (DHV 2000). The city council decided that the Tilburg CDS will be constructed in three phases. In the first phase, up to 2005, the shopping centre at the Pieter Vreede plein will be realised. The supply of goods will be carried out in the traditional manner; lorries will drive directly to a small terminal located at the shopping centre. In the second phase, 2005 to 2010, a terminal at the railway station and an underground connection to the shopping centre at the Pieter Vreede plein will be constructed. Automated Guided Vehicles will be used to supply the shopping centre. In the third phase, 2010 to 2020, the system will be extended to the Heuvelstraat. The transport of cargo units from the shopping centre to the Heuvelstraat will take place at surface level or underground. The Tilburg CDS stretches from a small labour-intensive logistic system in the first phase to a larger automated underground logistic system in the third phase.

4.1.2 Logistic Resources

The Tilburg CDS will use various logistic resources, such as AGVs, material handling stations, infrastructure elements, elevators and ramps. Labour costs make up a large part of the total logistic costs of urban goods distribution. The Tilburg CDS will use automated logistic resources to reduce labour costs. Although the investments for the Tilburg CDS are high it is expected that goods distribution will be carried out cost effectively by eliminating labour costs (DHV 2000). A number of employees will still be needed mainly at the terminal (Versteegt & Geerdes 2000). The AGVs are fully automated. It might be necessary for a CDS employee to travel with an AGV for safety reasons, when AGVs drive through shopping streets. Although there is no detailed technical design of the AGVs available some characteristics have already been fixed in the design (DHV 2000).

- The vehicles will have a maximum speed of 3 m/s.
- The dimensions of the AGVs will be 2.3x1.4x1.9⁷. A trade-off has been made between the size of the cargo units and the diameter of the tunnels. Larger AGVs can transport more types of cargo units, but large tunnel diameters are needed. Larger tunnels are more expensive to construct than smaller tunnels. The AGVs will be able to transport cargo units⁸ that are widely used in urban goods distribution, while the diameter of the tunnels is kept small.
- The AGVs will have a small turning circle. There will be little space available for AGVs to manoeuvre in the underground setting of the Tilburg CDS.
- The AGVs will be able to load and unload cargo units autonomously without human intervention.

The Tilburg CDS uses several levels of infrastructure; below and at surface level. AGVs have to transport cargo units between different levels. There is a range of possibilities to connect the different levels. The two most promising possibilities for the Tilburg CDS are ramps and elevators. Ramps need little maintenance and are robust, but AGVs need powerful engines to drive up slopes. Elevators need little space and the AGVs do not need to have such powerful engines, but elevators need maintenance and can only transport one vehicle at a time, which makes them a potential bottleneck. The long tunnels,

⁷ All sizes in: length x width x height in metres.

⁸ The AGVs will be able to transport three standardised types of cargo units; Euro pallets, industry pallets and rolling containers.

which will connect terminal and shops, will be single lane and bi-directional. AGVs will be able to drive through tunnels in both directions. Only AGVs driving in the same direction will be allowed to enter the tunnel simultaneously. A control system has to decide which AGVs are allowed to enter the tunnel and which AGVs have to wait.

4.2 Conceptual Models

The framework for simulation, sketched in chapter two, was followed to construct simulation models of the Tilburg CDS. A number of conceptual models were constructed of the physical components and control systems after the problem identification and problem formulation. A class diagram of the physical elements of the Tilburg CDS is shown in Figure 4-2. An activity diagram of the primary transport processes is shown in Figure 4-3. The class diagram and the activity diagram were used to gain insight into the physical components and as a communication tool during the design process.

Figure 4-2: Class diagram of the physical components of the Tilburg CDS⁹

The primary transport processes of the Tilburg CDS are sketched in activity diagram Figure 4-3. The secondary processes were not modelled in the activity and class diagrams, e.g. like recharging batteries of AGVs and maintenance.

⁹ An introduction in class diagrams can be found in Fowler & Scott (2000) and Rumbaugh et al. (1999). The classes are depicted in rectangles. Each class is described by its name (top rectangle), attributes (middle rectangle) and operations (bottom rectangle). The relations between classes are depicted by the lines and numbers between the classes.

Figure 4-3: Activity diagram of the primary transport processes of the Tilburg CDS¹⁰

4.2.1 Logistic Control Concept

The first objective of this case study was to develop logistic control concepts for the Tilburg CDS. The logistic control developed for the Tilburg CDS has a layered structure, following literature described in chapter three. The logistic control consists of two layers; customer order management and resource control, see Figure 4-4.

¹⁰ More information on activity diagrams can be found in Fowler & Scott (2000) and Rumbaugh et al (1999). The primary activities of the Tilburg CDS are depicted in the ovals. The beginning of the process is depicted by the filled circle; the end by the double circle. Broken lines depict the courses of action of physical objects. The uninterrupted line represents requests from the shops to retrieve cargo units from storage at the terminal, which are control actions.

The logistic system-being-controlled is located below the two control layers. Customer order management is responsible for dealing with the arrival of lorries and customer orders from the shops. The resource control is responsible for controlling the activities of the logistic resources. The main task of the resource control layer is the guidance of AGVs through the transportation network. Other tasks of the resource control layer consist of controlling the access of tunnels and controlling CDS employees.

Customer orders from the shops and information on the arrival of lorries arrive at customer order management. Customer order management uses this information to schedule docks and schedule CDS employees. Customer order management sends the schedules as coordination actions to the resource control. The resource control is responsible for carrying out schedules developed by customer order management. The resource control sends control actions to the logistic resources to perform the scheduled logistic services.

Figure 4-4: Logistic control architecture of the Tilburg CDS

The logistic control is based on the feedback control paradigm, described in chapter three. The control system is reactive and push oriented. The control system reacts to the arrival of lorries at the terminal and to requests of the shops owners. Cargo units are pushed from the terminal to the shops.

4.3 Empirical Models

The design and conceptual models of the physical components and the control system were translated into a simulation model to quantify the number of logistic resources, to measure the logistic performance and to provide detailed insight into the dynamic behaviour of the Tilburg CDS. The simulation model was constructed in Arena¹¹, a discrete event simulation package (Swets & Drake 2001, Kelton et al. 1998). We chose to construct the empirical model in Arena for a number of reasons. Arena has a flow oriented paradigm that closely represents the flows of cargo units in logistic systems and offers features for two-dimensional animations to represent the dynamic behaviour of the system.

Verification was performed by structured walk throughs of the simulation model. The computer code was discussed with a group of experts on simulation and logistics during the verification process. The simulation model was structurally validated (Sol 1982) as there is no real world data available on the Tilburg CDS. Animation was used to study the behaviour of AGVs and to follow cargo units through the model. The structure of the model was compared to the experiences of experts from the field of automated logistic systems. The experts made rough estimates on the logistic performance of the Tilburg CDS and these estimates were compared to the results of the simulation model (Versteegt & Geerdes 2000, DHV 2000).

The validation process led to a validated simulation model of the Tilburg CDS. The validation process also provided the problem owner with more insight into the problem situation. During the validation process it became clear that the results of the simulation model partially represented the expectations of the domain experts. The main difference between the results of the simulation model and expectations of the domain experts was the utilisation of the logistic resources (Versteegt & Geerdes 2000). The problem owner and domain experts expected higher utilisations of the logistic resources, especially the AGVs. The simulation model showed low overall utilisations of the logistic resources and a limited number of transported cargo units. This was mainly caused by deadlocks between AGVs behind shops at the shopping centre. In a deadlock AGVs block each others route in such a way that none of the AGVs can continue to drive (Nauta 1996). The routing of AGVs in feedback control systems proved to be problematic. The routing of AGVs is a difficult task within an underground system; there is only limited space available for AGVs to manoeuvre. The space behind the shops, called a corridor, is very limited. Deadlocks can easily occur when several AGVs are driving in the same corridor.

The resource control layer was extended to improve the logistic performance. The resource control layer was extended by adding a pro-active feed-forward control loop that prevents deadlocks before they can occur. AGVs are rerouted when a possible deadlock might occur, see Figure 4-5.

The first logistic control system is a feedback system that has a reactive nature. The second logistic control system combines feedback and feed-forward control. The reactive customer order management responds to the arrival of lorries and customer orders. The pro-active resource control looks 'ahead' to see whether the AGVs might cause deadlocks. The logistic performance of the combined reactive and pro-active control system appeared to be higher than the feedback control system, due to the prevention of deadlocks.

¹¹ Arena version 3.51

Figure 4-5: Re-routing algorithm to prevent deadlocks (Versteegt et al. 2001)

A second validation session was held with domain experts to validate the simulation model of the extended control system. The domain experts agreed that the simulation model represented the Tilburg CDS closely enough to use the simulation model in the design process of the Tilburg CDS. In the remainder of the chapter the simulation model of the extended control system is used to determine the number of logistic resources and to quantify the logistic performance of the Tilburg CDS.

4.3.1 Quantification of Logistic Resources and Logistic Performance

The number of required logistic resources and the performance of the logistic system were studied for three alternatives. Each alternative represents one or two of the phases mentioned in section 4.1.

1. *Terminal at Pieter Vreede plein with traditional supply.* This alternative represents the first phase of the Tilburg CDS. A small terminal will be constructed at the Pieter Vreede plein. Lorries will drive directly to the terminal and cargo units will be transhipped and distributed manually.

2. *CDS partially underground.* This alternative was used to study the second and third phase of the Tilburg CDS. The connection between the terminal and the shopping centre will be located underground; the connection between the Pieter Vreede plein and the Heuvelstraat will be located at surface level.
3. *CDS fully underground.* This alternative represents the third phase of the Tilburg CDS. All connections in the Tilburg CDS will be underground.

Two scenarios were evaluated for each alternative. The scenarios represented different transport demands, which were translated into different arrivals patterns of lorries and customer orders (Versteegt & Geerdes 2000). The first scenario, the 'Tuesday' scenario, represented the busiest day of normal weeks. The second scenario, 'Christmas' scenario, represented extremely busy days in December just before Christmas. The simulation model was used to determine the number of logistic resources needed in the Tilburg CDS. The number of required resources is given in Table 4-1.

Table 4-1: Quantification of the required logistic resources¹²

	Tuesday/Christmas scenario		
	Terminal with traditional supply	CDS (partially underground)	CDS (fully underground)
<i>CDS-employees (#)</i>	13	15 ¹³	7
<i>AGVs (#)</i>	0 ¹⁴	8	20
<i>Docks at terminal (#)</i>	4	8	8
<i>Terminal storage (# cargo units)</i>	20/20	230/390	230/390

The number of logistic resources in Table 4-1 was used as input to study the logistic performance of the Tilburg CDS. Three performance indicators were used, throughput time of lorries at the terminal, number of waiting lorries and throughput times of cargo units. The two performance indicators of the lorries were used, since the available space for waiting lorries will be limited near the terminal. The logistic performance of the Tilburg CDS is given in Table 4-2.

¹² The results given in Table 4-1 and Table 4-2 are the averages of 12 simulation runs. Only the averages are given. The problem owners and other stakeholders did not show any interest in the variations around the averages, the number of runs and the start-up period. These characteristics of simulation studies were only studied by the simulation model builders.

¹³ The AGVs are driverless, but CDS employees will have to travel with the AGVs in Heuvelstraat for safety reasons.

¹⁴ The goods are distributed manually.

Table 4-2: Logistic performance of the Tilburg CDS

	Tuesday/Christmas-scenario		
	Terminal with traditional supply	CDS (partially underground)	CDS (fully underground)
<i>Throughput time lorries at terminal (minutes)</i>	27/90	9/11	9/11
<i>Waiting lorries (#)</i>	13/50	5/12	5/12
<i>Throughput time cargo units (minutes)</i>	6/6	15/16 (Pieter Vreede) 19/22 (Heuvelstraat)	15/16 (Pieter Vreede) 19/21 (Heuvelstraat)

It is possible to compare the results of the “CDS (partially underground)” scenario and “CDS (fully underground)” scenario. This comparison was important for the city council to decide whether the Tilburg CDS will be completely or partially underground. Both scenarios could not be compared to the “terminal with traditional supply” scenario. The goal of the first scenario was to develop a transition path between the current and future situation of goods distribution in the inner city of Tilburg.

The numeric results provided the city council insight into the scale of the Tilburg CDS and its logistic performance. The number of logistic resources was used to calculate the investment needed to construct the Tilburg CDS. The logistic performance was used to check if the Tilburg CDS will be able to facilitate the customer demands.

4.3.2 Detailed Insight into the Dynamic Behaviour

The simulation model provided quantitative information and detailed insight into the dynamic behaviour of the logistic resources. Two-dimensional animations can easily be constructed in Arena (Swets & Drake 2001, Kelton et al. 1998). The animation models showed the movements of AGVs and the unloading of lorries. Detailed animation models were made of critical areas of the Tilburg CDS, like the corridors behind the shops and the terminal at the railway station, see Figure 4-6.

Figure 4-6: Screen dumps of the animations of the Tilburg CDS

The simulation model provided detailed insight into the dynamic behaviour of the Tilburg CDS. First, the logistic performance of the system does not increase when more AGVs are added to the system. It was expected that the logistic performance of the Tilburg CDS would increase when more AGVs are added to the system. The simulation model showed that the logistic performance of the Tilburg CDS decreases when more AGV are added. When more AGVs are moving through the system they interact more than expected, especially in the corridors and at the terminal. Second, it is not feasible for lorry drivers to deliver cargo units directly from the terminal to the shops in phase I. Lorries of drivers that have to deliver cargo units to the shops will occupy docks unnecessarily. Only a limited number of docks is available and lorries will have to wait a long time before a dock is available; waiting times of up to several hours will be common. Third, it is not advisable to use elevators to move AGVs up/down a level at the shopping centre on the Pieter Vreede plein. When an elevator breaks down the performance of the entire logistic system will decrease strongly. Ramps are robust and can even be used partially when an AGV breaks down on the ramp. Finally, the supermarket at the Pieter Vreede plein claims many AGVs. Cargo units for other shops have to wait long before they can be transported. This problem was solved by limiting the number of AGVs that the supermarket can claim in each time window. The cargo units for the supermarket are stored temporarily at the terminal and delivered to the supermarket spread out evenly over the day, instead of immediately after a lorry arrives containing goods for the supermarket.

4.4 Learning Moments

A number of learning moments was identified on controlling automated logistic systems during the inductive case study. The learning moments are clustered into three categories; automated logistic systems, logistic control and modelling automated logistic systems and their control systems.

4.4.1 Learning Moments on Automated Logistic Systems

Large scale automated and/or underground logistic systems will be *built in phases* (IPOT 2000). In many cases it is not possible for problem owners to finance such systems in one time. Constructing the logistic system in phases allows the investments to be spread over a number of years. Constructing automated logistic systems in phases makes it possible to use small scale systems as test environments or pilot studies. Issues regarding technology can be solved in a small scale setting. The logistic systems can be expanded into larger, more complex, systems after the technical issues have been dealt with.

Designing automated logistic systems is a *complex activity*. The design space is large and characterised by large numbers of *degrees of freedom*, it requires *multi-disciplinary* interactions and has a *multi-actor* setting. Most of the initiatives being undertaken on large scale automated underground logistic systems are still in their conceptual phases or feasibility studies are being conducted (IPOT 2000, 1998). During these preliminary designs many degrees of freedom exist. The design space has to be narrowed to reduce the complexity of the design process. The design space can be reduced by making explicit choices in the designs of subsystems, like choosing a specific layout of the transportation network and choosing specific technical specifications for the logistic resources. Such choices can be adjusted as new insight is gained into the logistic system in later phases of the design process.

The *transportation network* and the *available space* are the two most critical resources in automated logistic systems. The transportation network and the available space are separated from other traffic. Achieving this separation is expensive, especially when the separation is achieved by using an underground infrastructure. The transportation network is kept to a minimum to reduce costs. There is little space available for logistic resources and storage of cargo units. The AGVs have to drive closely spaced and with conflicting routes (Lindeijer 2003). Deadlocks can easily occur in such situations. Control systems have to be developed to prevent deadlocks and guarantee the safe operation of AGVs while retaining high levels of efficiency. These are conflicting objectives (Versteegt & Verbraeck 2001).

Large scale automated logistic systems are *abstract systems* (Latour 1996). Actors find it difficult to picture automated logistic systems and to understand the behaviour of such systems, especially those actors that have little knowledge of logistics and transportation. There are few real world implementations available of large scale automated logistic systems at this moment, such as automated containers terminals (chapter one). Automated logistic systems have to be made as concrete as possible in the design process. Making the systems more concrete stimulates research and makes it easier to mobilise decision makers around a project. Automated logistic systems can be made more concrete by conducting pilot studies, testing them in laboratory settings and visualizing them by using simulation and animation models.

4.4.2 Learning Moments on Logistic Control

Within the Tilburg CDS *little attention was paid to the control systems*, although control systems strongly determine the performance of logistic systems (Evers et al. 2000, Jing et al. 1998). Most attention was paid to the design of physical aspects of the Tilburg CDS, e.g. transportation network, AGVs and the terminal. We observed that the problem owner and other actors had little insight into the importance of control systems. Logistic control for the Tilburg CDS was developed on an *ad hoc* basis; there was little knowledge available regarding the decisions that needed to be taken. No structured approach or methodology was followed to develop the control systems. The result was that most of the attention was focused on controlling the logistic resources, e.g. movements of AGVs and transshipment operations. The scheduling of customer orders received no attention. All aspects of logistic control need to be taken into account to design adequate control systems; control of logistic resources and customer order management.

Little is known about the exact technical specifications of the automated logistic resources used in the Tilburg CDS. Some general characteristics have been decided, e.g. speed and size. It is necessary to have detailed insight into the technical characteristics of automated logistic resources to design automated logistic systems and their control systems. The exact specifications influence the control systems and the performance of the logistic system. For example, throughput will differ if AGVs can travel at higher speeds or are able to carry multiple loads. It is, therefore, not possible to design logistic control systems without a certain level of technical knowledge of the logistics resources. A joint design of the automated logistic systems and the control systems is needed.

Logistic control systems have to be *independent of the transportation network*. Different layouts for the transportation network were studied within the design of the Tilburg CDS. The exact layout was not known even after the preliminary design process for the Tilburg CDS was finished. The transportation network will also be expanded during the operational phases of the Tilburg CDS. The control systems can be used for any possible layout of the transportation network, when they are independent of the transportation network.

Control systems for automated logistic systems have to be *scalable*. Control systems have to deal with small numbers of logistic resources and few customer orders during early start-up phases. In later phases control systems have to deal with larger numbers of logistic resources and high transport demands. The performance of control systems, in terms of response times, should not decrease when the number of logistic resources and transport demands increase (Smith & Williams 2002).

4.4.3 Learning Moments on Modelling Automated Logistic and Control Systems

Tilburg CDS will use newly designed AGVs. The design of the AGVs had not yet been finished. Some of the characteristics of the AGVs had been decided, like the maximum speed and size. Many issues regarding the technology of the AGV still have to be solved, e.g. (un)loading of cargo units and guidance. These technological issues strongly determine the performance of the CDS Tilburg. A simulation model was constructed of Tilburg CDS. The simulation model was used to quantify the required number of logistic resources, to measure the logistic performance and to provide detailed insight in the logistic system. **Most of the technical aspects were not taken into account in the simulation model.** Some technical aspects of the AGVs were modelled, but only after a lot of assumptions and simplifications had been made. For example, technical failures of the AGVs were modelled implicitly by

reducing the maximum allowed utilisation of the AGVs. The simplifications and assumptions led to an unrealistically modelled behaviour of the AGVs. The communication between the control systems and AGVs was not taken into account. Communication is a vital aspect in automated logistic systems (Ulrich & Düring 1995). The communication is twofold. First, there is the communication between control systems and automated logistic resources. Second, there is communication between control systems.

Simulation models and animation models were used to support the communication between designers and the problem owner during the design. Animation models were used to present the design of the logistic system to actors, like political parties, shop owners and inhabitants. Actors got a better understanding of the logistic systems through the animations. We observed that the trust of the actors in the automated logistic system was increased as the actors got more insight into the system and more understanding of the behaviour of the system through the animations.

4.5 Towards a Support Environment

Designing control systems for automated logistic systems is a complex activity. Our research objective is to develop a support environment for designing control systems for automated logistic systems. Such a support environment should support designers in developing control systems for automated logistic systems. A number of the issues that were found during our inductive case study have to be taken into account in such a support environment.

- The design of control systems received little attention in the Tilburg CDS. During the design process most attention was focused on designing the infrastructure, AGVs and docks. We observed that most decisions on the logistic control were taken on an ad hoc basis. Designing control systems for automated logistic systems is a complex activity. Designers of different disciplines are involved in the design process. There is a need to provide a common background or a shared space of understanding (Schrage 1990, Senge 1994). This common background should provide involved actors insight into the decisions that need to be taken in designing control systems for automated logistic systems.
- When designing large scale automated logistic systems it is necessary to have detailed insight into the technology used in the logistic resources and into the communication. Large scale automated logistic systems will use new technologies, e.g. new types of AGVs (Kusters 2000) and new types of material handling systems (Pielage 2001). These are new technologies that have not yet been proven in practice. Many issues still have to be dealt with regarding these technologies (chapter one). The design of the logistic resources and the design of the control systems were developed independently in the design of the Tilburg CDS. The interactions between the technology, communication and control systems were simplified. The support environment should facilitate the joint design of the logistic resources, communication and control systems.

In the following chapter we develop a support environment for designing control systems for automated logistic systems.

*There should be no combination of events for which the wit of man cannot conceive an explanation.
Simple as a mental exercise, without any assertion that it is true, let me indicate a possible line of thought.
It is, I admit, mere imagination, but how often is imagination the beginning of truth.*

Sir Arthur Conan Doyle

5 Support Environment for Designing Logistic Control

A support environment to design control systems for large scale automated logistic systems is outlined in this chapter. This support environment can be used to support designers in developing control systems for large scale automated logistic systems. The proposed support environment consists of three parts. The first part is a generic structure for control systems. A holonic structure is introduced for controlling large scale automated logistic systems. The second part consists of a number of design guidelines that can be followed when designing control systems. Support facilities for the evaluation of the designed control systems are addressed in the third part of the support environment.

5.1 Introduction

Checkland (1981) states that decision makers may not be able to specify their problems precisely as the amount of problems they have to deal with simultaneously and the causes of these problems in a real life context are often overwhelming. Decision making and design processes are complex tasks. Simon (1969) introduces 'bounded rationality' to express the idea that people have limited mental capacities and can only cope with a limited amount of information and alternatives. The design of control systems for large scale automated logistic systems is a complex activity. Control systems for logistic and transport systems are classified among the most complex control systems in existence (Pyle et al. 1993). Our inductive case study provided insight into the complexity surrounding the design of control systems for automated logistic systems (chapter four). First, many actors from several disciplines are involved in the design process, each with different and often conflicting objectives. Second, many decisions in the design process are taken on an ad hoc basis. The designers and other actors do not follow a structured approach to design control systems. Third, much of the technology used for the logistic resources is complex and has not yet been proven in practice. Fourth, many actors have little understanding of the possibilities and operational behaviour of automated logistic systems.

We develop a support environment to support designers in developing control systems for large scale automated logistic systems. The support environment has two functions. First, it can be used as a foundation for developing control systems for automated logistic systems. The support environment helps designers and other actors to deal with the large amount of topics that need to be addressed when designing control systems. The support environment is designed to organise knowledge and design activities. Design guidelines and good examples are provided to support this process. The support environment is intended to help designers find their way through the design process as easily as possible. Second, the support environment provides a basis for evaluating control systems and recommends support facilities for evaluation. The support environment consists of three parts.

1. A generic structure for the design of control systems for automated logistic systems. The generic structure is presented in the form of a reference architecture. The reference architecture shows the overall structure of control systems and can be used as a basis to develop case specific system architectures.
2. A number of design guidelines to support designers in designing control systems. The design guidelines can be followed when developing case specific system architectures for control systems. The focus of these design guidelines is split between the structure of logistic control systems and communication.
3. Support facilities to evaluate control systems and automated logistic resources are recommended by the support environment. The support facilities can be used to evaluate the designed control systems before commissioning and implementation.

Several frameworks for designing complex systems can be found in literature (Pielage 2002, Cross 2000, Sage & Armstrong 2000). The proposed support environment is not constructed for one specific design framework; it is independent of the design framework. Sage & Armstrong (2000) propose a framework for designing complex systems, which consists of a number of sequential phases. The application of the support environment in the framework of Sage & Armstrong (2000) is sketched in Figure 5-1.

Figure 5-1: Application of the support environment

The development of generic models, or architectures, of logistic systems is an important aspect in the further development of large scale automated logistic systems (Lodewijks 2001). The introduction of new technologies without the simultaneous introduction of architectural approaches can have disastrous effects, especially as projects grow in size and complexity (Bass et al. 2003, Szyperski 1998). Designers can use architectures to make successful decisions in their designs and reuse successful designs from earlier projects (Bass et al. 2003, Gamma et al. 1995). Architectures are used to integrate separate but interfacing issues of a system and to define guidelines that help designers to achieve the overall design target without having to invent ad hoc compromises (Bongaerts 1998).

We propose an architecture for control systems. The term control systems is used in a broad sense; it encompasses all of the software, electronics, instruments and actuators required to achieve the goals of the system (Auslander et al. 2002). Our focus lies especially on the type of decisions that need to be taken and the implementation in software. Our definition of an architecture is, therefore, based on software architectures. A software architecture is (Bass et al. 2003, Bosch 2000):

"The structure, or structures, of the system, which comprise software elements, the externally visible properties of those elements and the relationships among them."

The architecture of control systems we present here is a reference architecture. Reference architectures are meta-architectures; they are architectures for system architectures (Bongaerts 1998). Wyns (1999) defines reference architectures¹⁵ as an abstraction of a generic solution that provides a set of models, a set of coherent engineering and design principles, and eventually a set of tools and a methodology used in a specific domain. A reference architecture is aimed at structuring designs of specific system architectures and contains one or more of the following aspects: a generic system structure, system components, behaviour, responsibilities, dependencies, interfaces, data, interactions, constraints, design rules and unified terminology (Wyns 1999, Bongaerts 1998, Selic et al. 1994). System architectures are abstractions or case specific architectures for a single system (Selic et al. 1994).

5.2 Requirements for Logistic Control Systems

We identified a broad range of issues in designing control for automated logistic systems during our inductive case study (chapter four). These issues are translated into requirements for control systems of automated logistic systems in this section. The requirements will be used to evaluate the designed control systems when the support environment is applied.

Logistic control systems have to be scalable. Scalability is the ability of a system to continue to meet its response times or throughput objectives as the demand for the systems functions increases (Smith & Williams 2002). Scalability means that a system and its application software do not have to be changed when the scale of the system increases (Tari & Bukhres 2001). Scalability has become a very important aspect of software and control systems, especially for distributed applications. A scalable control system can deal with small and large numbers of logistic resources and transported freight volumes without major losses of performance in terms of response times. The limits of scalability are case specific; the characteristics of the logistic system for which the control system is designed determine the number of logistic resources and transported volume that need to be controlled.

¹⁵ In the remainder of this dissertation we use term architecture as an abbreviation of reference architecture for the sake of convenience.

Logistic control systems have to be extendable. The operational life spans of large scale automated logistics systems are long. During this long period the automated logistic system will be required to offer new logistic services to customers, e.g. origins, destinations and customers will be added. Control systems need a structure that can facilitate such extensions without needing to make modifications to the structure of the control systems (Lindeijer 2003, Bongaerts 1998). For example, the Tilburg city distribution system will be constructed in phases to spread the investment for its construction over a longer period (chapter four). The Tilburg CDS will start as a small labour intensive system and will be extended to a larger automated logistic system. The infrastructure will be extended, the number of logistic resources will be increased and the level of automation will be increased during each phase. The control systems have to be able to facilitate such extensions without modifications to the structure of the control systems. *Logistic control systems have to be adaptive.* An adaptive control system must be able to deal with changes in the system and its environment without modifications to the structure of the control system (Bass et al. 2003). The system and its environment will change constantly; new types of logistic resources will be added to the system. A control system must be able to facilitate such changes without there being a need to make modifications to the structure of the control system.

Logistic control systems should enable efficient use of the logistic resources. The initial investments needed for automated logistic systems are high. The logistic control systems have to make efficient use of the logistic resources to justify such investments (Evers et al. 2000, Hammond 1986). Infrastructure especially can be a critical resource and has to be used efficiently. Large scale automated logistic systems are separated from other traffic. This separation is achieved by using a separated infrastructure, which can be costly to construct. The infrastructure will be minimised to reduce construction costs. Expanding an existing infrastructure is also difficult; constructing infrastructure is costly and has long throughput times.

Logistic control systems have to be robust. Robust control systems are able to continue to operate when disturbances occur, e.g. AGV breakdowns and communication failures (Bongaerts 1998). The technology used in large scale automated logistic systems has not yet been tested in practice (chapter four). It is expected that the technology of the logistic resources will show high levels of failure during the start-up phases of the logistic systems (Pielage 2001, Rijsenbrij et al. 2000). Control systems will have to be able to deal with high levels of failures. The separated setting of automated logistic systems adds another factor to the robustness of the system; parts of the system may be difficult to reach when they break down.

Logistic control concepts have to be independent of technology. Control systems and logistic resources from different vendors and manufacturers will be used in large scale automated logistic systems. Each control system and logistic resource will use its own specific technology. The control systems have to be able to work with the different technologies, both for hardware and software.

Logistic control systems have to be tested under real world circumstances before implementation. Most of the testing of control systems for automated logistic systems takes place on the shop floor after commissioning at this moment (McGregor 2002). This is an expensive, risky and error-prone way of testing control systems (McGregor 2002, Mueller 2001). Failures and disturbances during these tests disturb normal operations. An approach to test control systems is needed that can be carried out before commissioning, but it still has to represent real world circumstances. This testing under real world circumstances means that the logistic control system should be able to deal with incomplete and fuzzy

information (Ulrich & Düring 1995). Large scale automated logistic systems will use new technologies in the logistic resources. Not much is known on these technologies, they are not yet proven in practice. Technical aspects and communication have to be taken into account without making too many assumptions or simplifications in the design and construction of models of large scale automated logistic systems (chapter four).

5.3 Support Environment Part One: Generic Structure of Logistic Control

The first part of the support environment is a generic structure for control systems for automated logistic systems. The generic structure is a holonic structure. The theory behind holons was described in chapter three.

5.3.1 Holonic Logistic Control

We choose to use a holonic structure since such a structure closely accommodates the characteristics of large scale automated logistic systems. First, a holonic structure combines the autonomy of individual holons and the cooperation between holons. Large scale automated logistic systems use heterogeneous sets of automated logistic resources, like AGVs and material handling stations. Each set of logistic resources uses its own technology and has its own specific control systems. The different types of logistic resources have to cooperate to perform logistic services for customers. Each set of resources has its own separate autonomous holon in the holonic structure. All holons are part of the entire holonic structure and they cooperate to execute customer orders. Second, a holonic structure combines a hierarchical structure with a distributed setting. Logistic systems and their geographical settings are often modelled as hierarchical structures. Logistic systems are composed of a number of geographical areas, and each area consists of smaller areas until some elementary form of an area is reached (Simon 1969). While this modelled geographical setting has a hierarchical structure, the actual physical logistic services that are performed are not modelled as a hierarchical structure. This structure of hierarchy within a distributed setting is represented in holons (chapter three, Brussel et al. 1998). A holon has a number of hierarchical layers of control, while the physical parts are distributed. Finally, a holonic structure consists of stable systems and has a natural reactive-ness to disturbances, like machine break downs (Fischer 1998, Bongaerts 1998). The technology that will be used in large scale automated logistic systems is new and not yet proven. It is expected that such technology will initially show high levels of failure during the start-up phases (Rijsenbrij et al. 2000). A holonic structure should be able to deal with high levels of disturbance and failures.

5.3.2 Logistic Holons

A logistic holon is an autonomous and cooperative system for controlling the scheduling and the execution of logistic services. The holons in our support environment have the following characteristics.

- Holons have a *high degree of autonomy*. Holons create their own plans and are responsible for controlling the execution of their own plans.
- Holons are *goal oriented*. A holon works towards achieving its own goal. A goal is a state to be achieved; sub-goals are the result of the decomposition of goals (Meystel & Albus 2002).
- Holons *cooperate with other holons*. Holons cooperate with other holons to perform logistic services they cannot perform on their own. Holons develop and exchange mutually acceptable

plans with other holons. Individual holons are responsible for controlling the execution of the plans.

- Holons contain *control components and representations of physical resources*. The actual physical resources are placed outside the holons. The holons contain representations of the logistic resources.
- Holons have an *open character*. Holonic control systems are able to incorporate new holons, to remove or modify existing holons and to communicate with other control systems.

We follow the developments in Holonic Manufacturing Systems and identify three types of holons in holonic control systems, as can be seen in Figure 5-2.

- An *order holon* is responsible for dealing with customer orders and has to decide which resource holons are contacted to perform logistic services. Order holons can be seen as the interfaces between customers and logistic systems. An order holon is an internal customer in the logistic system; it contacts resource holons with requests to perform logistic services. The resource holons perform logistic services on behalf of the order holons. Order holons can not force resource holons to perform certain activities, because of the holonic structure. Order holons request the resource holons to perform logistic services. The resource holons are autonomous and responsible for controlling their own activities.
- A *resource holon* is responsible for scheduling and controlling the execution of logistic services provided by a set of logistic resources, e.g. AGVs and material handling stations. A resource holon contains control components and representations of the physical logistic resources. Resource holons have knowledge of the logistic services the resources can perform, their current state and schedules.
- A *load holon* is responsible for controlling the cargo units that are transported, transferred and stored. The primary function of a load holon is to provide information services to order holons and resource holons. Load holons contain information on how to perform logistic services on a cargo unit, e.g. how to deal with dangerous goods. A load holon can take control actions, e.g. turning on/off reefers to influence the temperature of cargo units. Load holons do not contain the actual physical cargo units; they contain representations of the cargo units.

Logistic systems will be controlled by several holons of each type. At least one order holon, one resource holon and one load holon will be present in a holonic control system. In practice several holons of each type will be located in large scale automated logistic systems.

Figure 5-2: Holonic control systems consist of three types of holons

Although the holonic structure follows the developments in Holonic Manufacturing Systems, abbreviated to HMS, there is a major difference. The resource holons contain the actual physical components in HMS. The resource holons do not contain the actual physical resources in the holonic structure for logistic control systems. The resource holons contain representations, or models, of the logistic resources. This makes the resource holons independent of the technology used inside the logistic resources. There are still many uncertainties regarding the technology in large scale automated logistic systems. The exact specifications of AGVs, material handling stations and infrastructure elements have not yet been decided. The logistic resources are placed outside the resource holons to make the resource holons independent of the technology. When changes are made to the technology of the logistic resources this does not affect the resource holons. The representation of the logistic resources does not change when the logistic resources are changed.

5.4 Support Environment Part Two: Design Guidelines for Logistic Control

A number of design guidelines for control systems is presented in this section. The design guidelines deal with the philosophy behind the holonic structure for logistic control systems. The design guidelines are divided into guidelines for the holonic structure and guidelines for communication.

5.4.1 Hierarchical Layered Control

Hierarchy is used to reduce complexity in decision making (Simon 1969). A complex problem is divided into smaller problems that are easier to solve. Hierarchy is often used in logistic control systems (chapter three). Hierarchy divides the power of decision among layers. The top layers have the highest level of power; the lower layers have less power. Higher layers decide the boundaries between which lower layers have to operate. Control actions and coordination actions are sent from higher layers to lower layers. The lower layers have to perform the control actions received from higher layers.

An important aspect in hierarchical control structures is the number of layers. The exact number of layers is an arbitrary question. There are no formulas to calculate the number of layers; in practice and theory different numbers of layers are used (Euwe 1999). The distinction into layers can be based on functional decomposition and differences in technologies; each layer offers different functionalities and uses its own specific technologies. A basic distinction is made between two layers in many AGV based

systems; the control layer and the physical AGV layer (Ulrich & Düring 1995, Cameron & Probert 1994, Hammond 1986). In other AGV based systems the control layer is divided into separate layers (Lindeijer 2003, Vlacic et al. 2001, Nauta 1996).

Design guideline 1

The resource holons have a layered structure. Three layers are identified; resource management, resource control and resource representation.

The resource holons in the holonic structure consist of three different layers; *resource management*, *resource control* and *resource representation*, as can be seen in Figure 5-3. The first distinction made is that between control system and system-being-controlled. This is a functional and technological decomposition. The top layers provide control functionalities, while the bottom layer is responsible for carrying out the physical services. The technologies used in the control systems and systems-being-controlled also differ. The control layer consists of control systems and control software. The system-being-controlled contains representations of the physical resources. The second distinction is the division of the control layer into two separate layers; resource management and resource control. This is a functional decomposition based on the span of control of the layer. The *resource management layer* is responsible for controlling entire sets of logistic resources. *Resource control layers* are each responsible for controlling exactly one logistic resource. The functionalities offered by the management layer differ from the functionalities of the control layers. For example, within in an AGV holon the management layer is responsible for controlling all AGVs, while the control layers are responsible for controlling single AGVs. The AGV management layer is responsible for positioning idle AGVs and scheduling the entire fleet of AGVs. The AGV control layers are responsible for controlling single AGVs, e.g. routing, parking, guidance and collision avoidance. The *resource representation layer* is the lowest layer and represents the physical aspects of the logistic resources.

Figure 5-3: Hierarchical structure of the resource holons

One resource management layer is responsible for controlling one or more different resource controls in an area. Each resource control is responsible for controlling one resource representation. The resource management layer has a layered structure to facilitate the modelled geographic structure of logistic systems. The highest management layer is responsible for controlling the entire system, while lower management layers are responsible for controlling smaller geographical areas or subsystems.

5.4.2 Distributed Control

Two control philosophies can be identified in logistic systems; *central* and *distributed* control (Hammond 1986, Simon 1969). In a centralised control system all essential control activities are performed at a single point or by one computer. In a distributed control system the responsibilities for control activities are divided among a number of points or computers. In distributed control systems the control processes are divided over several systems, which are connected and cooperatively try to achieve some common function (Boger 2001, Selic et al. 1994).

Distributed control systems offer several advantages over centralised control systems for controlling large scale automated logistic systems. First, most complex problem settings have a distributed nature (Crichlow 2000, Ferber 1999, Simon 1969). Distributed control follows the natural physical distribution of logistic and transport systems. Each geographically separated subsystem can be controlled by its own control system in a decentralised control system. Second, different control activities can be executed concurrently by distributing them over several computers (Coulouris et al. 2001, Fujimoto 2000). The execution time of the control process can be reduced up to a factor equal to the number of processors used. Third, centralised control systems use complex control algorithms (Arora et al. 2001). Such algorithms are calculation intensive. The response times of the control system become unacceptable when too many logistic resources are controlled by a centralised control system. This makes decentralised control systems better scalable than centralised control systems (Singh 1999). Fourth, central control systems have to communicate with all logistic resources in a system. This puts heavy burdens on the communication systems (Hammond 1986). The communication is distributed and divided among several control systems in a decentralised setting. Fifth, distributed control systems are more robust than centralised control system (Arora et al. 2001, Hammond 1986). When components of a centralised control system fail the entire logistic system breaks down. Distributed control systems can continue to operate even when some of the distributed components fail. Finally, large scale automated logistic systems do not operate on their own; they are connected to other logistic systems controlled by other organisations. Establishing centralised control in a transportation network in which several organisations are involved is difficult, or even impossible (Euwe 1999).

Distributed control has a major disadvantage. It lacks possibilities to optimise the system performance (Bongaerts 1998). The performance of central control systems is higher than of distributed control systems when compared (Hammond 1986). Simon (1969) states that it is not a question of whether or not to use decentralised control, but only to decide the degree of decentralisation. A completely decentralised system is inefficient and will lead to conflicts, while a completely centralised system is highly complex and less reliable (Arora et al. 2001).

Design guideline 2

Holonic logistic control systems have hybrid structures that combine a hierarchical structure in a distributed setting. The hierarchical structure can be found within the holons. The distributed setting can be found in the relations between holons.

Distribution can take many forms (Ferber 1999). Two types of distribution are used in the holonic structure for control systems; functional and geographical distribution. First, functional distribution is the distribution of the holons. Order holons, load holons and resource holons are autonomous and are responsible for their own control activities and distributed over several computers. Each holon, which has its own control functionalities, is placed on a separate computer or control system. Second, the geographical distribution is the distribution of the layers within resource holons over several computers. Each layer, i.e. resource management, resource control and resource representation, has its own computers and control systems.

5.4.3 Scheduling and Real-Time Control

Control for automated logistic systems consists of two processes (Hayes-Roth & Hayes-Roth 1979). Planning, the first process, consists of determining, in advance, a course of action aimed at achieving the systems goal. The course of action is called a plan or schedule. Control, the second process, consists of guiding and monitoring the plan to a successful conclusion. The first process is called scheduling in our support environment; the second process is called real-time control.

Scheduling consists of developing a detailed plan, or schedule, to determine the precise use of different manufacturing facilities within a specified time frame (French 1982). Scheduling is the process of optimising resource allocation decisions (Bongaerts 1998). Resource allocation consists of deciding when activities are carried out and what resource should be used to carry out the activities. The general problem in scheduling is to find a sequence, such that activities are performed in such a way that they are compatible with technological constraints and optimal with respect to some performance criteria (French 1982). *Real-time control* consists of the controlling the activities needed to carry out the schedules developed during the scheduling process.

Design guideline 3

Holonic logistic control consists of two separate interacting processes. The first process is scheduling of customer requests. The second process is real-time control of the execution of the developed schedules.

Scheduling and real-time control need to be designed in such a way that both processes facilitate the holonic structure introduced in our support environment. The scheduling process has to take the autonomy of the individual holons into account. Scheduling in automated logistic systems is incremental and does not produce complete schedules. Not all information is available to make entire schedules at one time (Hayes-Roth & Hayes-Roth 1979). Schedules grow as more information is obtained through the arrival of new customer requests. Single customer requests arrive at the logistic system. The order holons, responsible for the scheduling, cannot wait until a batch of customer requests has been collected; customer requests need to be scheduled directly. Customers want to know if their requests can be carried out as soon as possible. When a request can not be carried out customers must have enough time left to

look for alternative logistic service providers. This is important especially when dealing with rushed or late requests. Such requests arrive at the logistic system shortly before they have to be executed. Customers want a quick reply as to whether the order can be carried out or not; they have little time to search for alternatives.

Customers initiate the scheduling process, as can be seen in Figure 5-4. Customers *generate requests* based on their transportation demands. The requests contain information on the logistic services that the customers want the logistic system to perform. The customers *send their requests* to one or more order holons. The order holons are the interfaces between the customers that request logistic services and the resource holons that provide logistic services. Order holons and resource holons have to cooperate to schedule customer requests. Order holons have knowledge of the services the logistic system can perform and knowledge of the services the individual resource holons provide. The order holons *create sub-requests* based on the customer requests. The customer requests are divided into parts that individual resource holons can perform. Each sub-request is a part of the entire customer request that can be performed by a single resource holon. The order holons *send the sub-requests* to the resource holons.

The resource holons *create sub-offers*. A sub-offer is a scheduled logistic service that will be performed by a resource holon for an order holon. The resource holons create sub-offers based on the sub-requests of the order holons and their current schedules. A resource holon can send several sub-offers based on the same sub-request. The sub-request of the order holon provides the boundaries within which the resource holons can create sub-offers. The resource holons try to schedule the sub-offers in an optimal manner within their current schedules. The goal of a resource holon is to use the set of logistic resources it controls as efficiently as possible. Each sub-offer is a temporary claim in the schedule of a resource holon. The resource holons temporarily reserve capacity of a logistic resource to perform a logistic service. The temporary claims have short life spans; they are either deleted or changed into permanent claims. Temporary claims are deleted when a sub-offer is declined or when a certain amount of time has elapsed. Temporary claims are changed into permanent claims when a sub-offer is accepted. The resource holons *send the sub-offers* to the order holon.

The order holons are responsible for *joining the sub-offers* of the individual resource holons. The order holons *send the joint offers* to the customer. The customer interprets the offer and checks whether or not the offer fits the original request. The customer can either *accept or reject an offer*. The order holon *sends the acknowledgements or the rejections* of the offer to the resource holons. Finally, the resource holons *update their schedules*. The temporary claims that belong to accepted offers are changed into permanent claims. All other temporary claims are discarded. An offer that is accepted by a customer becomes a contract between the order holon and the resource holons; the resource holons are responsible for carrying out the contract.

Figure 5-4: Scheduling process of customer requests

Order holons join the sub-offers of several resource holons into offers for customers. The order holons have to take two aspects into account when joining sub-offers. First, the order holon has to join the sub-offers of several resource holons into one consecutive offer for the customer, see Figure 5-5. The logistic services that the individual resource holons provide have to connect seamlessly, e.g. the logistic service of the second resource holon has to start directly after the first resource holon has finished. The transportation network and available space are scarce resources in large scale automated logistic systems (chapter four). There is little to no room available to store cargo units temporarily, while waiting for the next resource holon to start its logistic service. Cargo units have to be transported through the logistic system as quickly as possible without delays. Second, the order holon is responsible for joining the sub-offers as efficiently as possible for the entire logistic system. The resource holons try to use the set of logistic resources they control as efficiently as possible. The resource holons try to optimise their own logistic resources, which can be sub-optimal for the entire logistic system. Order holons are responsible for the optimisation of the entire logistic system. Although the order holon has a more central position in the system, it can not force the resource holon to schedule specific sub-orders. The resource holons are autonomous and responsible for their own scheduling.

Figure 5-5: One offer consisting of three consecutive sub-offers

The resource holons are responsible for executing the schedules created in the scheduling process. The activities related to controlling the execution of schedules are called real-time control. The progression of time is specified in terms of the timeliness requirements dictated by the system or the environment in real-time control systems (Verissimo & Rodrigues 2001). A real-time control system has the capacity to decide control actions and coordination actions within pre-specified intervals. The time requirements are dictated by the logistic resources used in the logistic system. The resource holons initiate the real-time control processes, as can be seen in Figure 5-6. Resource holons *interpret their schedules*, which resulted from the scheduling process. The resource holons *send commands to the logistic resources* based on their schedules. A command is an order from a resource holon to a logistic resource to perform a certain activity at a specified moment. For example, an AGV holon can send a command to an AGV to drive towards a certain destination at specified time. The logistic resource will *perform the logistic service*, which is stated in the command. The logistic resource sends event notifications to the resource holon based on the progress of the execution of the logistic service. The resource holon uses the event notifications to decide new commands for the logistic resources and to *send event notifications to the order holon* on the progress of the execution of the customer order.

Figure 5-6: Real-time control process for the execution of schedules

5.4.4 Resource Representations and Autonomous Logistic Resources

The logistic resources are placed outside the resource holons in the holonic structure as stated in section 5.3. The physical AGVs, material handling stations and infrastructure elements are not part of the resource holons. The resource holons contain representations, or models, of the logistic resources. The resource representations are information objects that contain information on the logistic resources (Sol 1982). The resource representations are models of the physical logistic resources; they model the basic characteristics and the basic behaviour of the logistic resources. The resource representations contain knowledge on the logistic services the resources can perform and contain information on the state of the logistic resources. The resource representations are independent of the technology used inside the logistic resources. This is important in large scale automated logistic systems, in which there are many uncertainties regarding the technology. For example, an AGV holon contains representations of AGVs. The AGV representations model the basic characteristics and behaviours of AGVs. The most important behaviour of an AGV is driving. How it exactly drives, e.g. two- or four-wheel steering, is not important to the AGV holon.

Design guideline 4

Logistic resources are placed outside the resource holons; the resource holons contain representations of the logistic resources. The actual logistic resources have a high degree of autonomy; they are responsible for controlling many of their own activities.

We strongly advocate the use of autonomous logistic resources that are responsible for controlling many of the logistic services they provide (Aken 1978, Simon 1969). Using autonomous logistic resources is an extension of the second design guideline on distributed control. The responsibility of controlling logistic resources is distributed between the resource holons and logistic resources. The fourth design guideline is especially important for logistic resources which require a lot of control activities. The amount of control needed to control logistic resources differs for logistic resources. For example, material handling stations need only a limited amount of control compared to AGVs. The material handling stations provide simple logistic services and are fixed at one location. AGVs provide more complex logistic services and move throughout the logistic system. Many control activities are needed to guide AGVs safely through the logistic system, e.g. guidance, access control of single lane bi-directional tubes, controlling the distance to predecessors and deadlock avoidance. The AGV holon is relieved of many control actions by placing the responsible for controlling activities directly in the AGVs. Using autonomous logistic resources makes the resource holons better scalable, e.g. they are able to control larger sets of logistic resources. The resource holons are relieved of many control activities. Finally, autonomous logistic resources are less dependent on the resource holons. The logistic resources will be able to continue to operate for a large part if the resource holon breaks down.

5.4.5 Asynchronous Communication

Designers of logistic control systems have to pay explicit attention to communication. Timely and accurate information and information flows are essential in logistic control systems (Ulrich & Düring 1995). Without timely and accurate information logistic control is impossible and decisions are taken on an ad hoc basis. Large scale automated logistic systems are communication intensive (Lindeijer 2003). Communication in logistic systems can be a cumbersome activity, since heterogeneous data has to be communicated within strict time windows (Pyle et al. 1993).

Communication needs to be designed in such a way that it facilitates the holonic structure of logistic control systems introduced in our support environment. Logistic control is eventually achieved through communication. Control systems and systems-being-controlled exchange messages. Control systems send messages containing information on the control actions that have to be performed. Systems-being-controlled send messages on their state to the control systems. Two possible forms of communication exist for sending information from one process to another process; synchronous and asynchronous communication, as can be seen in Figure 5-7 (Ben-Ari 1990). In *synchronous communication* the processes that exchange information have to be synchronised before messages can be exchanged. The information is transferred only when one process is ready to send and the other process is ready to receive information. When one process is not ready, the other process has to wait before communication can take place. Synchronous communication can easily lead to nervous behaviour of the system-being-controlled. Many control and physical processes take place simultaneously within large scale automated logistic systems. When a control process is not ready to communicate, the physical logistic process has to wait, e.g. an AGV has to slow down before it receives permission to enter a crossing. Such delays are caused by the speed differences between control processes and physical processes.

In *asynchronous communication* a buffer is introduced to decouple the sending and the receiving processes (Ben-Ari 1990). This buffer is a queue of messages. Messages from the sending process are put in the mailbox, while the receiving process retrieves messages from the mailbox. Both processes can continue to operate without having to be synchronised. Asynchronous communication is based on the principle of 'send-and-forget'. The sending process sends a message to the mailbox, forgets about it and continues to operate normally. When the receiving process is ready it checks if there are messages in the mailbox. It should be noted that a buffer is of no use if the average speeds of the two processes are very different (Ben-Ari 1990). If the sending process is much faster, the buffer will fill up. If the receiving process is much faster the buffer will remain empty.

Figure 5-7: Synchronous (top) and asynchronous (bottom) communication

Design guideline 5

Communication in holonic control systems is asynchronous both within holons and between holons. Asynchronous communication allows continuous uninterrupted processes.

Asynchronous communication closely fits the characteristics of the holonic structure of control systems. Asynchronous communication allows holons to operate independently. Holons that exchange information do not have to be synchronised before communication. Holons can send and retrieve messages through the mailbox when they are ready.

5.4.6 Command/Event Based Communication

Communication in and between holons is asynchronous. The communication in the resource holons has a *command/event based structure*. Control actions or coordination actions of the control systems are sent in the form of commands that the logistic resources have to perform. Commands are sent top-down through the resource holons to the logistic resources. When the logistic resources have reached a certain state in executing the commands they generate an event and send an event notification back to the resource holons. The resource holons use the event notifications to decide what new control actions need to be taken. Three kinds of events can be distinguished; internal, external and periodical events (Platier 1996). Internal events are events that take place within the logistic system, e.g. an AGV arrives at a material handling station. External events are events that originate from outside the logistic system, e.g. a customer sends a request for a logistic service. Periodical events are events that occur on a time basis, e.g. a time out event on a service request.

Design guideline 6

Communication in the resource holons and between resource holons and logistic resources has a command/event based structure. The type and number of commands and events have to be carefully considered and minimised to limit communication.

Limiting or minimizing communication is an important aspect in large scale automated logistic systems. The technical possibilities of communication equipment for transport and logistic systems have increased strongly and prices have dropped significantly in the last years (Drane & Rizos 1998). However, for controlling large scale automated logistic systems it is still necessary to reduce or limit communication. First, limiting communication reduces the investment needed for communication equipment. Second, the dependency of the logistic system on communication is reduced when communication is limited. When the logistic resources are less dependent on communication they are able to continue to operate even when failures in communication occur. Third, communication is a potential bottleneck that limits the number of logistic resources controlled by a resource holon. Resource holons will be overloaded with messages when a lot of communication is needed. The resource holons need to evaluate each message and decide on the control actions that have to be taken. Resource holons can handle only a limited number of messages. The resource holons are able to control more logistic resources when communication is limited. Finally, the separation of large scale automated logistic systems from other traffic can be achieved using an underground infrastructure. Communication can be technically difficult in underground systems (Rijsenbrij et al. 2000). For example, radio waves are

blocked by the AGVs and absorbed by the walls of the tunnels. Expensive communication equipment is needed to support high levels of communication in underground systems.

Communication can be limited by carefully considering the type and the number of commands and events. The type and number of commands and events are case specific. Using many commands and events will result in a lot of communication, while using a few commands and events can make it difficult to control the logistic resources adequately. A trade-off has to be made between the number of commands and events and the effectiveness of the control.

5.4.7 Communication Through Information Services

The asynchronous and command/event based communication is implemented as an *information service* based on the publish/subscribe mechanism (Cugola et al. 2002, Gamma et al. 1995). In publish/subscribe mechanisms entities, such as holons, communicate by generating, sending and receiving messages. Two entities are identified in the information service; subscribers, also called receivers, and publishers. Subscribers are entities that want to receive certain messages. The messages are issued by publishers. The communication is limited to receivers that are interested and have subscribed to specific types of messages from a publisher. The publish/subscribe mechanism defines a one-to-many dependency between publisher and subscribers (Gamma et al. 1995).

Design guideline 7

Communication between holons and within holons is implemented through information services. The information services are based on the publish/subscribe mechanism. Holons subscribe only to the information services that provide the information they need.

Information services for communication in the holonic structure consist of four steps, depicted in Figure 5-8.

1. In the first step a subscriber that wants to receive a certain type of messages *subscribes* to an information service of a publisher. The subscription specifies the kind of message that the subscriber wants to subscribe to and limits the maximum and/or the minimum number of messages. The maximum limitation prevents an overflow of messages to the subscriber. The minimum limitation ensures that the subscriber gets updates on the state at least every time window.
2. In the second step the publisher *sends messages* to the subscribers. Messages are sent only to receivers that have declared an interest by issuing a subscription. The publisher is responsible for evaluating subscriptions and propagating messages to receivers.
3. When a subscriber no longer has a need for a certain type of messages it *un-subscribes* to the information service in the third step.
4. The publisher can also *stop* the information service provided to subscribers in the forth step.

Figure 5-8: Information service

The information services are asynchronous, as depicted in Figure 5-8 by half-headed arrows (Fowler & Scott 2000). Publishers and subscribers have mailboxes in which messages are placed.

Implementing communication using information services has a number of advantages (Gamma et al. 1995). First, the information services are scalable. Information services are independent of the number of subscribers. The messages are sent to all interested subscribers. Second, the information services are flexible. New subscribers can be added at any time and existing subscribers can be withdrawn at any time. The subscribing or un-subscribing by subscribers does not influence other subscribers. Third, the information services can be used to limited communication, as stated in design guideline six. Holons only subscribe to information services that provide information they need. The number of messages sent to a subscriber can also be limited in the subscription.

5.5 Support Environment Part Three: Evaluation of Logistic Control Systems

Control systems and logistic systems are fully evaluated after commissioning on the shop floor (McGregor 2002). Testing and evaluation takes place during the start-up phases of the logistic system. This is an unacceptable approach to evaluate control systems; it is expensive, risky, error-prone and it disturbs normal operations (McGregor 2000). Auinger et al. (1999) state that it is vital to test control systems before implementation and suggest testing control systems by using combinations of real and simulated systems, as can be seen in Figure 5-9.

1. *The traditional way to test control systems.* A combination of a real control system and real system-being-controlled. The control systems are tested on the shop floor during the start-up phase after commissioning. This is the current way of testing control systems.

2. *Soft commissioning*. Within soft commissioning the real control system is connected to a simulation model that imitates the production or logistic system (Schiess 2001, Mueller 2001). This combination is also called *emulation* (McGregor 2002).
3. *Reality in the loop*. A combination of a simulated control system and a real system-being-controlled.
4. *Off-line simulation*. A combination of a simulated control system and a simulated system-being-controlled.

Figure 5-9: Approaches to evaluate control systems

Each approach in Figure 5-9 has its own advantages and disadvantages (Auinger et al. 1999). The final part of our support environment recommends support facilities to evaluate the designed control systems. The support facilities used for the evaluation should evaluate the (McGregor 2002, chapter four):

- Designed control systems.
- Communication between control systems and logistic resources.
- Technology used inside the control systems and logistic resources.

Evaluation guideline 1

Use a combination of a simulated control system to control simulated, emulated and prototype logistic resources to evaluate the resource holons and the logistic resources.

The combination mentioned in evaluation guideline one can be used to address all three aspects mentioned above. The evaluation guideline combines three approaches mentioned in Figure 5-9, so the advantages of each approach are combined, while many of the disadvantages are discarded. The support facilities recommended by the support environment can be used to evaluate the resource holons, as can be seen in Figure 5-10. The load holon and order holon can be evaluated using only simulation. There are less issues to solve regarding the technology and communication used for the load holon and order holon.

Figure 5-10: Evaluation of resource holons and logistic resources

Evaluation guideline 2

Use a consistent interface between the simulated resource holon and the simulated, emulated and prototype logistic resources that are being controlled.

The control system has to be decoupled from the logistic resources to control all three types of models of the logistic resources. One consistent interface has to be developed between the simulated resource holon and systems-being-controlled. When a consistent interface is used the simulated resource holon can control all three different logistic resources in exactly the same way; using the same asynchronous command/event based communication structure. The simulated resource holon does not see any differences between simulated, emulated or prototype logistic resources. The resource holon can be developed once and can be reused when using a consistent interface.

5.5.1 Combination One: Simulation of Resource Holons and Logistic Resources

The first type of models consists of the simulation models of the resource holons and the logistic resources. Simulated resource holons are used to control simulated logistic resources. Simulation environments offer many advantages when studying logistic systems (Banks 1998, Law & Kelton 1991). A number of these advantages are especially useful for studying large scale automated logistic systems. First, the behaviour of logistic resources can be studied faster than in real-time. Failures that do not occur regularly can be easily found and studied, e.g. the finding and solving of deadlocks. Second, in a simulation environment researchers have good control over the experiments, e.g. problem situations can be easily recreated. Finally, a simulated environment is a safe environment for experiments with logistic resources. When working with real AGVs there always is the danger of collisions; in a simulated environment collisions have no physical consequences (Hammond 1986).

The simulated resource holon is used to control different types of models of the logistic resources; simulated, emulated and prototypes. This introduces special requirements for the simulation software.

- The simulation software has to have an *open architecture*. The simulation packages should be able to interact easily with other computer programs or control systems. The simulation software should be able to deal with standard communication protocols and user defined communication protocols (Versteegt & Verbraeck 2002c). Widely spread standard communication protocols are: DDE, DLL, TCP/IP, ActiveX, OPC, and DCOM¹⁶. The users should also be able to define custom made interfaces besides standard industry interfaces.
- The simulation software has to provide *real-time* capabilities. One of the main advantages of simulation is that systems can be studied faster or slower than real-time (Banks et al. 1996). Emulation and prototype logistic resources operate exactly at real-time. The simulated resource holon has to operate at exactly real-time to control emulated and prototype logistic resources. The simulation software has to contain functionalities to slow down or speed up the simulation models (Fujimoto 2000, 1998).

5.5.2 Combination Two: Emulation of Logistic Resources

The second type of models is emulation of the logistic resources. Within the simulation and the control systems communities emulation has been developed as a new improved way of testing control systems (McGregor 2002). A real control system is connected to a simulation model that imitates the machines or production systems in emulation (Schiess 2001, McGregor 2000). We follow a broad approach to emulation in this research; an emulation model is defined as a model where some functional part of the model is carried out by part of the real system (McGregor 2002). Emulation models in our research combine highly detailed simulation models of physical aspects of the logistic resources and the real onboard control systems. For example, in emulated AGVs the real onboard control systems control a simulation model of the physical movements of the AGVs. The emulation models are a special form of simulation models, built in such a way that they represent the physical systems much closer than normal developed simulation models (Versteegt & Verbraeck 2002c). We use emulation models mainly to study the communication between resource holons and logistic resources.

5.5.3 Combination Three: Prototype Logistic Resources

The third type of models of the logistic resources is the *prototype of the logistic resource*. Prototype logistic resources are physical models of the logistic resources that will be used in the large scale automated logistic systems. Manufacturers of logistic resources sometimes construct a limited number of prototypes, or first implementations, of a logistic resource for testing and demonstration purposes. The prototypes are lower-fidelity versions of the final product used to test products early in their life cycle (Bass et al. 2003). Prototyping can be seen as a form of simulation (Sol 1982). The objectives of prototype development are to assure that the design can be built as designed and will meet all customers requirements (Ribbens 2000). The prototypes are used to prove the feasibility of the design of logistic resources and are used to evaluate the technical and physical aspects of logistic resources (Pielage 2001).

¹⁶ DDE: Dynamic Data Exchange, DLL: Dynamic Link Library, TCP/IP: Transfer Control Protocol/Internet Protocol, OPC: Object Linked Embedding for Process Control, DCOM: Distributed Components Object Model.

Prototypes can be first implementations or scale models of the logistic resources. Scale models are easier to work with during experiments and less expensive than real prototypes. The behaviour of the prototype logistic resources should closely represent the behaviour of the full scale logistic resources. Prototypes can have the same properties as the final product, but with substantial better diagnostic capabilities (Auslander et al. 2002). The prototypes are used to study the technical aspects of the control systems and the logistic resources in our research. Prototypes are often used in transport and logistic related industries, e.g. automotive, aerospace, heavy-duty equipment (Ribbens 2000). Prototypes are used for several types of experiments, e.g. durability experiments, environmental tests or destructive tests.

5.6 Evaluation of the Support Environment

The support environment will be evaluated by applying it to design control systems for the Underground Logistic System Schiphol, abbreviated to ULS Schiphol. The ULS Schiphol is a future large scale automated logistic system near Amsterdam Airport Schiphol. The ULS Schiphol uses automated logistic resources, like AGVs and material handling stations. The support environment will be applied to design different types of control systems for the ULS Schiphol. The support environment will be evaluated in three steps.

1. The *technical feasibility* of the resource holons and the support facilities recommended to evaluate the designed resource holons are evaluated by using action research. The support environment is applied to design control systems for the automated logistic resources of the ULS Schiphol.
2. An action research to study the *usability* of the designed control systems when the support environment is applied. The support environment is applied to design a customer order management system for the ULS Schiphol.
3. Finally, a *group evaluation session* will be carried out. The support environment will be presented to a group of experts on automated logistic systems and control systems. The experts will study the support environment and compare the usability of the support environment to their own experiences and their own expectations. The support environment and the application of the support environment for the ULS Schiphol will be evaluated by the experts.

The technical feasibility of the support environment is discussed in chapter six. The usability of the support environment is discussed in chapter seven. Finally, the group evaluation session is discussed in chapter eight.

Any sufficiently advanced technology is indistinguishable from magic.

Arthur C. Clarke

6 Empirical Testing of The Resource Holons

The support environment presented in chapter five is evaluated using two action research cases and a group evaluation session. The selection of the case studies is based on the considerations introduced in chapter one. The central theme of the case studies is the design of control systems for the Underground Logistic System Schiphol, abbreviated to ULS Schiphol. The ULS Schiphol is a proposed future large scale automated logistic system to be located in the area around Amsterdam Airport Schiphol.

The first case study, described in this chapter, is aimed at evaluating the technical feasibility of the holonic control structure presented in the support environment. The first case study has two goals. First, to apply the support environment to the design of control systems for Automated Guided Vehicles and automated material handling systems for the ULS Schiphol. Second, to apply the support facilities recommended by the support environment to evaluate the designed control systems and the logistic resources. In the second case study, which is described in chapter seven, the support environment is applied to design an order management system for the ULS Schiphol. The final evaluation of the support environment consists of a group evaluation session. The support environment is presented to experts from the fields of automated logistic systems and control systems. The group session is discussed in chapter eight.

6.1 Underground Logistic System Schiphol

6.1.1 Overview Logistic System

Around Amsterdam Airport Schiphol and the Flower Auction Aalsmeer in the Netherlands the roads are heavily congested. This reduces the accessibility of the airport for passengers and freight, and has given rise to long throughput times and unreliable deliveries for the transport of time critical and expensive airfreight between Amsterdam Airport Schiphol, logistics centres near Schiphol and the Flower Auction Aalsmeer. The deteriorating accessibility, increasing traffic congestion and the growing logistic costs are threatening the competitive positions of the airport and the flower auction. Accessibility cannot be improved by expanding the current infrastructure. Expanding the current infrastructure is costly, difficult and undesirable and will not contribute to a better living environment in the region. An underground logistic system has been proposed for the transport of high value and time critical airfreight between

Amsterdam Airport Schiphol¹⁷, Flower Auction Aalsmeer¹⁸ and a proposed future rail terminal near Hoofddorp¹⁹. The ULS Schiphol will be separated from other traffic²⁰; this way the freight transport can be carried out in a congestion-free environment and with high levels of reliability.

Many possible layouts for the infrastructure of the ULS Schiphol have been studied (Ebben 2001, Versteegt et al. 2001). One layout that was frequently used in the design process of the ULS Schiphol is sketched in Figure 6-1. Long single lane bi-directional tunnels will be used to connect the airport, flower auction and rail terminal. AGVs will drive through the single lane tunnels in two directions. Only AGVs driving the same direction are allowed to enter the tunnel; AGVs driving in the opposite direction will have to wait before entering the tunnel. AGVs cannot pass each other within the tunnel, it is just wide enough for one AGV. Control systems will be used to decide which AGVs are allowed to enter the tunnel. Single lane bi-directional tunnels will be constructed rather than two single lane tunnels to reduce construction costs. The internal loop or circle at Amsterdam Airport Schiphol will add many possibilities for internal freight transport at the airport between freight terminals and the (un)loading areas for aeroplanes. This will reduce the number of lorry movements in and around the airport.

Figure 6-1: Possible layout of the ULS Schiphol (Versteegt & Verbraeck 2004).

¹⁷ Abbreviated to AAS.

¹⁸ Abbreviated to VBA (Verenigde Bloemenveiling Aalsmeer).

¹⁹ Abbreviated to RTH.

²⁰ The abbreviation ULS, which was originally used to designate an Underground Logistic System, has changed gradually. ULS is now used as an acronym for Undisturbed Logistic System (IPOT 2000). Within a ULS the undisturbed character is more important than the underground nature. An underground infrastructure is a possible manner to achieve separated and undisturbed movements.

The goals of the ULS Schiphol are broader than just efficient freight transport between AAS, VBA and RTH (Rijksenbrij et al. 2000). The ULS Schiphol is intended to:

- Create a high quality transport connection between Flower Auction Aalsmeer, Amsterdam Airport Schiphol and a future rail terminal near Hoofddorp towards the rest of Europe.
- Guarantee good accessibility of Amsterdam Airport Schiphol and Flower Auction Aalsmeer.
- Reduce the negative environmental impacts of freight transport near Amsterdam Airport Schiphol and Flower Auction Aalsmeer.
- Reduce congestion on the roads near Amsterdam Airport Schiphol and Aalsmeer.
- Stimulate the use of trains in intermodal transport chains.
- Generate knowledge on large scale underground and automated logistic systems. The ULS Schiphol and the Tilburg city distribution system (chapter four) are the main pilot projects for automated underground freight transport in the Netherlands (Ministerie van Verkeer en Waterstaat 2000, IPOT 2000).

A feasibility study for the ULS Schiphol was conducted (Pielage 2001, Rijksenbrij et al. 2000). The main conclusions were that the ULS Schiphol can make an important contribution to improving accessibility of Schiphol and can reduce the environmental impacts of freight transport near Schiphol. After the feasibility study was finished the functional requirements of possible future customers were identified and their expectations and demands were determined (NS Railinfrabeheer 1999, 1998). Preliminary designs of parts of the ULS Schiphol were made based on the functional requirements, e.g. AGVs, material handling stations and terminals (Rijksenbrij et al. 2000).

The case studies discussed in this chapter and chapter seven use these preliminary designs as starting points. The research described in this chapter forms part of the entire ULS Schiphol project. The objective of our case study is to:

'Develop control systems for the real-time control of Automated Guided Vehicles and automated material handling stations designed for the ULS Schiphol. Evaluate the technical feasibility of the AGVs, the material handling stations and their control systems.'

6.1.2 Logistic Resources of the ULS Schiphol

The ULS Schiphol uses highly automated logistic resources. The control over the logistic resources will also be automated. From a control perspective the most important logistic resources are the Automated Guided Vehicles, the automated material handling stations²¹ and the terminals (Rijksenbrij et al. 2000). The AGVs perform complex logistic services for which a lot of control activities are needed, like scheduling, routing and collision avoidance. Terminals are areas where several docks are located. Many interactions between AGVs and docks occur at the terminals; AGVs pick-up and drop-off cargo units at the docks. The AGVs drive in close proximity to other AGVs and the docks at the terminals, since the infrastructure is limited.

²¹ Also called docks.

Automated Guided Vehicles

The ULS Schiphol will use Automated Guided Vehicles to transport cargo units. The AGVs will be fully automated; driving, (un)loading and control will be carried out without human intervention (Kusters 2000). The AGVs will have the following specifications (Rijksenbrij et al. 2000).

Speed	6 m/s cruising speed, 7 m/s maximum speed
Speed at terminals	2 m/s
Speed on slopes	3 m/s on a slope with an angle of 12 percent
Acceleration	1 m/s ²
Deceleration	1 m/s ² normal circumstances, 2 m/s ² emergency stops
Load capacity	3,500 kg
Propulsion	electric

Three possibilities exist for guiding AGVs through transportation networks (Versteeg & Verbraeck 2001, Hammond 1986).

- *Physical guidance.* A mechanical or an electronic guidance system is used to guide the AGVs. AGVs can move freely in a longitudinal direction, while lateral movements are restricted. Several types of physical guidance systems are used in practice, e.g. rails, reflective stripes and electric guidance wires.
- *Virtual guidance.* Control systems limit the movements of AGVs by providing virtual tracks. The movements of AGVs are limited within a software based or virtual environment.
- *Free-ranging.* The AGVs drive freely in a two-dimensional space.

Free-ranging AGVs were chosen for the ULS Schiphol because of the high levels of flexibility they offer at the terminals (Rijksenbrij et al. 2000, Kusters 2000). Changes in the layout of the terminals or completely new layouts can easily be implemented without changes to the physical infrastructure. Changes to the infrastructure in physical guided systems are difficult and costly to incorporate since changes to the infrastructure have to be made. Free-ranging AGVs can cope better with local disturbances and can move around obstacles through a simple re-routing. In physically guided and virtual guided systems obstacles on routes block the progress of AGVs. However, it can still be necessary to limit the movements of free-ranging AGVs virtually for safety reasons at specific locations.

Material Handling Stations

The automated material handling stations, or docks, are used to tranship cargo units on and of AGVs. The material handling stations are based on two technologies, rolling and lifting technology (Pielage 2001). Cargo units can be either lifted or rolled on and off AGVs. Three types of docks were considered for the ULS Schiphol. Type I, sketched on the left side of Figure 6-2, tranships cargo units from the side of AGVs. The advantage here is that the AGVs do not have to perform complicated driving manoeuvres; AGVs only have to drive forward and get into position next to the dock. Docks of type II, in the middle of Figure 6-2, can tranship cargo units from both sides of AGVs. AGVs position themselves between the docks and cargo units can be unloaded and loaded simultaneously, which reduces transshipment time. Docks of type III, on the right side of Figure 6-2, can tranship cargo units from the front and the side of AGVs. The main disadvantage of Type II and Type III docks is that AGVs have to perform complicated

driving manoeuvres before and after transhipments. Although the actual transhipment can take place faster, the time AGVs need to position themselves next to docks of type II en III is longer. Docks of Type I were chosen in the preliminary design of the ULS Schiphol; AGVs do not have to perform complicated driving manoeuvres to position themselves next to a dock.

Figure 6-2: Docks (Rijssenbrij et al. 2000, Type I, II and III from left to right)

Cargo Units

The ULS Schiphol will transport many different types of freight, mainly time critical goods with a high value, e.g. flowers, spare parts and electronic components. The use of standardised cargo units is an essential prerequisite to implement fully automated transport systems (Binsbergen & Visser 2001). The transhipment can be automated more easily by placing freight in standardised cargo units, which leads to reduced transhipment times and reduced transhipment costs. Standardised cargo units are cheap to purchase and maintain. Finally, using standardised cargo units allows easy connections to other transport systems, like railways and aeroplanes. The following standardised cargo units, which are widely used in the airfreight industry and at flower auctions can be handled by the ULS Schiphol (NS Railinfrabeheer 1999).

- Pallet (Euro pallet 120x80x240²², industrial pallet 120x100x240)
- Flower carts (Danish cart 135x57x240; 400 kg and auction market cart 130x104x300; 600 kg)
- Main-deck aircraft pallet (318x244x300; 3,500 kg)

Main-deck aircraft pallets are the standard cargo unit in the ULS Schiphol. The cargo units have a modular structure; smaller cargo units have to be combined to form a main-deck aircraft pallet. An AGV can transport exactly one main-deck aircraft pallet, which is the largest cargo unit. The smaller cargo units are placed on a main-deck aircraft pallet. 6 industry pallets, or 6 Euro pallets, or 8 Danish carts or 4 flower auction market carts are combined to form one main-deck aircraft pallet (Pielage 2000).

²² All sizes are denoted as length x width x height in centimetres.

6.1.3 Challenges in Designing Logistic Control for the ULS Schiphol

Designing control systems for the ULS Schiphol is not a trivial case. The ULS Schiphol has a number of characteristics that differ from existing automated logistic systems, such as automated container terminals and automated warehouses (Kusters 2000). The ULS Schiphol is a large scale system compared to existing automated logistic systems (Müller 1983). The large scale has two dimensions; the large number of logistic resources and the large travel distances. The ULS Schiphol will use more AGVs than current automated logistic systems. The actual number of AGVs depends on the exact layout of the infrastructure that will be implemented. The number of logistic resources for the layout sketched in Figure 6-1 is given in Table 6-1. This layout uses single lane bi-directional tunnels, which increases the number of required AGV strongly compared to two single lane tunnels. More AGVs are needed, since AGVs have to drive through the tunnels in convoys; AGVs have to wait until a convoy has been formed and the handling times of entire convoys at the terminal are large. The travel distances in the ULS Schiphol are larger than the travel distances in existing automated logistic systems (Müller 1983). The travel distances are up to 13 kilometres in the ULS Schiphol, which results in long travelling times.

Table 6-1: Estimated number of required logistic resources (Ebben 2001)

	AGVs	Docks RTH	Docks VBA	Docks AAS
<i>Single lane bi-directional tubes</i>	360	8	8	3 x 2

Although the ULS Schiphol is a large scale automated logistic system, the available space to carry out the logistic services is limited. The ULS Schiphol will be separated from other traffic; large parts will be located below surface level. A separated infrastructure is expensive and should be kept to a minimum to reduce the construction costs. Large numbers of AGVs will have to operate in the system, but there will be a limited amount of space available. Deadlocks can easily occur in such cases (chapter four, Nauta 1996). The control systems that are responsible for controlling AGVs are more difficult to design and will be more critical than those used in other AGV based logistic systems (Verbraeck et al. 2000a).

The ULS Schiphol may use several types of AGVs and docks from various vendors and manufacturers. This makes the ULS Schiphol independent of specific technologies or a single manufacturer. Using several types of AGVs and docks will allow the ULS Schiphol to transport a greater variety of cargo units. The control systems should be able to control logistic resources from different manufacturers.

Finally, at the moment of this research (2004) there are few real world implementations of large scale automated logistic systems. Thus there is little experience in designing and operating such complex systems. Some systems are comparable, like the automated container terminals in Rotterdam (ECT) and Hamburg (CTA).

6.2 Logistic Resources at the TestSite

The ULS Schiphol has a number of new requirements for the AGVs and the docks compared to existing automated logistic systems, e.g. AGV based systems in factories and warehouses. The most important characteristic is the separated setting. Large numbers of AGVs have to operate in an underground setting where there is little room for manoeuvring. Other requirements concern the demands of potential customers, e.g. the cargo units that have to be transported (NS Railinfrabeheer 1999, 1998). The AGVs and docks will have to handle other types of cargo units than traditional AGV systems. Current technologies for AGVs and docks do not meet these requirements.

New AGVs and docks have been designed to meet the specific requirements of the ULS Schiphol (Rijssenbrij et al. 2000, Kusters 2000). It was decided to evaluate the technical feasibility of the designed AGVs and docks before the implementation starts (Rijssenbrij et al. 2000). A special laboratory, called the Connekt TestSite, was constructed to evaluate the designs of the AGVs and docks. The TestSite has been especially equipped for testing new technologies for automated logistic and transport systems (Verbraeck & Versteegt 2000). The TestSite has an area of 1,600 m² and is equipped with the following prototype AGVs and prototype docks (Table 6-2 and Figure 6-3).

- 3 prototype AGVs, scale 1:1
- 10 prototype AGVs, scale 1:3
- 2 prototype docks, scale 1:1 (rolling and lifting technology)
- 2 prototype docks, scale 1:3

Table 6-2: Characteristics of the prototype AGVs (Kusters 2000, Rijssenbrij et al. 2000)

	Consortium of Spijkstaal, Lamboo, Frog and TNO-TPD	Lödige	Consortium of Brabant van Opstal and Delft University of Technology
<i>Description</i>	Based on technology that proved reliable in other application areas	Hybrid AGV, combines technology of road vehicles and trains	Technology with low complexity, all parts are kept simple and robust
<i>Cargo units</i>	Main deck air-pallets Flower carts Front and side loading	Main deck air-pallets Containers Two side loading	Main deck air-pallets One side loading
<i>Guidance</i>	Rubber tires Front-wheel steering Battery powered	Mechanical guidance (in tunnel) Free ranging, four-wheel steering (at terminal) Battery powered on terminal and power rail in tunnel	Self-guidance by gravity in tunnels Front wheel steering Battery powered

Three full scale prototype AGVs were designed for the ULS Schiphol. Each prototype AGV is based different technologies, as can be seen in Table 6-2. A number of scale model prototypes were also constructed. The scale models of the AGVs are based on the same technology as the full scale prototype AGV, but are easier to handle during experiments. One of the goals at the TestSite was to use the same control systems to control all the different prototype AGVs and docks. This constraint puts a heavy burden on the design process of control systems. The control systems have to be independent of the technology of the logistic resources and to be able to control all the different logistic resources without adjustments having to be made to the structure of the control systems.

Figure 6-3: Three prototype AGVs developed for the ULS Schiphol.

Left-top: Spijkstaal, Lambou, Frog and TNO-TPD

Right-top: Lödige

Left-bottom: Consortium of Brabant van Opstal and Delft University of Technology (Delft Tunnel Mover)

Pictures taken from Rijsenbrij et al. (2000)

The AGVs, both scale 1:1 and scale 1:3, are free-ranging, but their movements are virtually guided for safety reasons. The behaviour of virtually guided AGVs is more predictable than the behaviour of free-ranging AGVs. Control systems provide the virtual routes for the AGVs. The AGVs take care of guidance themselves by using dead-reckoning systems to keep track of their positions (Drane & Rizos 1998, Hammond 1986). AGVs are equipped with odometry encoders that monitor the number of rotations and the orientation of the steering wheels. Based on this information AGVs are able to keep track of their position. A calibration system is needed, since the odometry encoders are not completely accurate and reliable (Drane & Rizos 1998). A magnet grid in the floor was used for calibration purposes. The AGVs are also equipped with other sensors, e.g. distance sensors and obstacle sensors. The AGVs can measure the distance to predecessors and objects and the speed of their predecessors. Based on this information AGVs can keep a safe distance from predecessors and obstacles.

6.3 Resource Holons at the TestSite

Two resource holons²³ were developed following the holonic structure and design guidelines presented in chapter five. One resource holon was developed for controlling AGVs and one for controlling docks. The technical implementation of the AGV holon and the Dock holon is sketched in Figure 6-4.

Figure 6-4: Technical implementation of the AGV holon and Dock holon (Versteegt & Verbraeck 2002b)

The customers and Order holon were implemented in a simplified manner and will be discussed in more detail in chapter seven. The operators, which are responsible for conducting experiments, represent the customers and provide customer orders to the Order holon through a web page. The customer orders were simplified to two types of customer orders; dispatching AGVs and transshipping cargo units. A web server checks the validity of the customer orders and sends the customer orders to the order management. A web based approach is used because of the flexibility web pages and web servers offer. Changes in the Order holon, AGV holon or Dock holon are automatically updated in the web pages the operators use to communicate with the order holon. The web based interface offers possibilities to use

²³ When resource holon and order holon are written with lower cases the general concept is meant. Case specific implementations are meant when Resource holon and Order holon start with a uppercase.

graphical interfaces (Auslander et al. 2002). A graphical interface makes it easier for the operators to control the logistic resources. The Order holon translates the customer orders into orders for the AGV holon and the Dock holon.

The design guidelines stated in chapter five are followed in the design of the AGV holon and Dock holon. The resource holons combine a hierarchical structure in a distributed setting, following design guidelines one and two. The responsibility for control is distributed over several points; the separate hierarchical layers of the AGV holon and Dock holon are distributed over several computers. The AGV holon consists of three layers. The AGV Management is responsible for controlling the entire fleet of AGVs at the TestSite, e.g. routing of AGVs and collision avoidance. An AGV Control is responsible for controlling one specific AGVs, e.g. guiding an AGV. An AGV representation is the representation of an actual AGV and consists of information on the state and behaviour of the physical AGV. The Dock holon consists of one extra representation layer. A dock is constructed of a number of handling stations. The individual handling stations within a dock have to cooperate to transfer cargo units.

Design guideline three, which combines scheduling and real-time control is discussed in two chapters in this dissertation. A number of technical limitations regarding the equipments made it only possible to study real-time control functionalities at the TestSite. The control activities at the TestSite are aimed at the real-time control of the AGVs and docks. The scheduling of customer orders is described in chapter seven.

The logistic resources are placed outside the resources holons, following design guideline four. This makes the resource holons independent of the technology used within the logistic resources. Representations of the logistic resources are placed inside the holons. Representations contain information on the activities the logistic resources can perform and information on the actual state. The logistic resources have a high degree of autonomy. The responsibility for many control activities is placed directly in the onboard control systems of the logistic resources. The design guidelines on communication and the evaluation guidelines are described in the next two sections.

6.3.1 AGV Holon

A communication protocol was developed for the AGV holon to control AGVs. The communication protocol follows the design guidelines on communication given in chapter five. The communication protocol has an asynchronous command/event based structure, following design guidelines five and six. Communication is implemented through information services, following design guideline seven. All AGVs controlled by an AGV holon have to comply to the predefined communication protocol sketched in this section. The communication between AGV holon and AGVs is independent of the technology used in the AGVs and control systems.

A limited number of commands and event notifications is used to minimise communication. Commands are sent from the AGV holon to the AGV to perform logistic services. Three commands are used, as sketched in Figure 6-5 (Versteegt 2002).

- *CORBA*²⁴ *Init* is used to register, or bind, an AGV and the AGV holon to the CORBA Name-server. Each AGV that wants to join an experiment has to register with the CORBA Name-server at the beginning of the experiment. The AGV holon also registers with the CORBA Name-server. The *CORBA Name-server* translates signals between the AGV holon and the AGVs. The CORBA Name-server operates as a list, or telephone book, of IP addresses²⁵. AGVs and the AGV holon register their IP address with the CORBA name-server. The CORBA Name-server keeps track of how an AGV and AGV holon can be reached. The CORBA Name-server operates as a post office. All signals between AGVs and AGV holon are sent to the CORBA Name-server. The CORBA Name-server takes care of the delivery of commands and event notifications.
- *AGV Init* initialises an AGV at an initial position with an initial orientation. The AGV Init has the following attributes: AGVname (string), Xbegin (real), Ybegin (real) and Obegin (real). The Xbegin and Ybegin form the initial location of the AGV. The Obegin is the orientation of the AGV at the initial location. The AGVs are placed on fixed positions with fixed orientations when they enter an experiment; the initial position and initial orientation are known to the AGV holon. The AGVs do not know the initial position and orientation. The AGV holon sends a message to the AGVs through the CORBA name-server containing the initial position and the initial orientation of the AGV. The odometry of the AGV is responsible for keeping track of the position and the orientation of the AGV after the AGV Init command has been executed.
- *AGV Exec* provides a new destination to an AGV. The AGV holon sends an AGV exec command to the CORBA Name-server. The CORBA Name-server delivers the exec command to the AGV. The AGV sends event notifications²⁶ back to the CORBA Name-server when it has reached certain stages in the execution of the exec command. The CORBA Name-server places the event notifications in a mailbox. The AGV holon checks, or peeks, the mailbox every time unit to see whether there are any messages. The AGV exec command has the following attributes: AGVname (string), Trackname (string), Xdestination (real), Ydestination (real), Odestination (real), MaximumSpeed (real).

The communication protocol is sketched in Figure 6-5. The sequence of messages within the communication protocol is sketched along the vertical axis. The CORBA Init command and the AGV Init command are repeated once for every AGV and AGV holon that are joined to an experiment. The AGV exec command is executed repeatedly for all AGVs during experiments. Communication is asynchronous, depicted by the half arrowheads.

²⁴ CORBA is the abbreviation of Common Object Request Broker Architecture. An architecture that enables computers to communicate (Tari & Bukhres 2001).

²⁵ IP address is the abbreviation of *Internet Protocol address* (Simon 1996). An IP address is an unique number used to identify a computer. It is a combination of the identification of the network in which the computer is located and the computer itself. When a computer moves into another network a new IP address has to be given to the computer.

²⁶ The events: on, near, positioned, and passed are explained in Figure 6-6.

Figure 6-5: Communication protocol between AGV holon and AGVs

Automated logistic systems are communication intensive systems as stated in chapter five. Special communication collecting agents were introduced. These agents, called *listeners*, collect commands or event notifications on behalf of the operators. The operators can initiate listeners. Listeners have to subscribe to specific commands or specific event notifications at the CORBA Name-server, since all communication is based on information services. The listeners do not subscribe to the AGV or AGV holon directly. A more convenient way is to subscribe to the CORBA Name-server, since all communication is directed through the CORBA Name-server. Listeners collect commands or event notifications and add additional information to messages, e.g. source, destination and a time stamp.

The AGVs keep track of their positions based on the readings of the odometry encoders when executing AGV exec commands. An AGV generates an event when it reaches a certain position on the track towards its destination. The AGV sends a notification of the event to the AGV holon. The AGV holon uses the event notification to decide the new command for the AGV. The AGV holon has to subscribe itself to specific events, since all communication is based on the publish/subscribe mechanism. AGVs can generate four track-related events, see Figure 6-6.

- *On-event.* The front of the AGV has reached the beginning of the new track. The on-event has a fixed position on a track; it is located in the space domain of the track. The on-event is mainly used to indicate that an AGV has entered a certain area, like a terminal, crossing or parking.
- *Near-event.* The front of the AGV has reached the point at which the AGV has to start braking to come to a complete stop before leaving the current track. The position of a near-event is speed dependent and a position in the space/time domain. A fast AGV generates a near-event earlier than a slower AGV. The near-event of the faster AGV will be located further away from the end of the track, because the braking distance of the faster AGV is longer. The near-event is used by the AGV holon to provide a new AGV exec command to the AGV. When an AGV has generated a near-event there are two possibilities. First, the AGV does not receive a new exec command and has to start to brake and stop. Second, the AGV receives a new AGV exec command and can execute the new AGV exec command.
- *Positioned-event.* The front of the AGV has reached the end of the track. The positioned-event has a fixed location on a track and is located in the space domain. The positioned-event is used to give a signal to the AGV holon that an AGV has positioned itself next to a dock.
- *Passed-event.* The back of the AGV has left the track; the track is free. The passed-event has a fixed position on a track and is located in the space domain. The passed-event is used to indicate that an AGV has left a critical area.

Figure 6-6: Track related events for AGVs (Versteegt & Verbraeck 2002a)

The AGV holon can generate one special event, the *time out-event*. The AGV holon can estimate the expected execution time of a command. When the execution of a command takes longer than expected a time out-event is generated. The operators, which are automatically subscribed to all time out-events, receive all time out event notifications from the AGV holon. The operators can accordingly decide on corrective actions to solve the cause of the time out-event.

6.3.2 Dock Holon

The docks consist of a number of handling stations. A handling station can transfer or temporarily store a cargo unit. Three types of handling stations are identified.

- 1. A fixed handling station that can transfer cargo units in two opposite directions.
- 2. A fixed handling station that can transfer cargo units in four directions, i.e. two times two opposite directions.
- 3. A moving handling station, placed on an AGV.

Cargo units are transferred from one handling station to an adjacent station. The basic scheme of a dock consisting of two two-directional fixed handling stations is shown on the left side of Figure 6-7. An AGV with a moving handling station and a fixed four-directional handling station are shown on the right side.

Figure 6-7: Handling stations at the TestSite

A Dock holon was developed to control the transshipment and the storage of cargo units. The design of the Dock holon is based on the AGV holon. Part of the control concept of the AGV holon was reused in the Dock holon for efficiency reasons; the control did not need to be developed from scratch. The same control concepts are used to keep the control simple, transparent and clear. Controlling docks differs, however, from controlling AGVs on three key points.

- A single AGV is responsible for transporting a cargo unit. A dock consists of a number of handling stations. Two adjacent handling stations need to coordinate their actions to transfer a cargo unit.
- An AGV is an active element that transports a passive cargo unit. The cargo units are passive objects at a dock, but they are actively transferred; cargo units trigger control actions for a dock.
- The control points of AGVs and docks are located at different positions. The control point of an AGV is located at the front of the AGV. The control point of a handling station is located in the middle of the handling station.

When a cargo unit needs to be transferred from one handling station to another station the activities of both stations have to be coordinated. The first handling station, the *sender*, can only start moving a cargo unit when the second handling station, the *receiver*, is ready to receive the cargo unit. The same applies when a cargo unit has to be transhipped on or off an AGV.

Several possibilities exist to coordinate the activities of the sending and the receiving handling stations (Verbraeck 2000). A coordinating agent, called *handler*, was introduced to coordinate the activities between handling stations in the Dock holon, see Figure 6-8. The Dock holon has a command/event based communication structure. The Dock holon uses only one command; the *handling command*. The handling command contains information on how to transfer a cargo unit and has three attributes; name of the sending station (string), name of the receiving station (string) and the name of the cargo unit (string).

Figure 6-8: Structure of the Dock holon to transfer cargo units

Seven steps have to be performed when a cargo unit is transferred from one handling station to another.

1. *Initialisation*. Preparations are made for the transfer of the cargo unit. Checks are made to see if the handling stations are available and functioning.

2. *Create handler and handling command.* A handler and a handling command are created. A handler is created that coordinates the activities of the sending and the receiving handling stations. A handling command is an information object that contains data on how to transfer a cargo unit. A handling command is created for every transfer that takes place and exists as long as the transfer lasts.
3. *Prepare handling.* The handler determines how to carry out the transfer. The handler receives information on the transfer from the dock management in the handling command.
4. *Coordination.* The handler performs a number of checks to see if the transfer can be performed. First, the handler checks if the handling stations are free and that there is no other cargo unit blocking the transfer. Second, the handler checks if the position of the two handling stations are adjacent. This is a necessary check when one of the handling stations is a moving station on an AGV. Third, the handler checks if the handling stations can transfer the cargo unit. When all three checks are correctly performed the transfer can start. When one of these checks fails an error message is sent to the dock management and the operators are notified.
5. *Starting stations.* The handler sends a signal to the handling stations to start their engines. The handling stations send a signal back that the transfer can begin. The handling stations are now ready to start the physical transfer of the cargo unit.
6. *Handling.* The cargo unit is transferred from the sending station to the receiving station. After the sending station has generated a passed event notification, it can be switched off. After the near event notification the cargo unit is slowed down by the receiving station. The receiving station can be switched off after the positioned event notification has been received by the handler. If the cargo unit needs to be transferred further the engines of the receiving station stay turned on. The receiving station becomes the sending station in the next transfer operation.
7. *Clear handler.* The handler is terminated after the transfer when one of the handling stations is located on an AGV. When an AGV is involved in the transfer a new handler needs to be created for every transfer, since the transfer can take place on a new location. Handlers are fixed to a specific location. The fixed handling stations do not change their positions. The handlers for transfers between fixed handling stations are persistent objects. The clear step is carried out after the positioned event notification has been received by the handler from the receiving station.

When the cargo units are transhipped events are generated based on the position of the cargo units on the sending and receiving dock. These events are similar to the events of the AGV holon, but the moments at which the events are generated differ. The position of the control point on a handling station is located in the middle of the handling station. The events are used by the Dock holon to decide the next command for the docks. Four events are used when a cargo unit is transferred, see Figure 6-9.

- *On-event.* The cargo unit is located at the middle of the sending station. The transfer operation can start.

- *Passed-event*. The cargo unit has left the sending station and entered the receiving station completely. The sending station can start a new transfer operation or be switched off. If the sending station is an AGV, the AGV can start driving when it has received an exec command from the AGV holon.
- *Near-event*. The cargo unit is 'nearing' the middle of the receiving station. The receiving station can slow the cargo unit down if the receiving station is the final destination. When the cargo unit has to be transferred further a new transfer operation is started.
- *Positioned-event*. The cargo unit is positioned at the middle of the receiving station. The transfer has been finished.

The moments at which the events are generated depend on the size of the dock, the size of the cargo unit and the transfer speed. A time out-event is also introduced; for failures in the communication between Dock holon, handler and handling stations. The operators, which are automatically subscribed to the time out-event notifications, receive all time out-events and can solve any problems that might have caused the time out-events.

Figure 6-9: Events for the transfer of cargo units

6.4 Safeguarding the Concurrent Use of Infrastructure

The available transportation network or infrastructure can be the most critical resource in an automated logistic system (chapter four). Automated logistic systems are separated from other traffic. The separated infrastructure is costly to achieve and commonly kept to a minimum. The infrastructure of the ULS Schiphol will be constructed underground. Some parts will be located at the surface level, mainly at the airport and the flower auction, where there is only a limited amount of space available. Although the available space is very limited large numbers of AGVs have to make use of the infrastructure. This makes the control systems for the AGVs critical systems (Verbraeck et al. 2000a). Deadlocks are bound to occur, when large numbers of AGVs with conflicting routes, have to operate in small areas.

An equilibrium between safety and performance has to be reached when designing control systems for AGVs. The control systems must support an efficient use of the infrastructure, while retaining high levels of safety. High levels of performance can only be achieved when the AGVs drive at high speeds with minimum separation, but collisions must be prevented. These are conflicting objectives. An additional constraint for the ULS Schiphol is that the control systems will have to offer a high level of flexibility with regard to changes in the layout of the infrastructure (Rijsenbrij et al. 2000). The control systems should not restrict the flexibility that free-ranging AGVs offer. The layouts of the terminals will not be fixed and can easily be reconfigured; the control systems should be able to facilitate such reconfigurations.

The TRACES²⁷ concept was chosen for the ULS Schiphol as the means to safeguard the concurrent use of critical pieces of infrastructure, like crossings and joins. The TRACES concept was originally introduced by Evers et al. (2000) and is based on concepts developed in the field of concurrent programming (Ben-Ari 1990, Dijkstra 1968). The TRACES concept is a generic and flexible traffic control framework that is able to handle high traffic densities efficiently on any scale (Lindeijer 2003). The basic idea behind TRACES is that AGVs use a formal language, which consists of statements, to determine their movements through infrastructure. Some of the statements execute logistic activities, like driving from one location to another. Other statements claim access to critical pieces of infrastructure, where AGVs can easily collide without safety mechanisms. The claims for critical pieces of infrastructure are made using semaphores. The semaphores are an extension of semaphores used in concurrent programming (Dijkstra 1968). Semaphores are multi-valued; they can contain one or more tickets. Simple semaphores contain one ticket; more advanced semaphores contain several tickets. A semaphore can be compared to a virtual police officer who controls traffic on a crossing. Semaphores decide which AGVs can enter the safeguarded area and which AGVs have to wait.

6.4.1 Implementation of TRACES in the AGV Holon

The basic structure for safeguarding the conflicting use of infrastructure can be seen in Figure 6-10. Logistic systems consist of domains through which AGVs drive. A domain consists of a collection of infrastructure elements and fixed logistic resources, like docks. Domains have a hierarchical structure; one domain can contain a number of sub-domains and each sub-domain can also contain a number of sub-domains. Each domain has one or more scripts. Each script contains commands that the AGVs have

²⁷ TRACES is the acronym of TRAnsport Control Engineering System

to carry out to perform logistic services. A ScriptDispatcher is located in each domain that provides the correct scripts to the AGV Controls. The script that is send to the AGV control depends on the route and destination of the AGV; AGVs with different destinations and different routes carry out different scripts. The AGV Management provides the destinations to the AGV Controls. The ScriptDispatcher sends the corresponding script to the AGV controls. The AGV control interprets the lines of the script and sends the commands to the AGV. The AGV executes the commands.

Figure 6-10: Class diagram of the TRACES implementation in the AGV holons

The safeguarding of the infrastructure is virtual and does not depend on the physical characteristics of the infrastructure or the technologies used in the AGVs. The AGV holon can control all types of AGVs mentioned in section 6.2 and any possible layout of the infrastructure.

A script consists of lines and each line contains a command that an AGV has to execute. The commands used in scripts of the AGV holon are given in Table 6-3 (Versteegt & Verbraeck 2001). When an AGV has reached certain stages in executing commands it generates events, see Figure 6-6. A notification of the event is sent to the AGV Control. The AGV Control interprets the event notification, retrieves the next command from the script and sends this command to the AGV. When the entire script has been executed the AGV control sends a notification to the ScriptDispatcher. The ScriptDispatcher then selects the next script for the AGV and sends this script to the AGV Control.

Table 6-3: Commands used in scripts

Command	Interpretation by AGV
Insist SA, 1	Claim one ticket from semaphore SA; SA is the identifier of the semaphore. When an AGV is executing an insist command it has to claim ticket(s). The AGV will not carry out the command on the next line of the script before it has received the ticket(s). In practice this means that an AGV will not drive onto the critical piece of infrastructure before it has received permission, in the form of a ticket, to enter the safeguarded piece of infrastructure. The insist command is used together with the near-event (Figure 6-6). When an AGV 'nears' a critical piece of infrastructure, it insists permission to enter the safeguarded area. The integer behind the name of the semaphore indicates the number of tickets that have to be claimed.
Exec TrackA	Execute TrackA; drive following virtual TrackA.
Exec TrackB, SA, 1	Execute TrackB; drive following virtual TrackB. When the AGV has left TrackB entirely one ticket is returned to the semaphore SA. The integer behind the name of the semaphore indicates the number of tickets that will be returned to the semaphore SA. The tickets are returned after the passed-event has been generated for trackB.
Free SA, 1	Return one ticket to semaphore SA. The free command is independent of the current position of the AGV. The integer behind the name of the semaphore indicates the number of tickets that are returned to semaphore SA.
Attempt b, SA, 1	Attempt to claim one ticket from semaphore SA. When the claim is successful, a ticket is returned and the value of the Boolean b is set to true. When the claim is unsuccessful, Boolean b is set to false and no ticket is returned. Using an attempt command the AGV can continue to execute the next command of the script, whether the attempt is successful or not. The attempt command is used to claim critical pieces of infrastructure far in advance, so that the AGV can always continue to drive. The insist command is used to claim pieces of infrastructure directly, when an insist command is refused the AGV stops.
Assign, if, then, else, while, end, loop, until, local variables, call s(p1,p2)	Other statements available in generic programming languages can be used in TRACES, such as assignments, if-then-else constructions, while-loops, and loop-until constructs. Another available feature is the use of subscripts, i.e. procedures or subroutines, which can be called from a script. Parameters and return values can be passed between scripts. TRACES can be seen as an extension of any generic programming language, like C++ or JAVA, in this sense. TRACES is independent of the programming language in which it is implemented.

6.4.2 Safeguarding Simple Infrastructure Elements

The TRACES concept was used in the AGV holon to safeguard different types of infrastructure, e.g. crossings, junctions, parkings and docking areas. The junction BCF, in Figure 6-11, can concurrently be entered by AGV1 and AGV2. The junction is safeguarded by semaphore SemBCF with a capacity of 1 ticket. The scripts that the AGV Controls have received from the ScriptDispatcher are shown at the

bottom of Figure 6-11. Each script consists of exec commands and an insist command to ask for permission to the semaphore SemBCF to enter the critical area BCF. In both scripts AGVs first drive towards the critical area BCF. When an AGV nears the area BCF it sends an insist for one ticket from the semaphore SemBCF. The exact position, in time and place, at which the near-event is generated depends on the actual speed of the AGV. Faster AGVs will generate a near-event earlier than slower AGVs. Both AGVs insist the same ticket, the position at which the ticket is insisted differs. The Semaphore BCF has only one ticket; only one AGV is allowed to enter the junction.

The semaphore has to decide which AGV can enter the junction first when several AGVs are competing for the same ticket. The semaphore can use several assigning strategies, like first-comes-first-served, last-comes-first-served or priority mechanisms. In most cases the first-comes-first-served mechanism is used. Priority mechanisms can give priority to AGVs that transport priority cargo units or AGVs that are behind schedule. After an AGV has received the insisted ticket it is allowed to access the critical piece of infrastructure and can execute the next exec command from the script. The AGV that does not receive the ticket does not carry out the next exec command and starts to brake. This AGV waits until it has received the insisted ticket. If the AGV receives the ticket during braking, it will accelerate and continue to drive on. If the AGV does not receive the ticket during braking, it will come to a complete stop before entering the conflict location BCF. An AGV will return the ticket after it has completely left the conflict location BCF and generated a passed-event for the track BC (AGV1) or track FC (AGV2).

Figure 6-11: Safeguarding a junction with a single semaphore containing one ticket (Versteegt & Verbraeck 2001)

The process of insisting, processing and sending tickets requires time. The Semaphore SemBCF processes the insist command. The semaphore has to check if the ticket is available and has to decide which AGV will be allowed to enter the junction. The communication between AGVs, AGV Control and Semaphores takes a certain amount of time. When the processing time and the communication time

are not taken into account AGVs will generate the near-events too late. An AGVs will start decelerating after the near-event, because it has not yet received the ticket and will accelerate as soon as the ticket is received. This continuous accelerating and decelerating will lead to 'nervous' behaviour of AGVs. This leads to nervous behaviour of other AGVs in the system, since AGVs will react to the nervous behaviour of the other AGVs. When the processing time and communication time are explicitly taken into account such nervous behaviour is prevented. The near-event is generated a bit earlier than the exact moment in time and place at which AGV has to start breaking in order to come to a complete stop before entering the safeguarded area. The extra time that is taken into account before generating the near-event is equal to the processing time of the semaphore and the communication time.

6.4.3 Safeguarding Complex Infrastructure Elements

The AGV holon can safeguard more complex infrastructure elements, like the crossing sketched in Figure 6-12. Several possibilities exist to safeguard this crossing using semaphores. A single semaphore with a single ticket can be used. It is clear that one semaphore with one ticket guarantees the safety, but the crossing will not be used efficiently. Only one vehicle is allowed at the crossing. In some cases it is safe to allow two AGVs at the crossing simultaneously. If AGV1 is driving from A to H, and AGV2 is driving from E to D, both vehicles can enter the crossing simultaneously without any danger of collisions. This is not allowed when a single semaphore containing one ticket is used.

Figure 6-12: Complex crossing safeguarded by multiple semaphores (Versteegt & Verbraeck 2001)

Both AGVs can be allowed to enter the crossing simultaneously when several semaphores are used. AGVs can only enter the crossing simultaneously when both are making a turn. When one of the AGVs has to drive straight on, the other one always has to wait. The ScriptDispatcher provides the right script to the AGV Control based on the destination of the AGV. The scripts for driving straight on and making a turn are different, see Table 6-4.

Table 6-4: Scripts to safeguard the complex crossing shown in Figure 6-12

Script AD (AGV1)	Script AH (AGV1)	Script EH (AGV2)	Script ED (AGV2)
Exec AB	Exec AB	Exec EF	Exec EF
Insist Scomm,1	Insist Scomm,1	Insist Scomm,1	Insist Scomm,1
Insist SBJ,1	Insist SBJ,1	Insist SFI,1	Insist SFI,1
Insist Sx,1	Insist SJG,1	Insist Sx,1	Insist SIC,1
Insist SIC,1	Free Scomm,1	Insist SJG,1	Free Scomm,1
Free Scomm,1	Exec BJ	Free Scomm,1	Exec FI
Exec BM	Exec JG, SBJ,1, SJG,1	Exec FK	Exec IC, SFI,1, SIC,1
Exec MN, SBJ,1, Sx,1	Exec GH	Exec KL, Sx,1, SFI,1	Exec CD
Exec NC, SIC,1		Exec LG, SJG,1	
Exec CD		Exec GH	

The semaphore Sx is used to safeguard the centre of the crossing. Semaphores SBJ, SJG, SFI, and SIC safeguard the branches of the crossing. When AGVs need to claim more than one semaphore, like the scripts shown in Table 6-4, there is a potential risk of deadlocks²⁸. Deadlocks can be avoided by carefully assuring that the semaphores are always claimed in the same order. This is, however, a very error-prone process. A communication semaphore, called Scomm, was introduced to prevent deadlocks. The communication semaphore contains one ticket. The Scomm ticket needs to be claimed before the more deadlock sensitive tickets can be claimed. The communication ticket remains claimed by an AGV until the other tickets have successfully been claimed. As long as an AGV has the communication ticket other AGVs can not claim tickets. The communication semaphore can be seen as a semaphore built on top of other semaphores. The communication semaphore safeguards the concurrent use of the other semaphores. The communication semaphore is freed using a free command, in contrast to the other semaphores, which are freed after executing an exec command. The communication semaphore is freed in the time domain, directly after the AGV has received the tickets it insisted from the semaphores. The semaphores that are claimed for driving safely are freed by a passed-event, when the AGV has completely left the area guarded by the semaphore.

6.4.4 Safeguarding Other Infrastructure Elements

When too many AGVs drive in a terminal they will hinder each other and the logistic performance of the terminal will drop, as stated in chapter four. This has a negative influence on the performance of the entire logistic system (Verbraeck et al. 2000a). The Terminal Semaphore was introduced to ensure that not too many AGVs are located simultaneously in an area at any point in time (Versteegt & Verbraeck 2001). The Terminal Semaphore is a semaphore with multiple tickets, which limits the number of AGVs in a larger safeguarded area, like a terminal. The initial number of tickets indicates the maximum number of AGVs that is allowed simultaneously within the area that the Terminal Semaphore safeguards. The Terminal Semaphore is used in the same way as other semaphores. When an AGV

²⁸ The most elementary form of a deadlock is a situation in which two AGVs have to claim two tickets to proceed. Suppose AGV1 first has to claim semaphore S1 and then semaphore S2, while AGV2 first has to claim S2 and then S1. If AGV1 has successfully claimed S1 while AGV2 has successfully claimed S2, both scripts halt and will not continue; a deadlock has arisen.

wants to enter the terminal it has to insist a ticket from the Terminal Semaphore before entering the terminal²⁹. If the Terminal Semaphore has tickets available the AGV is allowed to enter the terminal and the number of tickets is decreased by one. When an AGV has completely left the terminal a ticket is returned to the semaphore. When the Terminal Semaphore has no tickets left, no more AGVs are allowed to enter the terminal.

6.5 Evaluation of the AGV Holon and Dock Holon

The support facilities prescribed by the support environment were applied for the evaluation of the AGV holon and the Dock holon (chapter five). A combination of simulation, emulation and prototyping was used to evaluate the resource holons and logistic resources, as sketched in Figure 5-10.

Simulation models of the logistic resources were constructed in the first step. The resource holons were also translated into simulation models. The simulated resource holons were used to control simulated logistic resources. Emulation models of the logistic resources were made in the second step. The simulated resource holons were used to control the emulated logistic resources. Prototype logistic resources were controlled by the simulated resource holons in the third step.

The simulation models of the resource holons and the simulation models of the logistic resources can communicate directly. The simulation models cannot communicate directly with the emulated and prototype logistic resources. A translator was constructed in the interface between the simulated control system and the emulation models and the prototypes of the logistic resources. The translator translates messages from the simulation model of the resource holons into messages that the emulated and the prototype logistic resources can understand and vice versa.

6.5.1 Simulation Models

The first models are the simulation models of the logistic resources and logistic system, e.g. AGVs, docks and infrastructure. The AGV holon and the Dock holon are implemented in simulation models. The simulation models are used to evaluate the control logic inside the resource holons. Simulation environments offer many advantages when studying logistic systems (Banks 1998, Law & Kelton 1991). A number of these advantages were especially important for the TestSite. First, simulation offers possibilities to study the behaviour of the logistic system faster than real-time. Problems in the control logic of the resource holons could be found quickly. Problems that do not occur regularly, like deadlocks, could be quickly identified. Second, researchers have good control over the experiments in a simulated environment. Experiments could quickly be started or recreated. Prototype AGVs and cargo units are difficult to handle because of their size. Simulated AGVs and cargo units were easy to deal with in experiments. Finally, simulation offers a safe environment for experiments. The control logic of the AGV holon could be tested in a fully simulated environment before its was used to control prototype AGVs. The prototype AGVs are large vehicles weighing up to 10,000 kg and driving up to 6 m/s. If the AGV holon was implemented directly, this could lead to potential dangerous situations for the operators at the TestSite and damage to the AGVs.

²⁹ The Terminal Semaphore can use the same assigning strategies as normal semaphores.

An important requirement of our support environment is the need to be independent of technology, both for hardware and for software, as stated in chapter five. The resource holons are independent of the technology of the logistic resources, since the logistic resources are placed outside the resource holons. The resource holons were implemented in three different simulation packages to test the software independence; Simple++, Arena, and AutoMod³⁰. All three of the simulated resource holons were used to control simulated, emulated and prototype AGVs. This allowed us to demonstrate that the resource holons are independent of the software platform in which they are implemented. Furthermore, implementing resource holons into different simulation packages provided insight in the possibilities each package offers for modelling large scale automated logistic systems (Versteegt & Verbraeck 2002c).

6.5.2 Emulation Models

The emulation models of the logistic resources are highly detailed simulation models of the logistic resources. The high levels of detail focus mainly on the control systems of the logistic resources. The control systems in the emulation models are the real onboard control systems of the logistic resources. For example, the emulation models of the AGVs contain the actual software used in the onboard control systems of the prototype AGVs. The physical movements are simulated, e.g. driving and transshipments. The emulated logistic resources had two goals.

- *Evaluating the onboard control systems of the logistic resources.* The emulation models of the logistic resources contained the actual software used in the logistic resources. The physical activities were simulated. The emulation models were used to evaluate the software of the onboard control systems of the logistic resources before the implementation in the prototype logistic resources.
- *Studying communication.* The resource holons use the same communication protocol to control simulated, emulated and prototype logistic resources. The emulation models were used to study the communication between the resource holons and logistic resources. Listeners were used to record communication. Finally, communication failures and how the resource holons and logistic resources responded to communication failures were studied. It is important that all operations of the AGV are carried out in a failsafe way. When the communication between AGVs and the AGV holon failed, AGVs came to a complete stop after finishing their current track and waited until communication was resumed.

6.5.3 Prototypes

The prototypes were used to prove the technical feasibility of the design for the logistic resources of the ULS Schiphol. The evaluations using the prototype AGVs and docks was mainly aimed at studying the technical aspects of the logistic resources (Pielage 2001, Versteegt & Verbraeck 2001, Rijsenbrij et al. 2000).

- *Precision tests.* The AGVs have to drive in a constricted space, close to other AGVs and to other objects, in some cases there will only be a couple of centimetres space in between objects. The AGVs have to be able to manoeuvre very accurately.

³⁰ Simple++ 6.0 (Kalasky & Levasseur 1997), Arena 4.0 RT (Kelton et al. 1998), AutoMod 9.1 (Stanley 2001, Banks 2000).

- *Testing of sensors.* The logistic resources at the TestSite are autonomous and responsible for controlling many of their own activities, following design guideline four stated in chapter five. The automated logistic resources use many sensors to obtain information about their environment. This information is used by the onboard control systems of the logistic resources to take control decisions. Different types of sensor were tested, e.g. laser sensors, infrared sensors and obstacle bumpers. The reactions of the onboard control systems of the AGVs to obstacles were evaluated.
- *Evaluation of odometry encoders and calibration system.* The prototype AGVs have odometry encoders, which monitor the number of rotations and the orientation of the steering wheels, to keep track of their position. The odometry encoders are not entirely accurate and have to be calibrated (Drane & Rizos 1998). A magnet grid in the floor and magnet sensors under the AGVs were used as a calibration system. The magnet grid only allows relative calibrations. The AGVs do not differentiate between the magnets. The magnet sensors proved not to be reliable at speeds higher than 4 m/s and when the distance between the magnets and magnet sensor became too large (Hylckama-Vlieg et al. 2003). The AGVs will drive very closely together in the ULS Schiphol, closer than the accuracy of the magnet grid. The calibration system proved to be accurate enough for the AGVs at the TestSite. The calibration system was easy to construct and robust. An absolute calibration system is needed in addition to the magnet grid in the real implementation of the ULS Schiphol, especially at critical locations such as the terminals³¹.

6.5.4 Synchronisation of Time and Place

Synchronisation proved to be a difficult task during the evaluation. The simulated, emulated and prototype logistic resources had to be synchronised to the simulated resource holons. Two types of synchronisation are distinguished; *time* and *place* (Versteegt & Verbraeck 2002c).

The synchronisation of time is aimed at synchronizing the simulation clock of the simulated resource holons with the clocks of the simulated, emulated and prototype logistic resources. The internal clocks of the emulated and the prototype logistic resources run at real-time. Synchronisation of time is aimed at ensuring that the simulation clock runs at real-time. Arena 4.0 RT and Simple++ 6.0 offer standard built-in features for real-time progress. A wall clock pecker was constructed for AutoMod 9.1. Every fixed time unit, e.g. every tenth of a second, the wall clock pecker synchronised the simulation clock to the internal computer clock. In general the internal clock of the simulated resource holons and simulated logistic resources had to be slowed down to synchronise with the clocks of the emulated and prototype logistic resources. In some cases, however, the simulation models had to catch-up with the computer clock. This occurred mainly when calculation intensive control algorithms had to be executed by the AGV holon, e.g. several AGVs that were passing through a complex crossing. The simulation models of the resource holons then lagged behind and had to catch-up. Two solutions were chosen to solve this problem caused by the speed differences between control and physical processes. First, the calculation intensive algorithms were transferred from simulation code into C++ code. The calculations can be

³¹ Absolute calibration systems can be used to exactly determine the position of AGVs. Absolute calibration systems can determine the position of the AGVs with more reliability than relative calibration systems (Drane & Rizos 1998). Several absolute calibration systems are available, like transponders with a fixed location and GPS based systems (Global Positioning System).

executed faster in C++ than in simulation software. Second, asynchronous communication proved its added value here, in asynchronous communication a buffer of messages is used. This allows processes to send messages without having to synchronise. The control and physical processes are decoupled from a communication point of view. A process sends messages to the mailbox and continues to operate as normal without having to wait for the other process.

Within synchronisation of place the position and orientation of logistic resources in the simulation models had to be synchronised with the actual position and orientation of the physical logistic resources. This proved to be more complicated, especially for the AGVs that moved through the logistic system. The AGVs at the TestSite have no absolute system to determine their position and orientation. The AGVs are equipped with odometry encoders to keep track of their position and use a magnetic grid in the floor for relative calibrations. The emulated and prototype AGVs send event notifications to the simulation models when they have reached certain positions on the virtual tracks they are following in order to synchronise their positions and orientation.

6.6 Learning Moments

Two resource holons were designed for the TestSite; an AGV holon and a Dock holon. The holonic structure of logistic control and the design guidelines prescribed by the support environment were used to support the design process. The support facilities recommended by the support environment were used to evaluate the resource holons.

The AGV holon was responsible for controlling a fleet of AGVs. The Dock holon was responsible for controlling the automated material handling stations or docks. The AGV holon was developed first; the design of the Dock holon was partially based on the design of the AGV holon. The technical implementation of the resource holons was different, because of the differences between AGVs and docks. First, AGVs drive through the logistic system, while docks have a fixed position. Second, the docks consist of a number of handling stations that need to coordinate their actions, while AGVs can perform activities on their own without the need for coordination with other AGVs.

The design of the AGV holon and the Dock holon were evaluated by studying their performance on the identified requirements identified in section 5.2. The holonic structure for the AGV holon was *scalable*. The limits of scalability are decided by the logistic system-being-controlled. The AGV holon was able to control the entire fleet of AGVs at the TestSite; consisting of 10 scale models prototypes. This was the maximum number of AGVs available at the TestSite. The physical space available did not allow experiments with more AGVs.

The AGV holon was *adaptable*. Several changes to the logistic system were incorporated in the resource holons. The changes made to the AGV holon were; adding new types of AGVs and new types of docks during experiments. The AGV holon could continue to operate without any changes to its structure while the changes were incorporated.

Both the AGV holon and Dock holon proved to be *robust*. Several potential disturbances that are likely to occur in the ULS Schiphol were studied. The disturbances of the AGVs were for example not following the correct tracks and errors in the sensor readings. The disturbances of the docks were for example cargo units that are not transhipped properly and AGVs that were not parked accurately. Finally, communication disturbances were studied, such as communication equipment failures and the

loss of messages. The AGV holon and Dock holon proved to be able to deal with the mentioned disturbances. The AGV holon and the dock holon operated in a failsafe manner (Verbraeck & Versteeg 2001). When disturbances occur the current logistic operations were finished and new ones were not started until the disturbance was solved. For example, when a communication failure occurred between an AGV and a semaphore the AGV stopped and waited until the communication was resolved.

The AGV holon and Dock holon were *independent of the technology used in the logistic resources*. The AGV holon was able to control all different AGVs, e.g. simulated, emulated, and prototype AGVs. The AGV holon did not see any differences between the different types of AGV. The AGVs are placed outside the AGV holon. The AGV holon is independent of the software platform. The AGV holon was implemented in three simulation packages to test the software independency. Although the three implementations were different from each other, they all offered the same basic control functionalities.

The *asynchronous communication* enabled the control and the physical processes to operate independently. When one process was delayed, the other process could continue to operate as normal. This was very important because of the large speed differences between control and physical processes. The control processes are executed within tenths of a second, while the physical processes take longer, e.g. AGVs driving on a track and transshipping a cargo unit. When AGVs wanted to enter a critical area of infrastructure it was still possible that AGVs had to wait until the control process was ready and had given permission to enter the area. This could occur when complex crossing had to be passed for which the controls algorithms were calculation intensive. Although this looks like synchronous communication it is still asynchronous. The AGVs were delayed on purpose, until it is safe for them to enter the complex crossing.

The communication between the resource holons and logistic resources was limited. To limit the communication the number of commands and events was limited. The most critical communication was between the AGV holon and AGVs. This communication was carried out through a wireless communication network with only limited capacity. In order to further reduce the communication the AGVs did not generate all track based events for each individual track. The AGV holons are only interested in those event notifications to which they have to react and have to subscribe to the corresponding information services.

Within the AGV holon the TRACES concept was used to safeguard the concurrent use of infrastructure (Evers et al. 2000). The AGV holon was able to guide the AGVs safely through the infrastructure at the TestSite. The routing of AGV, guiding of AGVs and claiming permission to enter critical areas was completely virtually and did not depend on the technology of the AGVs or the layout of the infrastructure. The AGV holon was able to safeguard the infrastructure for all types of AGVs at the TestSite. The AGV holon provided high levels of flexibility by using free-ranging AGVs. The semaphores could be used to safeguard any layout of the infrastructure. New layouts of the infrastructure could be used without any changes to structure of the AGV holon. Only the scripts and semaphores had to be changed when a new layout was used.

There were some aspects within the TRACES concept that had to be dealt with. First, the claiming and releasing of tickets is carried out completely virtual. This makes it sometimes difficult to see which AGV is claiming what tickets. The operators of the TestSite could start listeners, which subscribed to insist commands of AGVs and the sending of tickets by semaphores, to study this. The listeners recorded all the communication that was used to claim and release tickets. Second, how far in advance and how

many tickets should be claimed? When only one ticket is claimed by an AGV the AGV might show nervous behaviour. The AGV has to decelerate each time it does not have a ticket and accelerate when it receives a ticket. When AGVs claim many tickets in advance, the distance between the AGVs becomes larger and the overall efficiency drops. The exact points where tickets are claimed is important. The near-event was used at the TestSite. AGVs have to start braking at this point to come to a complete stop before entering the safeguarded area. When AGVs generate a near-event, a near event notification is sent to the AGV holon. The AGV holon decides whether the AGV can continue to drive or not. The communication time and calculation time of this process have to be taken into account. Otherwise the near-event is generated too late and the AGV will not come to a complete stop before entering a critical area, which leads to dangerous situations. Finally, there were no time components in the TRACES concept. This means that no scheduling can be carried out in the TRACES concept. This problem was solved by placing planning and scheduling components at higher layers of control within the AGV holon. The higher layers of control of the AGV holon were responsible for the scheduling of AGVs. The lower layers of the AGV holon, in which the TRACES concept was implemented, were responsible for carrying out the schedules and traffic control.

The emulation models and prototypes used to evaluate the resource holons can be seen as a type of simulation. The emulation models and prototypes at the TestSite were highly detailed models of the logistic resources. This way the technical aspects can be tested under real world circumstances before the implementation of the ULS Schiphol will start. The ULS Schiphol will use new technologies for both AGVs and docks. The risks of investing in wrong technology are minimised by using the support facilities recommended by the support environment.

Automated logistic systems and automated control systems lack capabilities to deal with extraordinary situations compared to human based systems. As long as the environment is stable and no unforeseen situations occur automated systems function normally. Automated systems become more of a burden than a support when changes in the environment and unforeseen events occur (Ulrich and Düring 1995). Human based systems can better react to unforeseen circumstances. The human operators had to identify and solve many problem situations at the TestSite, like deadlock situation, failed docking operations and AGV crashes.

Finally, the TestSite had positive side effects besides the testing of AGVs, docks and their control systems. Automated logistic systems are abstract systems. Actors with little knowledge of logistics and transportation have little insight into how such systems will behave (chapter four). This makes it difficult to mobilise decision makers to make decisions within the design process. The prototype AGVs and prototype docks at the TestSite made the ULS Schiphol more concrete. Generally speaking, research is stimulated and it becomes easier to mobilise decision makers around the design of innovative transport systems when the projects are made more concrete by using a laboratory setting (Latour, 1996).

*What information consumes is rather obvious: it consumes the attention of its recipients.
Hence, a wealth of information creates a poverty of attention and a need to allocate that
attention efficiently among the overabundance of information sources that might consume it.*

Herbert Simon

7 Empirical Testing of The Order Holon

In the first case study, described in chapter six, the technical feasibility of the support environment was tested. The support environment was used to design and evaluate resource holons for the control of AGVs and material handling stations. In the second case study, described in this chapter, the support environment is applied to design a customer order management system for the Underground Logistic System Schiphol. This second case study is selected based on the considerations mentioned in chapter one. The goal of the case study is to develop a Holonic Order Management System that allocates the scarce capacity of the logistic resources to the demands of customers.

The holonic structure prescribed by the support environment in chapter five is used to design the Holonic Order Management System. Simulation models are constructed to evaluate the designed control system. The performance of the designed Holonic Order Management System is compared to the requirements on logistic control stated in section 5.2. The other support facilities prescribed by the support environment are not used, e.g. emulation models and prototypes. There are only a few issues on the technology of the Holonic Order Management System that need to be answered; there is no need for emulation models and prototypes. The framework for simulation, sketched in chapter two, is used to construct the simulation models.

7.1 Introduction

The ULS Schiphol will be a highly automated logistic system; the logistic resources will be fully automated. Besides the automation of the physical activities, the control activities will also be automated. Recent advances in control systems and developments in Information and Communication Technology offer new possibilities to control automated logistic systems (Vlasic et al. 2001, Drane & Rizos 1998).

Logistic control consists of two separate but interfering processes, as stated in design guideline three; scheduling and real-time control (chapter five). The real-time control of logistic resources has been dealt with in other parts of the ULS Schiphol research project (chapter six), while the scheduling of customer

orders has received little attention (Rijsenbrij et al. 2000). In the design of the Tilburg city distribution system the control over the logistic resources received most attention, while the scheduling of customer orders was discarded (chapter four). The topic in this chapter is the design of control systems to schedule customer orders. The goal of the second case study is to:

'Study the added value of a holonic customer order management system for the Underground Logistic System Schiphol.'

We develop such a system, named Holonic Order Management System, abbreviated to HOMS, following the holonic structure of control systems and the design guidelines stated in chapter five. The HOMS has to match the scarce capacity of the logistic resources to the demands of the customers.

7.2 Structure of the Holonic Order Management System

Two different holons are used in the Holonic Order Management System for the ULS Schiphol; order holon and resource holon³². Three resource holons are used to schedule the logistic services provided by the logistic resources³³; AGV holon, Dock holon and Maintenance holon. The AGV holon and Dock holon were introduced in chapter six.

Maintenance will play an important role in the ULS Schiphol. The ULS Schiphol uses new technologies for the AGVs and the material handling stations. These technologies are not yet proven in practice. It is expected that the logistic resources will show high levels of failures, especially during the start-up phases. These failures will disrupt normal operations (Ebben 2001, Rijsenbrij et al. 2000). Regular maintenance to the logistic resources is needed to prevent failures and to minimise the negative consequences of failures. Maintenance is carried out by maintenance engineers. Maintenance engineers have only a limited capacity; they are a scarce resource. A maintenance holon is introduced to schedule the services provided by the maintenance engineers to the AGVs and material handling stations.

The general structure of the Holonic Order Management System is sketched in Figure 7-1. The HOMS is responsible for the scheduling of customer orders and the scheduling of maintenance to the logistic resources. The scarce capacity of the logistic resources to perform logistic services has to be matched to the demands of logistic services. The most important aspect in the HOMS is the interaction between the holons. The holons have to cooperate to schedule logistic services. The AGV holon and Dock holon have to cooperate with the Order holon to schedule logistic services. The Maintenance holon has to cooperate with the AGV holon and Dock holon to schedule maintenance. The cooperation between holons is carried out by sending requests and offers. When a holon needs to cooperate with another holon it sends a request for a service to the other holon. The second holon can send an offer based on the request. The second holon does not need to cooperate, because of the autonomy the holonic structure offers.

Two types of communication exist in the HOMS. First, the communication between customers and order holons. Second, the communication between the holons. Holons communicate with each other when cooperation is needed.

³² A load holon is not developed. Load holons mainly provide information services to the other holons (chapter five). These information services are divided between the order holon and the resource holons.

³³ The general concept of the holons is meant when order holon and resource holon are written with a small capital. When Order holon, AGV holon and Dock holon are written with a capital the specific implementation for the second case study is discussed.

Figure 7-1: Holonic Order Management System for the ULS Schiphol³⁴

7.2.1 Order Holon

Order holons are the interfaces between customers that demand logistic services and resource holons that provide logistic services. Order holons match the scarce capacity of the resource holons to the demands of the customers. The order holons are responsible for scheduling customer orders in cooperation with the resource holons. Order holons have to cooperate with the resource holons; order holons can not force resource holons to schedule logistic services. The order holons send a sub-request to perform a logistic service to the resources holons. The resource holons can send sub-offers to perform this request, or choose not to respond to the request.

Several order holons can be present in one logistic system. This allows competition within a logistic system; several order holons compete for the scarce capacity of the same resource holons. This can be compared to the separation of track and train operations after the privatisation of the railways in Europe (Smith 2003). Within railway systems it is common that several train operating companies operate passenger rail services on the same tracks provided by one party. The order holons can also be located in competing logistic systems, e.g. one order holon of the ULS Schiphol and one order holon of a trucking company.

³⁴ Customers are modelled as holons, although they are not part of the HOMS.

7.2.2 Resource Holons

Resource holons are responsible for scheduling the logistic services that the logistic resources have to perform. The term logistic resource is used in a broad sense. Many different types of logistic resources are used in logistic systems, e.g. AGVs, docks, terminals, tunnels, employees and battery recharging spots. We choose to focus on scheduling AGVs, docks and maintenance engineers in the HOMS. In the real implementation of the ULS Schiphol more types of logistic resources will be used, e.g. tunnels, storage systems and battery recharging spots. We choose not to take them into account; such logistic resources were studied in other parts of the ULS research project (Ebben 2001, Rijsenbrij et al. 2000).

AGV Holon

AGV holons are responsible for scheduling of the activities of the AGVs. The scheduling of AGVs is the most difficult of the resource scheduling in the ULS Schiphol (Verbraeck et al. 2000). First, AGVs drive through the system while other resources have fixed locations. The location of the AGVs at present and in the future has to be taken into account during the scheduling process. This is difficult, since some of the customer orders have to be scheduled well in advance and the location of an AGVs changes during operations. Second, the duration of the activities of AGVs is more stochastic than the activities of the fixed logistic resources. For example, the driving times of AGV are stochastic due to possible congestion in the system.

The AGV holons are responsible for the scheduling of the logistic services provided by the AGVs. The AGVs are responsible for carrying out the scheduled logistic services. The AGVs have five possible states in the scheduling process. The state of an AGV is *claimed* when the transport of a cargo unit has been scheduled. The state of an AGV is set to *docking* when a transhipment of a cargo unit between the AGV and a dock has been scheduled. The state of an AGV is set to *transfer* when the AGV is scheduled to drive to a location where it has to start a new logistic service or where it will receive maintenance. The state of an AGV is set to *maintenance* when maintenance has been scheduled to the AGV. Finally, the state of an AGV is *parked* when nothing else has been scheduled; this is the default state.

A possible schedule of an AGV to perform logistic services is depicted in Figure 7-2. The AGV receives maintenance at the beginning of the sequence; the state is *maintenance*. After the maintenance has been finished the AGV drives towards a dock where it has to pick up a cargo unit; the state of the AGV is *transfer*. The cargo unit is transhipped from the dock onto the AGV; the state is *docking*. After the transhipment has been finished the AGV drives towards the destination of the cargo unit; the state is *claimed*. The cargo unit is transhipped from the AGV onto a dock at the destination of the cargo unit; the state is *docking*. After the logistic service has been finished the AGV has no new logistic services scheduled; the state is *parked*.

Figure 7-2: A possible schedule of an AGV

Dock Holon

Dock holons are responsible for scheduling the logistic services that the docks provide. The docks tranship cargo units on and off AGVs. Docks have three possible states in their schedules; busy, maintenance and idle. When a transshipment of a cargo unit is scheduled the state is set to *transshipping*. When a maintenance engineer is carrying out maintenance on a dock the state is set to *maintenance*. The default state is *idle* when no transshipments of maintenance activities are scheduled.

The holonic structure of the Dock holon for the ULS Schiphol has several management layers. The highest layer is the Dock Management layer for the entire ULS Schiphol. Lower Dock Management layers are responsible for controlling the docks at a terminal. Each terminal, geographically separated from other terminals, consists of one or more docks.

Maintenance Holon

Maintenance to the logistic resources is a critical aspect in the ULS Schiphol. The ULS Schiphol uses new technologies for AGVs and docks (chapter six). These new technologies have not yet been fully tested and proven in practice. It is expected that the AGVs and the docks will show high levels of failures initially (Pielage 2001). A Failure Mode and Effect Analysis³⁵ was conducted for the ULS Schiphol (Rijssenbrij et al. 2000). An FMEA is a systematic study of the reliability and effects of failures of all components of a system. The AGVs especially will show many types of failures; mechanical failures and failures of the control systems. Such failures will disturb normal operations; scheduled customer orders can not be performed within the promised time windows. This will lead to unsatisfied customers that will no longer make any use of the services provided by the ULS Schiphol. Maintenance on the logistic resources has to be carried out regularly to minimise the frequency of failures. This way the number of failures is reduced and the negative effects of failures are minimised.

Maintenance engineers are responsible for the maintenance of AGVs and docks. Maintenance engineers are scarce resources with a limited capacity to perform maintenance services. Maintenance engineers are controlled by a Maintenance holon in the HOMS. The Maintenance holon offers maintenance services to other resource holons; AGV holon and Dock holon. The Maintenance holon, AGV holon and Dock holon have to cooperate to schedule maintenance activities; the schedules of the AGVs and the docks have to match to the schedules of the maintenance engineers. The AGV holon and the Dock holon are responsible for scheduling maintenance in the schedules of the AGVs and the docks. The Maintenance holon has to schedule the activities of the maintenance engineers.

Two possible states are used in the schedules of maintenance engineers; busy and idle. The state in the schedule of a maintenance engineer is set to *busy* when a maintenance activity on an AGV or dock is scheduled. The default state is *idle* when no maintenance activities are scheduled. Each terminal in the ULS Schiphol will have a small maintenance area where maintenance engineers can work (Rijssenbrij et al. 2000).

³⁵ Abbreviated to FMEA (Stamatis 2003).

7.3 Holonic Scheduling Process

Two scheduling processes are distinguished in the HOMS.

7.3.1 Part One: Scheduling of Customer Orders

The order holon and resource holons in the HOMS have to cooperate to schedule customer orders and maintenance. The scheduling of customer requests is based on the scheduling process introduced in design guideline three (chapter five) and is sketched in Figure 7-3. The interactions needed to schedule maintenance are depicted in Figure 7-4.

Figure 7-3: Scheduling process of customer requests

Customers have transportation demands, which are translated into individual requests for logistic services provided by the logistic system. The customers send their requests to the order holon. The customers interact only with order holons. The customers have no direct interactions with the resource holons. This reduces the complexity of the scheduling process for the customers; when many interactions are needed with different holons the process becomes too complex for the customers. The customers receive offers from the order holons and compare the offers to their original request to decide to accept or to decline the offers.

Order holons are responsible for facilitating the cooperation between resource holons in the scheduling process. Several resource holons have to cooperate to perform logistic services for customers. There are no direct interactions between the resource holons in the scheduling process of customer requests; all interactions are facilitated by the order holon. First, the order holons receive requests from customers. Order holons divide the requests into parts that the individual resource holons can perform. These parts are called sub-requests. The sub-requests are sent to the resource holons. Second, order holons join the sub-offers of the resource holons into offers. The offers are sent to the customers. Finally, order holons are responsible for informing the resource holons as to whether a customer has accepted an offer or not.

Resource holons are responsible for scheduling the logistic services provided by the logistic resources. The resource holons receive sub-requests from the order holons and create sub-offers based on the sub-requests. The sub-offers are temporary claims in the schedules of the logistic resources. The order holons join the sub-offers of several resource holons into offers for the customers. The temporary claims are turned into permanent claims when a customer accepts an offer. The temporary claims are deleted from the schedules when an offer is rejected.

7.3.2 Part Two: Scheduling of Maintenance

Maintenance is initiated by the resource controls in the resource holons, as can be seen in Figure 7-4. The resource control and resource manager form the resource holon; the maintenance manager and maintenance engineer form the maintenance holon. Resource controls have knowledge of when maintenance is needed for a logistic resource. Resource controls keep track of the last maintenance interval of the logistic resources and know when new maintenance intervals are needed. The resource controls *schedule maintenance* for the logistic resources and send *requests for maintenance* to the resource manager. The request consists of a time window and a location for the maintenance. Resource managers are responsible for scheduling the activities of the entire set of logistic resources. The resource manager *checks* if the requested maintenance can be carried out. For example, the resource manager can overrule requested maintenances during peak hours and can ensure that the maintenance of all resources is not scheduled in the same time window. The resource manager sends a *request for maintenance* to the maintenance manager if the maintenance can be carried out. The resource manager sends a *denial for maintenance* to the resource control when it is not favourable to carry out the maintenance. The maintenance manager *checks* whether the request can be carried out. If the maintenance request can be carried out the maintenance manager *updates the schedules of the maintenance engineers*. Based on whether maintenance can be scheduled the maintenance manager *sends an offer or denial* to the resource manager. The resource manager *updates its own schedules* and *sends the offer or denial* to the resource control. Finally, the resource control *updates the schedule of the logistic resource*.

The scheduling process is started again when a requested maintenance of a resource control can not be carried out. The attributes of the request for maintenance are changed, e.g. a new time window or another location. The values of the attributes of the new maintenance request are as close to the original request as possible.

Figure 7-4: Scheduling process of maintenance

The procedure for scheduling maintenance can be used for scheduling maintenance to any type of logistic resources. The maintenance of AGVs and docks is taken into account in this case study. The scheduling of maintenance of AGVs is more complicated than the maintenance of docks; AGVs drive through the logistic system, while docks have a fixed location. The AGV controls schedule the maintenance of AGVs at the expected location at the time of maintenance. The AGV control determines the location of the AGV just before the maintenance time window; this way AGVs do not have to travel empty through the system for maintenance purposes.

7.4 Specification of the HOMS

Simulation models are constructed to evaluate the designed Holonic Order Management System. The other support facilities prescribed by the support environment are not used, e.g. emulation models and prototypes. There are only few issues on the technology of the Holonic Order Management System that need to be answered; there is no need for emulation models and prototypes. Some important parts of the HOMS and their implementation are discussed in this section. The parts are chosen based on discussions with domain experts.

7.4.1 Object Oriented Structure

The holons are implemented in simulation models in eM-Plant³⁶. The holons are modelled following an object oriented modelling approach, in such a way that the advances of object orientation can be used, e.g. abstraction, polymorphism, inheritance and encapsulation (Fowler & Scott 2000, Weisfeld 2000, Rumbaugh et al. 1999).

The most fundamental class, from which most other classes inherit attributes and methods, is the *Global Logistic Object*, abbreviated to GLO, as can be seen in Figure 7-5. The GLO contains the most basic attributes and methods that each object and holon must contain in the holonic structure³⁷. The GLO has a mailbox for the asynchronous communication. The GLO can subscribe itself to information services provided by publishers. The GLO has a world model, which is used to make decisions on control actions and coordination actions.

Figure 7-5: Classes that form the holons in the HOMS

³⁶ Version 7.0 (Tecnomatix 2002)

³⁷ For reasons of clarity not all attributes and methods are depicted in Figure 7-5.

The attributes and methods created for the GLO can be reused by the classes that inherit from the GLO. This saves time during the design process of the control system. Using inheritance makes the HOMS maintainable; changes made in the GLO are automatically implemented in the classes that inherit from the GLO.

7.4.2 Communication in the HOMS

Communication in the HOMS is asynchronous, following design guideline five (chapter five). The asynchronous communication is implemented through mailboxes. All objects in the HOMS have their own mailbox, as can be seen in Figure 7-6. Mailboxes are used for sending and receiving messages. The publisher *creates a message* and *places the message* in its own mailbox. The mailbox of the publisher *checks* whether there are any messages in the mailbox or not. The mailbox of the publisher *sends the message* to the mailbox of the subscribers when there are messages available. The mailbox takes care of delivering the messages to the correct destination. The mailbox of the subscriber *checks* whether there are any messages in the mailbox and *passes the message* to the subscriber. Finally, the subscriber *handles the message*. The subscriber takes decisions on control actions and coordination actions based on the messages it received.

Figure 7-6: Asynchronous communication through mailboxes

The communication is asynchronous; the processes sketched in Figure 7-6 are completely decoupled. The processes of checking the mailboxes for messages, sending messages to other mailboxes and the handling of messages are independent. The mailboxes check if there are any messages themselves. Such checks are carried out at regular intervals. An interval of 1 minute was chosen in the HOMS for the ULS Schiphol. This is a much longer time interval than the time interval used in the AGV holon for real-time control (chapter six). For real-time control a short time interval is needed, since the AGV holon has to make immediate decisions based on the messages in the mailbox. For the HOMS a longer time interval can be taken since the scheduling process takes place well before the actual customer orders have to be

performed. The length of the activities also differs for the real-time control and scheduling. In real-time control many activities take place that only last part of a second, e.g. an AGV driving on a short track. The AGV holon needs to be up-to-date with all messages, therefore small time intervals are needed. The shortest time interval in the scheduling process of the HOMS is a transshipment of a dock, which takes up to 60 seconds.

Communication is implemented through information services, following design guideline seven (chapter five). When an object needs certain types of information it subscribes to a publisher that can provide this information. Each object has a subscriber list and subscription list. The subscriber list contains the subscribers that are subscribed to the information service that the object offers. The subscription list contains all the information services to which the object has subscribed. The lists contain information on the maximum and minimum number of messages that are received in a time window.

7.4.3 Maintenance for the Logistic Resources

The resource controls inside the resource holons decide when maintenance is needed for the logistic resources. Maintenance is scheduled after a certain amount of operating time has elapsed in the ULS Schiphol. The time between maintenance intervals and the time needed for maintenance are given in Table 7-1.

Table 7-1: Maintenance of docks and AGVs

	Time between maintenance (hours)	Maintenance time (hours)
<i>AGV</i>	250	2
<i>Dock</i>	1000	0.5

Other maintenance strategies are possible in the holonic structure, e.g. AGVs need maintenance after driving a number of kilometres or docks need maintenance after a number of transshipments. A maintenance strategy based on operating time between maintenance was chosen in the HOMS for the ULS Schiphol.

7.4.4 Performance Indicators

Performance indicators are used to study the performance of the HOMS. The performance indicators, shown in Table 7-1 were derived from interviews with logistic experts involved in the ULS Schiphol research project. The performance indicators are divided into four categories, e.g. customer, order holon, resource holons and communication. The performance indicators on the order holon and customers are related to the matching of customer requests and offers from the logistic system. They are used to indicate how well the ULS Schiphol is able to facilitate the demands of customers. The performance indicators on the resource holons indicate how efficient the logistic resources are scheduled in the HOMS. Communication is a vital aspect in logistic control systems (Ulrich & Düring 1995). The performance indicators on communication can be used to analyse the communication in the HOMS.

Table 7-2: Performance indicators

Performance indicator	Measurement unit ³⁸
Customer	
Send requests to order holon	#
Received offers from order holon	#
Denied offers	#
Accepted offers	#
Order holon	
Send sub-request (related to customer requests)	#
Received sub-offers (related to sub-requests)	%
Resource holons	
Utilisation AGVs (claimed, docking, transfer, maintenance, parked)	%
Utilisation docks (transshipping, maintenance, idle)	%
Maintenance engineers (received requests and accepted requests)	#
Communication	
Messages (related to customer requests)	#

The measure unit of some of the performance indicators is related to the number of requests from customers. This choice was made to increase the comparability of the results of the experiments.

7.4.5 Initial Treatment

Simulation experiments embody a number of simulation runs under the same treatment. A treatment consists of the specification of the input data, specification of the initialisation conditions, specification of the run control conditions and specification of the output data (Sol 1982, Ören & Zeigler 1979). The initialisation conditions and run control conditions are decided by the system under investigation. The HOMS for the ULS Schiphol is a non-terminating system as we are interested in the long term steady state of the system and there is no natural event to specify the length of a simulation run (Law & Kelton 1991). When studying non-terminating systems the start-up time, run length and number of replications have to be decided (Sol 1982). As we are interested in the long term behaviour of the model we must remove the initial conditions, or transient phase, from the simulation results (Banks 1998). Customer requests are constructed up to one week before they have to be executed. After one week all the customers have generated their requests for the next week and the generation of customer requests has

³⁸ The measurement unit # stands for number. The # *send requests to the order holon* stands for the number of requests send to the order holons by the customers

reached a steady state. A start-up time of at least one week needs to be taken into account³⁹; to be on the safe side a start-up time of 10 days is used. After the first 10 days have been completed the collection of the values of the output variables starts. The run length can heuristically be taken to be equal to three times the maximum cycle time (Sol 1982). The customers generate requests for the HOMS based on a weekly pattern. A run-length of at least three weeks should be taken into account. Most data on transportation demands of customers and transportation flows has been studied on a monthly basis in the ULS Schiphol project (Rijssenbrij et al. 2000). Therefore, the run length is extended to 28 days or 4 weeks. The total simulation time per simulation run is at least equal to the sum of the start-up time and run-length. The total simulation time is set to 40 days.

The *number of replications* is determined by performing a small number of initial replications (Meel 1994). The utilisation of AGVs is used to decide the number of replications. The formula used to decide the number of replications is (Soest 1997, Law & Kelton 1991):

$$n \geq \frac{4t_{\alpha/2, n_0-1}^2 s^2}{\delta^2} \quad (1)$$

In this formula n is number of replications, $t_{\alpha/2, n_0-1}$ is the t-value of the student t-distribution for a given $\alpha/2$ significant level with $n_0 - 1$ degrees of freedom. δ is the width of the confidence interval, and s^2 the variance of the output values after n_0 replications. This formula assumes that the results of the replications are independent and normally distributed. Initially ten replications were made with a significance level of 95%, which makes α equal to 0.05. After investigating several output variables we concluded that the initial 10 replications were sufficient for statistical analysis at the chosen level of confidence.

7.4.6 Verification and Validation

Verification is substantiating that the model is transformed from one form into another as intended with sufficient accuracy (Balci 1998). Validation is substantiating that within its domain of applicability the model behaves with satisfactory accuracy consistent with the study objectives (Balci 1998). We see verification and validation as a continuous activity throughout the entire life cycle of the simulation model. We chose to verify and validate objects, sub-models and parts of the model as soon as they are constructed rather than waiting until the entire model is finished. Relatively small parts of the model are studied during verification and validation this way, which makes the process more transparent and easier than verifying and validating entire models at one time. The entire simulation model, which consists of earlier verified and validated sub-models, is verified and validated when the object and sub-models have been validated. The simulation model is verified during code inspection meetings (Banks 1998). The goal of the computer code is explained to simulation experts in several inspection meetings. The experts study the computer code and check whether the code is correct and meets its intended goal. Problems or errors in the computer code are discussed, documented and solved.

A distinction can be made between replicative validation and structural validation (Sol 1982). Replicative validation is comparing the values of the endogenous attributes with the ones found in the

³⁹ The number of scheduled customer requests was used to test whether this one week period was sufficient. The moving average of the number of scheduled customer orders stabilised after this one week period.

real system, as far as these are measurable. Structural validation refers to the inspection and validation of the simulation models with expectations based on experiences with real systems. Replicative validation can be performed if there is sufficient empirical data available. The simulation model is validated in a structural way, as there is a lack of empirical data in our research area.

Two types of structural validation are used (Banks 1998). First, experts are consulted to validate the model structurally using face validity. The simulation model and the behaviour of the model are presented to experts familiar with logistic systems. The experts check whether the behaviour of the simulation model appears to be reasonable compared to their expectations. Second, extreme conditions tests are performed. The behaviour of the simulation model under extreme input data is tested. For example, the arrival rate of customer requests is set to extreme values or the AGVs drive much faster than normal.

7.5 Experiments with the Holonic Order Management System

7.5.1 Transportation Flows Prognosis

The Holonic Order Management System is evaluated using a simulation model. Inputs for the model are the estimated number of logistic resources and the estimated transport flows that the ULS Schiphol needs to handle in the year 2020. All transport flows are measured in cargo units. A cargo unit is the largest type of cargo that has to be handled; the main deck aircraft pallet. The prognoses of the transport volumes within the ULS Schiphol for the year 2020 are given in Table 7-3 (Rijnsbrij et al. 2000).

Table 7-3: Estimated transport volumes (1,000 cargo units per year in 2020)

	(to) airport	(to) rail terminal	(to) flower auction
(from) airport	-	122	67
(from) rail terminal	182	-	197
(from) flower auction	10	414	-

The first experiments were conducted with a simulation model of the entire ULS Schiphol; 360 AGV, 6 docks at the airport, 8 docks at the flower auction and 8 docks at the rail terminal (chapter six). The entire estimated transport volume was used. The throughput times of the simulation experiments with the model of the entire ULS Schiphol proved to be unacceptably long. The HOMS implemented in a simulation model was not able to handle such large numbers of cargo units and logistic resources. The main problem was the large amount of communication within the HOMS. The simulation software⁴⁰ used was not able to deal with the large amount of messages exchanged within and between the holons.

To be able to conduct experiments with the simulation models of the HOMS a model of a scaled down version of the ULS Schiphol was made. This scaled down model was made in cooperation with

⁴⁰ eM-Plant version 6.

researchers within the ULS Schiphol project to reduce the time needed for experiments. It is important to note that the simulation model of the scaled down version of the ULS Schiphol is still a valid model of the entire ULS Schiphol. Only two characteristics of the ULS Schiphol were changed; the number of logistic resources and the transportation flow. Fewer AGVs and fewer docks are used and the transportation flows are reduced in the scaled down version of the ULS Schiphol. In a final validation session the experts agreed that the scaled down version still represents the ULS Schiphol for research purposes. The scaled down version of the simulation model represents the most important characteristics of the ULS Schiphol. First, the disproportions in the transport flows still exist. The flows between flower auction and rail terminal, and vice versa, are the largest. Second, there are imbalances in the transport flows. There are moments during the day, week and year that the ULS Schiphol has to facilitate peak demands from the customers. The imbalances and disproportions of the transport flows are still present in the simulation model of the scaled down version of the ULS Schiphol. Third, no reductions are made to the geographic structure of the ULS Schiphol. The entire transportation network is still used in the scaled down version. Finally, no simplifications or reductions are made for the scheduling process of customer orders and maintenance.

7.5.2 Experiments

Experiments were conducted to study the behaviour and performance of the HOMS. The goal of the experiments was to explore and to get understanding of the behaviour of the HOMS and study its added value for the ULS Schiphol. A number of scenarios was developed to study possible 'to-be' situations of the HOMS and the ULS Schiphol. The scenarios were developed in cooperation with researchers involved in the ULS Schiphol project and represent their expectations on how the ULS Schiphol will function. The following scenarios were identified.

1. *Standard situation.* This is the basic scenario, representing the start-up phases of the ULS Schiphol. The HOMS consists of one order holon and three resource holons, i.e. AGV holon, Dock holon and Maintenance holon.
2. *Competing resource holons.* The possibilities of competing logistic service providers are studied in this scenario. The goal of this scenario is to test if the HOMS is able to facilitate competing AGV holons in the same logistic system. Two AGV holons make use of the same transportation network and offer their logistic services to the same order holon. The order holon can use the services provided by each of the two competing AGV holons; the AGV holons provide the same logistic services. The order holon sends sub-requests for logistic services to both AGV holons and chooses the best sub-offer it receives from the AGV holons. The order holon should not prefer one specific AGV holon over the other, when their sub-offers are equal; the order holon should treat both AGV holons equal. This scenario is used to test if the order holon does treat similar resource holons in the same way.
3. *Competing order holons.* The possibilities of competing order holons are studied in this scenario. Two order holons are present in the same logistic system and make use of the same AGV holon and Dock holon. Customers can send their requests to both order holons and can choose from the offers created by the order holons.

4. *Competing order holons and competing resource holons.* This scenario is a combination of scenarios two and three. Two competing order holons make use of the logistic services provided by two AGV holons and one Dock holon.

Table 7-4: Scenarios to evaluate the HOMS

	standard situation	competing resource holons	competing order holons	competing order/resource holons
<i>Order holon</i>	1	1	2	2
<i>AGV holon</i>	1	2	1	2

Only one Dock holon and one Maintenance holon are used in all scenarios. Although several dock holons and maintenance holons can be present in the HOMS, only one of each was used. It is expected that only one Dock holon will be operational in the ULS Schiphol. The docks have fixed positions and the services that the docks offer are basic functions that the ULS Schiphol should provide to AGV operators within the ULS Schiphol.

Scenario 1: Standard Situation

This is the basic scenario of the HOMS. The HOMS consists of one Order holon, one Dock holon, one AGV holon and one Maintenance holon. The goal of this scenario is twofold. First, the HOMS can be studied in a small and transparent setting. Second, the start-up phases of the ULS Schiphol can be studied. During the start-up phase there will be no competing holons in the HOMS. The start-up phase is an important phase for the ULS Schiphol. Currently, customers use competing transport systems to transport cargo units between the flower auction and airport. The ULS Schiphol has to convince potential customers to make use of the logistic services provided by the ULS Schiphol during the start-up phases. The performance of the HOMS in the standard scenario is given in Table 7-5.

Table 7-5: Results of scenario 1 (standard situation)

Performance indicator	Unit	Mean	St. Dev.
<i>Customer</i>			
Send requests	#	5974.5	14.6
Received offers	#	5573.0	117.4
Denied offers	#	558.6	15.4
Accepted offers	#	5015.2	115.2

<i>Order holon</i>				
Send sub-request (related to customer request)	#		6.0	0.4
Received sub-offers (related to sub-requests)	%		86.4	1.2
<i>Resource holons</i>				
AGVs	%	claimed	50.4	1.3
		docking	1.9	1.4
		transfer	18.2	2.0
		maintenance	0.7	0.03
		idle	28.8	1.8
Docks	%	transshipping	4.1	2.3
		maintenance	0.05	0.0
Maintenance engineers	#	sub-requests	129	-
		sub-offers	129	-
<i>Communication</i>				
Messages (related to customer requests)	#		59.3	0.42

The average utilisation of the logistic resources seems low at first sight. The AGVs are scheduled to perform logistic services for about 50% of their operational time. The docks are idle almost all of the time; they are only occupied for about 4% of their operational time. There are several explanations for the low utilisations. The ULS Schiphol is scaled to handle peak demands. First, the demand for logistic services change during the day, week, month and year. The ULS Schiphol is designed to be able to handle peak demands⁴¹. The peak demands in the ULS Schiphol are mainly demands on services provided by the AGV holon. During the peak hours all the AGVs are used efficiently; they are transporting cargo units to other terminals. The utilisation of the AGVs outside the peak hours is low. Second, there are imbalances in the transportation flows. The transportation flow from the flower auction to the rail terminal is larger than the flow from the rail terminal to the flower auction. Many AGVs transport flowers from the auction to the rail terminal, but return empty. There are no cargo units to return to the flower auction and the AGVs can not wait at the rail terminal, because of the limited space to park AGVs. The imbalances in the transportation flows cause vehicles to drive empty through the transportation network and reduce the average utilisation of the AGVs.

⁴¹ The ULS Schiphol is designed to handle all customer demands, except the 10 busiest days of the year. During those 10 days it is not possible to handle all customer demands. Most of the peaks in the customer demands are caused by the transport of flowers. The customer demands change during the day, week, month and year. The peak hours during the day are in the morning just as the auction process has finished. The busiest days of the week are Monday and Tuesday. The busiest days of the year are for example the days before Christmas and Valentines Day.

The low utilisation of the AGVs allows the AGV holon and Maintenance holon to schedule maintenance outside the peak hours. The AGV holon prevents maintenance during peak hours. The AGV holon schedules maintenance when the utilisation of the AGVs is low; this way the AGVs can be used to transport cargo units when there is high demand for their services.

The docks are not a critical resource; the utilisation of the docks is low even during peak hours. There are two reasons for the low utilisations of the docks. First, the transfer operations performed by the docks are carried out quickly and take only up to one minute. The time needed for transshipments is relatively short compared to the times needed to transport cargo units. The docks have high capacities and can transfer many cargo units compared to the number of cargo units transported by the AGVs. Second, the terminals in our research are equipped with two docks. One dock is more than sufficient for each terminal. In the design of the ULS Schiphol it was decided that each terminal has at least two docks. When one dock fails the other dock can still be used for transshipments. Dock failures will disrupt the operations of the AGVs when only one dock is available at each location. The AGVs will not be able to deliver cargo units at their destination and have to deliver their cargo units to another location. Such failures have negative consequences for the performance of the entire logistic system. Each terminal is therefore equipped with two docks.

The Maintenance holon can schedule all the requests for maintenance it receives. This means that all the AGVs and docks can receive maintenance on a regular basis. This is important, especially during the start up phases of the ULS Schiphol, in which the logistic resources will show high levels of failure. The maintenance to AGVs is scheduled outside the peak hours. The maintenance to docks can always be scheduled even during peak hours. The low average utilisations of the logistic resources were compared to earlier research on the ULS Schiphol. Earlier research also shows low utilisations of the logistic resources (Versteegt et al. 2002, Ebben 2001). Finally, the low utilisations of the logistic resources were presented to researchers involved in the ULS Schiphol project. The utilisations of the logistic resources were according to the expectations of the researchers. The AGVs drive empty through the transportation network for about 18% of their scheduled time. There are three causes for AGVs driving around empty. First, there are the imbalances in the transportation flows. AGVs transport cargo units to a terminal and have to drive back empty, since there are no cargo units available to return. Second, there is only little space available to park idle AGVs; idle AGVs need to drive to another terminal to park and wait for a next assignment. Third, AGVs have to drive to another terminal for maintenance when the maintenance can not be carried out at their present location. The most common cause of AGVs driving around empty is the imbalance in the transportation flows.

The largest part of the customer requests can be handled by the ULS Schiphol. About 7% of the customer requests can not be scheduled. The requests that can not be scheduled are mostly late requests from customers that arrive during peak hours. The late requests arrive at the Order holon just before they have to be executed. This leaves little possibilities for the Order holon and the resource holons to fit the late request into their current schedules. When the Order holon can not come up with an offer for the customer this is always caused by the AGV holon; there are no AGVs available to perform the requested logistic services. There are no problems with the Dock holon; the docks have enough capacity left to handle late request by customers even during peak hours. The Dock holon can change the time window of the transshipment when a sub-request can not be performed. The Order holon will use this new time window and requests the AGV holon to delay the AGV.

Scenario 2: Competing Resource Holons

The possibilities of competing logistic service providers are studied in the second scenario. Two AGV holons make use of the same transportation network and offer their logistic services to the same Order holon. The Order holon sends sub-requests for logistic services to both AGV holons. The AGV holons can decide to create a sub-offer and send this sub-offer to the order holon. The Order holon can choose the best sub-offer from both AGV holons; the sub-offer that fits best to the sub-offers of the Dock holon and the original customer request.

Table 7-6: Results of scenario 2 (competing resource holons)

Performance indicator	Unit	Mean	St. Dev.
Customer			
Send requests	#	5969.6	18.0
Received offers	#	5348.1	186.1
Denied offers	#	540.0	17.9
Accepted offers	#	4803.5	183.8
Order holon			
Send sub-request (related to customer request)	#	12.0	0.1
Received sub-offers related to sub-requests)	%	85.8	0.7
Resource holons			
AGV holon 1 / (AGV holon 2)	%	claimed	50.8 (50.7) 2.0 (2.0)
		docking	2.0 (2.0) 1.6 (1.8)
		transfer	17.9 (17.7) 3.0 (5.7)
		maintenance	0.7 (0.7) 0.5 (1.0)
		idle	28.6 (28.9) 2.6 (1.9)
Docks	%	transshipping	3.9 3.8
		maintenance	0.05 0.0
Maintenance engineers	#	sub-requests	129 -
		sub-offers	129 -
Communication			
Messages (related to customer requests)	#	88.2	0.8

The performances of both AGV holons are comparable. This is according to the expectation of researchers involved in the ULS Schiphol project. Each AGV holon is responsible for controlling the same number of AGVs. The AGV holons are similar; they use the same strategies to schedule the sub-offers received from the Order holon. The Order holon sends the sub-requests to both AGV holons and

chooses the best sub-offer from both AGV holons. The small differences between the performance of both AGV holons are caused by differences in the locations of AGVs in the transportation network and differences in the time needed to create sub-offers. First, the locations of the AGVs differ for both AGV holons and the location of AGVs influences the scheduling process. Second, the time that the AGV holons need to come up with a sub-offer differs. Normally, the Order holon has enough time to choose between the competing sub-offers from the AGV holons. The Order holon has little time to come up with an offer for a customer when handling late requests. The Order holon will then not wait until both AGV holons have send a sub-offer; the Order holon will choose the first available sub-offer.

More communication is needed in the HOMS when two AGV holons are used, although the same number of AGVs is used in the system. The increase in communication is caused by the communication between the Order holon and the two AGV holons.

The most important conclusion of this scenario is that the HOMS can facilitate several logistic service providers in the same automated logistic system. This allows competition of logistic service providers in the same logistic system. This can be compared to several train operating companies operating passenger rail services on the same transportation network (Smith 2003). The customer requests are divided fairly between both AGV holons, which should be the case since both AGV holons use the same strategies to schedule customer requests. The Order holon does not give priority to one of the AGV holons. The Order holon chooses the best sub-offer it receives from both AGV holons.

Scenario 3: Competing Order Holons

The third scenario was developed to study the possibilities of several order holons competing in the same logistic systems. Two Order holons are used, one AGV holon, one Dock holon and one Maintenance holon. Customers send requests for logistic services to both Order holons. The Order holons try to create offers for the customers. The customers can choose the best offer they receive from the Order holons. The Order holons have to compete with each other for the logistic services provided by the AGV holon and Dock holon.

Table 7-7: Results of scenario 3 (competing order holons)

Performance Indicator	Unit	Mean	St. Dev.
<i>Customer</i>			
Send requests	#	5975.8	45.8
Received offers	#	5239.3	18.5
Denied offers	#	529.6	23.8
Accepted offers	#	4698.5	32.8
<i>Order holon 1 / Order holon 2</i>			
Send sub-request (related to customer request)	#	6.0 (6.0)	0.2 (0.2)
Received sub-offers (related to sub-requests)	%	76.9 (76.8)	0.3 (0.2)

Resource holons

AGVs	%	claimed	52.0	0.6
		docking	2.0	0.5
		transfer	18.0	1.3
		maintenance	0.7	0.5
		idle	27.3	1.4
Docks	%	transshipping	3.9	1.8
		maintenance	0.05	0.0
Maintenance engineers	#	sub-requests	129	-
		sub-offers	129	-

Communication

Messages (related to customer requests)	#	106.6	0.3
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The most important conclusion of this scenario is that the HOMS can facilitate several Order holons competing against each other in the same automated logistic system. The Order holons compete against each other to come up with the best offer for the customers. The customers will choose the best offer. The customer can also choose to decline both offers, when the offers do not comply to the original request. The performance of both Order holons is comparable. The Order holons use the same strategy in dividing customer requests and joining sub-offers. Differences are mainly caused by the time differences in the arrival of the customer requests at the Order holons. More communication is needed in the HOMS in the third scenario compared to the first and second scenario. This is mainly caused by the extra communication between the second Order holon and the resource holons. Most communication in the HOMS is between the order holons and resource holons, especially the AGV holon.

Scenario 4: Competing Order Holons and Competing Resource Holons

This scenario is a combination of scenarios two and three. Two competing order holons make use of the logistic services provided by two AGV holons and one Dock holon. This scenario represents a possible operational state of the ULS Schiphol, after it has been operational for some years.

Table 7-8: Results of scenario 4 (competing order holons and competing resource holons)

Performance indicator	Unit	Mean	St. Dev.
<i>Customer</i>			
Send requests	#	5970.5	37.4
Received offers	#	5219.4	29.6
Denied offers	#	526.6	18.0
Accepted offers	#	4682.7	33.3

Order holon 1 / (Order holon 2)

Send sub-request (related to customer request)	#	12.0	(12.0)	0.2	(0.2)
Received sub-offers (related to sub-requests)	%	79.4	(74.3)	0.3	(1.8)

Resource holons

AGV holon 1 / (AGV holon 2)	%	claimed	51.7	(51.7)	0.8	(0.9)
		docking	2.0	(2.0)	0.9	(1.1)
		transfer	17.7	(17.5)	0.9	(1.8)
		maintenance	0.7	(0.6)	2.1	(0.6)
		idle	27.9	(2.1)	2.5	(2.0)
Docks	%	transshipping	3.9		1.6	
		maintenance	0.05		0.0	
Maintenance engineers	#	sub-requests	129		-	
		sub-offers	129		-	

Communication

Messages (related to customer requests)	#	106.7		0.3	
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The most important conclusion of the fourth scenario is that the HOMS is able to facilitate several order holons and several resource holons competing in the same logistic system. More communication is needed to perform the same amount of customer requests compared to the first and second scenario. The same number of customer requests is scheduled. There is no extra communication compared to the third scenario. The AGV holon limits the number of sub-offers send to the Order holon to reduce communication.

7.6 Evaluation of Holonic Order Management System

The HOMS was evaluated by studying 'how well' it meets the defined requirements for logistic control from section 5.2.

The *scalability* of the HOMS was not shown during our action research. The implementation of the HOMS in a simulation model assessed to be not scalable. The time needed for experiments with the simulation models was unacceptably long to conduct the number of replications needed in our research. This was caused by software limitations of the simulation package. The simulation software used was not able to deal with the large amount of asynchronous communication between and within the holons. A simulation model of a scaled down version of the ULS Schiphol was used for the experiments. The scaled down version is valid for our study, as the most important characteristics of the ULS Schiphol are kept unchanged. It can not be concluded that the HOMS is or is not scalable based on the results from our study.

The *extendibility* of the HOMS was tested by extending the transportation network by adding new destinations. The HOMS was able to incorporate these expansions during the experiments without modifications to the structure of the HOMS. For such extensions the world model the AGV holon and the Order holon of the infrastructure had to be changed. New destinations can be added and used directly in the holonic scheduling process. Other extensions were the adding of customers to the HOMS. The extension of the transportation network and the adding of new customers are the two most likely expansions of the ULS Schiphol. New customers register for information services at the Order holon and can send customer requests directly after the information services have started. The HOMS was able to facilitate both expansions without the need for modifications to the structure of the holons.

The HOMS is an *adaptive* control system. Changes were made to the logistic resources controlled by the AGV holons. The characteristics of the AGVs and docks were changed. The HOMS was able to schedule these new logistic resources directly after the changes were made. Using new types of logistic resources is one of the most likely changes that can occur in the ULS Schiphol. The HOMS was able to facilitate such changes without the need to make modifications to the structure of the holons.

The logistic resources are not scheduled *efficiently* in the HOMS in the traditional sense of efficient (Evers et al. 2000, Bowersox & Closs 1996). The average utilisation of the AGVs and docks proved to be low. The ULS Schiphol is designed to handle peak demands from customers. The AGVs are used efficiently during peak hours; during peak hours the AGVs are used to transport cargo units. Outside the peak hours the AGVs are used less efficiently. The docks are not used efficiently; the capacity of the docks is used only partially even during the peak demands from the customers. Efficiency for large scale automated logistic systems should not only be measured by the utilisation of the logistic resources, it also has to be measured by how well the logistic system is able to handle peak demands. The AGV holon prevents maintenance during peak hours. The AGV holon and Maintenance holon schedule the maintenance to AGVs outside peak hours. The AGV Manager inside the AGV holon prevents maintenance during peak hours. The AGVs are used for transporting cargo units during peak hours. The docks are not a critical resource in the ULS Schiphol. The docks have more than enough capacity to deal with the customer demands. The utilisation of the logistic resources is comparable in all scenarios studied during our action research. This is according to the expectations of the researchers involved in the ULS Schiphol project. The same transportation flows, the same transportation network and the same number of logistic resources are used in each scenario.

Roughly the same number of customer requests can be scheduled in each scenario. The number of customer requests that can be scheduled does not depend on the number of order holons or resource holons, but on the capacity of the AGVs. When the Order holons can not create an offer for a customer this is always caused by the AGV holon. The AGV holon can not schedule the sub-request of the Order holon. The Dock holon could schedule all customer requests in all scenarios. When the Dock holon could not come up with a sub-offer directly, it created an alternative sub-offer, in which the transshipment is scheduled directly after the original sub-request of the Order holon. The Order holon used this alternative sub-offer and notified the AGV holon to delay the AGV during the transport to the dock.

Although the average utilisation of the AGVs seems low at first sight, no extra customer requests can be performed during peak hours. During peak hours the utilisation of the AGVs is high and the AGVs can not transport more cargo units. More customer requests can be transported only when they can be carried out outside the peak hours. Most of the customer requests, however, arrive during the peak hours.

The HOMS is *communication* intensive both within and between holons. The holons have to communicate to cooperate in the scheduling process of logistic services for customers. The large amount of communication puts heavy burdens on the communication network. This seems a paradox compared to design guideline six, which emphasises minimisation of communication. Communication in the HOMS can be facilitated by fixed networks with high capacities. The part of the communication that will be implemented through a wireless network, for example communication between the AGVs and the AGV holon, still has to be kept to a minimum as stated in chapter six. The design guideline six has, therefore, to be changed to minimise or limit the communication between resource holons and logistic resources that communicate through wireless communication networks.

The scaled down version of the simulation model still validly represents the ULS Schiphol for our research purposes. The scaled down version still contains the most important characteristics of the ULS Schiphol, e.g. the imbalances and disproportions in the transportations flows and geographical structure. It must be noted that the estimated transport flows are not accurate. Accurate estimations are not possible, since the growth of the transport market around Amsterdam Airport Schiphol depends on highly volatile aspects, such as economic growth. The estimated transport flows originate from before the 11th September 2001. The growth scenarios for the air transportation market have been adjusted after 11th September 2001.

*In science one tries to tell people, in such a way as to be
understood by everyone, something that no one ever
knew before. But in poetry, it is the exact opposite*
Paul Dirac

8 Group Evaluation Session

The final evaluation of the support environment was done during a group evaluation session. The group evaluation session was conducted after the technical feasibility and the usability studies were finished (chapter six and seven). The support environment was presented to a group of experts on automated logistic systems and control systems. The experts studied the support environment and compared the usability of the support environment with their own experiences and expectations. The group of experts focused on two aspects during the evaluation: the support environment and the application of the support environment during the case studies⁴².

8.1 Introduction

The goal of the group evaluation session was *an independent evaluation of the support environment by actors not involved in the development of the support environment*. The participants⁴³ of the group evaluation are all involved in the ULS Schiphol project, but not actively involved in development of the support environment. The participants work in the field of developing innovative transport systems and have extensive knowledge of the latest developments in automation of logistic resources. Participants from universities and companies joined the group session, drawn from different disciplines and expertise areas. This way a group of people from different disciplines was used to evaluate the support environment.

8.2 Structure of the Group Evaluation Session

A structured approach consisting of six steps was followed during the group evaluation session, see Figure 8-1 (Verbraeck 2003). The session was developed in cooperation with a facilitator. The facilitator was responsible for preparing the session and guiding the experts during the session.

⁴² The results of the group evaluation session are described in more detail in: Verbraeck & Versteegt (2003), Kuik-Onrust (2003), Hylckama-Vlieg et al. (2003).

⁴³ The participants are listed in the appendix.

Figure 8-1: Structure of the group evaluation session

A short summary of the ULS Schiphol project was given to the participants in the first step of the group session. The history and some recent developments of the project were introduced. In the second step the requirements for the control systems were identified. The experts were asked to define a number of requirements to evaluate control systems for large scale automated logistic systems. The requirements were used to evaluate the support environment in the remaining part of the group evaluation session. The requirements defined in section 5.2 were used besides the requirements defined by the experts.

The support environment was presented to the experts in the form of a structured walk through in the third step. The goal, the structure and possible applications of the support environment were discussed. The holonic structure and design guidelines were presented and evaluated in the fourth step. This step ended in studying the support environment and the choices made within the holonic control structure prescribed by the support environment. The case studies conducted to evaluate the support environment were discussed in the fifth step. In the sixth, and final step, the participants further explained their motives for their evaluations.

8.3 Evaluation of the Holonic Structure

The holonic structure and design guidelines were evaluated by checking 'how well' they met the requirements on control systems as identified in step two and section 5.2.

Open Structure of the System

The participants found that the holonic structure has an open structure (Verbraeck 2003, Kuik-Onrust 2003). The holonic structure allows easy connections to other systems, like customer control systems and management information systems. The communication protocols and the messages used in the holonic structure are well documented. Control systems of other actors that want to join the ULS

Schiphol can communicate with the holonic control system, as long as they comply to the predefined communication protocols. It is important that a group of potential customers is contacted on the communication protocols they currently use before the control systems for the ULS Schiphol are constructed. The communication protocol used in the holonic control structure should closely resemble the current way of doing business by the customers. This will keep the barriers low for potential customers that want to switch to the ULS Schiphol.

An open system should be independent of specific hardware and specific software. The holonic structure is independent of the software platform. The AGV holon was implemented in three different simulation packages to evaluate the feasibility of the software independence (chapter six). All three simulation packages were able to control the AGVs at the TestSite. The resource holons are independent of the technology used within the logistic resources. The actual physical logistic resources are placed outside the resource holon. A representation of the logistic resources is placed inside the resource holon. The AGV holon at the TestSite was able to control the different prototypes of the AGVs (chapter six). The experts were convinced that the AGV holon can control more types of AGVs, as long as the AGVs comply to the predefined communication protocol sketched in section 6.3.

The participants studied the holonic structure and the communication protocols and concluded that the holonic structure has an open structure and does not lay boundaries on the hardware and software within the logistic systems. The only factor of concern is the large amount of communication within the holonic structure. The software platform and communication network should be able to facilitate large amounts of communication.

Adaptability

An adaptable control system is able to deal with changes in the system itself and its environment without major modifications to the structure of the control system (Bass et al. 2003). The adaptability of the ULS Schiphol is mainly aimed at offering new logistic services to customers. For example, new logistic resources can be added to the system to perform new services. Such new types of logistic resources are controlled by their own resource holons. It should be possible to add new holons to the system without major changes to other holons.

The participants found that the holonic structure is adaptable; new holons can be added to the holonic structure without modifications to the existing holons. New resource holons can easily be added; only the interactions between the existing order holons and the new holons have to be defined.

Expandability

Expandability is a requirement for the long term exploitation of the ULS Schiphol. The experts predicted that the ULS Schiphol will be expanded in the future; new destinations will be added or connections to other logistic systems will be made. An important requirement for the control systems is that they are able to facilitate such expansions without modifications to the structure of the control systems.

Expandability in the holonic structure is achieved through independence of infrastructure. The holonic structure is independent of the transportation network and infrastructure at the terminals. The order holons only have knowledge of the infrastructure at a high level of abstraction. The order holons know the destinations between which cargo units can be transported and the predicted travel times. Detailed knowledge of the infrastructure is only present in the resource holons that are connected to the infrastructure; the AGV holons. The AGV holons have knowledge of the layout of the transportation network and current usage of the transportation network. Such knowledge of the transportation network can easily be changed.

The participants found that the holonic structure complies to the requirement of expandability through the independence of infrastructure. Two types of experiments were performed to test the expandability. The first type of experiments showed that new destinations could be added to the order holons and resource holons during normal operations (chapter seven). The second type of experiments was changing the layout of the transportation network at the TestSite (chapter six). The safeguarding of infrastructure by the AGV holon is completely virtual; changes can be implemented quickly without physical changes to the infrastructure (Versteegt & Verbraeck 2001). Extensions to layout of the transportation network can be implemented without any modifications to the structure of the AGV holon.

Scalability

Scalability is the ability of a system to continue to meet its response times or throughput objectives as the demand for the systems functions increases (Smith & Williams 2002). Scalability for the control systems of the ULS Schiphol has two axes. First, more logistic resources can be added to the resource holons, e.g. more AGVs can be added to the system. The resource holons need to be able to control larger number of logistic resources. Second, the transportation demands of the customers can increase. The customers will send more requests to the order holons. The limits of scalability are decided by the system under investigation. The resource holons of the ULS Schiphol should be able to control 360 AGVs and 22 docks (Ebben 2001). The order holon and resource holons should be able to schedule up to 3,000 logistic services each day in the year 2020 (Rijnsbrij et al. 2000).

Scalability in the holonic structure is facilitated by the combination of the hierarchical and the decentralised structure (Kuik-Onrust 2003). When too many logistic resources are controlled by one resource holon the response times for control actions become too long. The long response times can be reduced in two ways. First, in the hierarchical structure an extra management layer can be added in the resource holon to reduce the load factor of existing management layers. Second, in the decentralised approach an additional resource holon can be added. The controlled logistic resources are controlled by different resource holons.

The AGV holon at the TestSite was able to control up to 10 physical AGVs and 2 docks. It was not possible to test the scalability of the AGVs holon beyond this point because of the physical limitations of the TestSite (chapter six). Larger numbers of logistic resources could be studied in the HOMS (chapter seven). The implementation of the HOMS was able to control 120 AGVs and 30 docks within the time constraints defined by the participants. The experiments described in chapter seven are based on a scaled down version of the ULS Schiphol; the number of AGVs, docks and customer order were reduced. A scaled down version of the ULS Schiphol was used during the experiments to reduce the time needed for experiments.

The scalability of the holonic structure was not fully assessed during our evaluation according to the participants. The participants were convinced that the combination of the decentralised and hierarchical structure is scalable, at least within the limits of the ULS Schiphol.

Efficiency

Automated logistic systems use expensive automated logistic resources. It is important that these resources are used efficiently (Evers et al. 2000, Hammond 1986). The transportation network has to be used efficiently, since this is the most expensive resource and most difficult to expand (chapter four). Two aspects are important when regarding the efficiency of logistic resources in the ULS Schiphol. First, efficiency will not be the most important requirement during the start-up phases of the ULS Schiphol. Only a few customers will make use of the ULS Schiphol at the beginning. Reliability and throughput times will be more important to convince more potential customers to use the logistic services offered by the ULS Schiphol. Efficiency will become more important when more customers use the services offered by the ULS Schiphol. Second, the ULS Schiphol is designed and scaled to deal with peak demands in the transportation flows between the Flower Auction Aalsmeer, Amsterdam Airport Schiphol and the Rail Terminal Hoofddorp. These peak hours occur regularly throughout the day, the month and the year. Such peak hours are for example, at the end of the auction process when a lot of flowers and plants need to be transported. The logistic resources have to be used as efficiently as possible during peak hours to fulfil as many customer orders as possible.

The participants initially had some problems with the decentralised components in the holonic structure although they offer many advantages over centralised control structures (chapter five). A decentralised control system makes it difficult to guarantee a minimum level of efficiency (Bongaerts 1998). The holonic structure combines decentralised and hierarchical control. This dual structure makes it possible to use the logistic resources efficiently, while still operating a distributed setting. The distributed resource holons are responsible for scheduling their own set of logistic resources as efficiently as possible. The more centralised order holons are responsible for the efficient behaviour of the entire system. The order holon tries to schedule the customer requests as efficiently as possible for the entire system.

Participants found that the Holonic Order Management System schedules the logistic resources efficiently during peak hours. During the rest of the day the utilisation of the logistic resources is lower; there are less cargo units that need to be transported. The experiments described in chapter seven showed that although the AGVs are used to the fullest during peak moments, their overall utilisation over the entire day remains low. This closely follows the expectations of the participants.

Reliability and Robustness

Robust control systems are able to continue to operate as much as normal when disturbances occur (Bongaerts 1998). It is expected that the technology used in the AGVs, the docks and the control systems of the ULS Schiphol will initially show high levels of failures (Pielage 2001, Rijsenbrij et al. 2000). The control systems have to be able to deal with such disturbances.

The participants found that the resource holons and order holon are reliable for disturbances. The distributed structure of the holons makes it possible to first try to solve disturbances locally without the help of other holons. Disturbances in one holon do not influence other holons. When a holon cannot solve the disturbance other holons are contacted. The distributed setting of the holonic structure and high levels of autonomy allow other holons to continue to operate up to a certain level, when disturbances occur. Although failures of one holon influence the other holons, the consequences of failures are minimised. According to the participants the consequences of a disturbance in a centralised control system are larger; the entire system and the logistic system will come to a complete stop more quickly.

The participants highly valued the failsafe handling of disturbances in the resource holons. The AGVs and the docks can only perform activities when all the sensors give a signal that the activities can be carried out safely at the TestSite. When one of the sensors does not give a safe signal the logistic service is not started or stopped (Versteegt & Verbraeck 2001). For example, when communication failures occur AGVs finish their current activities and brake to come to a complete stop. The AGVs can start to drive after the communication failure has been solved and the communication is resolved.

8.4 Evaluation of the Case Studies

The participants appreciated the selection of the case studies described in chapter six and seven. The ULS Schiphol is a good example of a large scale automated logistic system. The case studies together provide a good basis in which the most important aspects in the design of large scale automated logistic systems were studied.

In the first case study an AGV holon and a dock holon were developed. The choice to focus on AGVs, docks and terminals was supported by the participants. The AGVs are the most complex logistic resources in the ULS Schiphol from a control point of view. The technology used inside the AGVs is complicated and has not yet been proven in practice. The control over AGVs is also complicated; many AGVs drive in small areas. The terminals are the most important areas from an operational point of view. Many interactions between AGVs and docks take place at the terminals. Many AGVs drive on the terminals, where there is only limited space available for manoeuvring. The choice to use autonomous AGVs was supported. Autonomous AGVs are responsible for controlling many of their own activities. The control systems inside the AGV holon are relieved of some of the control activities by using autonomous AGVs. This makes the AGV holon better scalable.

The second case study on the Holonic Order Management System was seen as a good exploration of the customer order management system. The participants thought that the handling of customer requests as a part of the ULS Schiphol research project had not received much attention before our research started (Rijsenbrij et al. 2000). The participants initially had some doubts on the handling of customers requests that arrive simultaneously at the order holon. This problem was solved in the HOMS. The proposed scheduling process (chapter five), which was implemented in the HOMS allows for the simultaneous arrival of several customer requests. Customer requests that arrive simultaneously are processed in a sequential way by the individual resource holons.

8.5 Enhancements for the Support Environment

In the final step of the group evaluation session the participants were asked what enhancements should be added to the support environment for future usage.

The connections between the ULS Schiphol and the customers have to be studied further. The connections have two axes. First, there is the physical connection between the ULS Schiphol and the customers. The customers have to deliver their cargo units to the ULS Schiphol and vice versa. The location of this point and the transfer of responsibility have to be studied. Second, there are the connections between control systems. Information between control systems of the customers and the ULS Schiphol has to be exchanged to schedule and perform logistic services. Both types of connections should be studied before the implementation of the ULS Schiphol starts.

More realistic customer behaviour has to be added to the research on the ULS Schiphol. The customers were modelled in a simplified way during both case studies. The operators of the TestSite played the role of customers at the TestSite (chapter six). The customer behaviour was simplified to creating requests and accepting/rejecting offers in the HOMS in chapter seven. The participants of the group evaluation session suggested a gaming environment in which potential customers of the ULS Schiphol will be involved in further research.

The participants found that the proposed information services have one major disadvantage; the undetected loss of messages. Senders can not be certain that the last message they send has actually been received by the receiver. Messages could, for all kinds of reasons, get lost during communication. The loss of messages is directly noted in synchronous communication. The loss of messages is not noticed in asynchronous communication. This perceived problem was solved by numbering the messages. When a publisher sends a message it adds a message number. The receiver checks the message number and compares it to the number of the last received message. When the number does not directly follow the last number some messages have not been delivered. When the receiver has not received messages it contacts the publisher with a request to send the messages that have not been received again. According to the experts this solved the largest part of the communication problems. There can, however, still be a time delay before the loss of messages is detected. The effects of such time delays have to be studied.

A final conclusion of the group evaluation session was that the holonic structure fits the requirements the ULS Schiphol puts on control systems well. The holonic structure follows a number of recent developments in industry (Heragu et al. 2002). The strength of the holonic control structure was further proven by the fact that a holonic structure was chosen to be implemented in the ULS Schiphol by the actors responsible for the further implementation of the control systems (Kuik-Onrust 2003). Finally, the participants found that the research on the support environment and the technical feasibility studies at the TestSite have generated exportable knowledge on control systems and automated logistic systems, which was one of the overall goals of the ULS Schiphol (chapter six).

*The great tragedy of Science. The slaying of
a beautiful hypothesis by an ugly fact.*

Thomas H. Huxley

9 Epilogue

Our research began with the observation that recent developments in automation of logistic systems ask for a new approach in controlling automated logistic systems. The objective of our research was to develop a support environment to help designers in developing control systems for automated logistic systems. The support environment was evaluated after it was developed. The evaluation consisted of two case studies and a group evaluation session. The support environment was applied to design control systems for the Underground Logistic System Schiphol. First, control systems were designed for the real-time control of AGVs and material handling stations. Second, a control system was developed for the scheduling of customer orders. Finally, the support environment was presented to a group of experts on automated logistic systems. The experts compared the support environment with their expectations and evaluated the application of the support environment. We reflect upon our research by discussing our research, research findings and provide starting points for further research in this final chapter.

9.1 Research Findings

We discuss our research findings by discussing and answering our research questions in this section. The holonic structure and the modelling of automated logistic systems are also discussed in this section.

9.1.1 Research Question One

Our first research question was formulated as *what are the generic characteristics of large scale automated logistic systems?* We answered this question by studying literature (chapter one and three) and conducting an inductive case study (chapter four). Automated logistic systems are seen as promising solutions to facilitate the growth of goods distribution in highly populated areas. Automated logistic systems consist of four elements; Automated Guided Vehicles, material handling stations, transportation network and control systems. AGVs transport cargo units between material handling stations through a transportation network. Control systems control the operations of the AGVs, material handling stations and transportation network. The AGVs, material handling stations and transportation network all have their own control systems. Automated logistic systems have three basic functions; transport, transfer and storage. Cargo units are transported through and stored in automated logistic systems. A transfer has to

be performed to change from a transport activity to a storage activity and vice versa. Automated logistic systems will be separated from other traffic. This makes the operations of the logistic resources easier to automate. The separation also has other benefits; a congestion-free environment, no influences of weather conditions and safety benefits. Large scale automated logistic, which form the topic of our research, have not yet been constructed. Some comparable systems are available, like automated container terminals. Large scale automated logistic systems will use large numbers of logistic resources, the transport distances will be large and the freight volumes will be large.

We ended our study of automated logistic systems with four observations, which formed the starting points for developing the support environment. First, the control activities of automated logistic systems will be automated. Second, the design of control systems for automated logistic systems is a complex process. The design process is characterised by many involved actors, complex technology, many degrees of freedom and uncertainties on the economic aspects, social aspects and juridical aspects. Third, there are many issues regarding the technology used inside the automated logistic resources that hinder implementation. Finally, there are many issues regarding the control of large scale automated logistic systems. The issues on the technology and the issues on the control hinder the implementation of large scale automated logistic systems. These issues have to be solved before actors are willing to invest in large scale automated logistic systems. The goal of our research was to solve a number of issues on the technology and on the control of automated logistic system. This way it should become easier for actors to invest in and develop large scale automated logistics systems to facilitate the growth of goods distribution in a sustainable manner.

9.1.2 Research Question Two

Our second research question was formulated as *what concepts can be used for controlling large scale automated logistic systems?* This question was answered by studying literature on control systems and logistic control (chapter three). There are two opposite structures in logistic control; hierarchical and heterarchical control. Traditionally, hierarchical structures have been used in logistic control systems. Complex systems are divided into a number of smaller well ordered sub-structures to form hierarchical structures. Control over the smaller subsystems is easier than control over the entire complex systems. Several drawbacks of hierarchical control systems can be found in literature. First, hierarchical systems have a rigid structure and modifications are hard and costly to implement. Second, hierarchical control is static and cannot cope efficiently with disturbances. Heterarchical control structures were developed to overcome the drawbacks of hierarchical control. Heterarchical control is a flat control structure composed of independent agents without centralised or explicit direct control. An agent is an encapsulated computer system situated in an environment and capable of autonomous actions to meet its design objectives. Heterarchical control overcomes a number of the drawbacks of hierarchical control. Heterarchical control, however, has its own drawbacks. First, the large number of interactions between agents results in complex behaviour that is difficult to understand, control, predict and scale. Second, heterarchical structures tend to be inefficient and unwieldy when applied to large systems. Third, agent based systems cannot guarantee system optimisations, since all forms of hierarchy are banned. Finally, agent based systems lack real world implementations and most research on agents is carried out within simulated environments. We ended our study of literature with the observation that recent developments suggest using a combination of hierarchical and heterarchical control. This combines the advantages that hierarchical and heterarchical control offer, while disregarding any disadvantages.

9.1.3 Research Question Three

We observed in our inductive case study that little attention was paid to control systems in designing automated logistic systems, although control systems strongly determine the performance of logistic systems. Most attention was paid to the design of physical aspects, e.g. transportation network, AGVs and the terminal. We observed that the problem owner and other actors had little insight into the importance of control systems. Logistic control systems are developed on an ad hoc basis; with little knowledge available regarding the decisions that needed to be taken. There is a need to provide a common background, or a shared space of understanding, when designing control systems. We want to provide a support environment that acts as such a shared space of understanding and supports designers in developing control systems. Our third research question was formulated as *what does a support environment for designing control systems for large scale automated logistic systems look like?* The support environment consists of three parts. First, it contains a general structure or reference architecture for control systems. Second, it contains a number of design guidelines. Finally, the support environment recommends support facilities to evaluate the designed control systems.

The first part of the support environment is a holonic structure of control systems. The holonic structure consists of three holons, e.g. order holon, resource holon and load holon. The order holon matches the demand of logistic services by the customers to the supply of logistic services by the logistic system. The resource holons are responsible for controlling the logistic resources. The load holon is responsible for controlling the cargo units that are transported. The holons and the interactions between the holons were designed in the holonic structure. The second part of the support environment consists of a number of design guidelines. The design guidelines organise our ideas on designing good control systems and provide guidelines that can be followed when designing control systems. The design guidelines are divided into guidelines on the holonic structure and guidelines on communication. Design guidelines on communication were developed, since large scale automated logistic systems are communication intensive. The third part of the support environment recommends the support facilities to evaluate the designed control systems and automated logistic systems.

The usability of the support environment was tested by applying the support environment to design control systems for the Underground Logistic System Schiphol (chapters six and seven). The holonic structure and design guidelines were used as 'to-be' models for logistic control systems in two action researches. The support environment was applied to design control systems for the real-time control of AGVs and material handling stations in the first action research. The second action research aimed at developing a customer order management system. Finally, the support environment and its application were evaluated by a group of experts on automated logistic systems. The experts evaluated the support environment by comparing the support environment to their expectations. The participants identified requirements for logistic control systems and compared "how well" the control systems designed by using the support environment scored on each requirement. It can be concluded that the holonic structure and design guidelines can be used to design effective and efficient control systems for large scale automated logistic systems.

9.1.4 Research Question Four

Our fourth and final research question was formulated as *how can large scale automated logistic systems and their control systems be evaluated before implementation?* Currently, most of the testing and evaluation of control systems and automated logistic systems takes place on the shop floor during the

start-up phases. This is an unacceptable approach to test control systems; it is expensive, risky, error-prone and disturbs normal operations. An approach is needed that can evaluate the control system and logistic system before implementation, but still represents real world circumstances. The support environment recommends the support facilities to evaluate designed control systems; simulation models, emulation models and prototypes of the logistic resources.

The participants of the group evaluation session found the combination of simulation, emulation and prototypes very powerful. The participants, all familiar with designing and implementing automated logistic systems, found a number of advantages of the prescribed support facilities. First, the participants found that the support facilities recommended by the support environment strongly decrease the throughput time of the evaluation process. This reduced throughput time results in a faster time to market of automated logistic systems. The logistic systems can be quicker operational, which provides a competitive advantage. Second, the risks of investing in wrong technologies for the control systems and automated logistic systems are reduced. Many of the issues on the control systems and technology are first studied in simulation and emulation models. Investments in expensive physical logistic equipment takes place after the issues have been studied in simulation models, emulation models and prototypes. The technology of the automated logistic resources is evaluated using prototypes, which requires less investment than constructing the entire logistic system. Third, the combination of simulation, emulation and prototypes provides a rich testing environment for evaluating logistic resources and control systems. Each support facility in the support environment has its own strengths for evaluating automated logistic systems that are combined when using them together. The simulation models provide a safe and faster than real-time environment to test the control systems. The emulation models provide good possibilities to study the communication between control systems and automated logistic resources. Finally, the technical aspects of the automated logistic systems are studied in detail by using prototypes.

9.1.5 Holonic Structure of Control Systems

The holonic structure of control systems forms the first part of our support environment. The holonic structure was applied to design control systems for the ULS Schiphol in two case studies. Two resource holons for the real-time control of AGV and docks at the TestSite were designed in our first case study. A Holonic Order Management System to schedule customer orders was developed in the second case study. A holonic structure for control systems was originally chosen because it was expected that it could accommodate the requirements for control systems for automated logistic systems well.

We may conclude that *holonic control systems are scalable*. A scalable control system can deal with small and large numbers of logistic resources and transported freight volumes without major losses of performance in terms of response times. The limits of scalability are case specific; the characteristics of the automated logistic system decide the limits. The AGV holon and Dock holon developed in chapter six were scalable within the boundaries of the TestSite. The scalability of the HOMS was not fully assessed (chapter seven). The HOMS was studied for a scaled down version of the ULS Schiphol. This was not caused by the lack of scalability of the holonic concept, but by limitations in the simulation software. Finally, the participants of the group evaluation session concluded that the holonic structure is scalable within the limits of the ULS Schiphol.

We may conclude that *holonic control systems are extendable*. The extendibility of the holons was tested by adding more logistic resources and destinations to the logistic system. New logistic resources and destinations were added to the AGV holon and Dock holon without disturbing normal operations and without modifications to the structure of the holons (chapter six). The extendibility of the HOMS was tested by adding logistic resources, destinations and customers. The HOMS was able to incorporate these extensions without modifications to the structure of the order holon (chapter seven). Finally, the participants of the group evaluation session concluded that the holonic control systems are extendable and able to facilitate the most likely extensions of the ULS Schiphol.

We may conclude that *holonic control systems are adaptable*. An adaptive control system is able to deal with changes in the system and its environment without modifications to the structure of the control system. New types of logistic resources were added to the holons to test the adaptability. All holons could incorporate new types of logistic resources during their operational phases without changes to their structure. The adaptability was tested for the most likely changes to the systems, e.g. new types of AGVs, new types of docks and changes to the layout of the transport network. Finally, the participants of the group evaluation session concluded that the holonic control system is adaptable for the most likely changes within the ULS Schiphol.

We may conclude that *holonic control systems make efficient use of logistic resources*. The initial investments needed for automated logistic systems are high, thus the logistic control systems have to make efficient use of the logistic resources to justify such investments. This is especially important for the transportation network, which often is the most costly resource and most difficult to expand. The TRACES concept was used in the AGV holon to control and safeguard the concurrent use of infrastructure. The AGV holon was able to control the AGVs in such a way that the operations were carried out safely, while retaining high levels of efficiency. The overall efficiency of the HOMS for the ULS Schiphol seemed low at first sight (chapter seven). The average utilisation of the AGVs was about 50%; the average utilisation of the docks was below 5%. The low average utilisation does not mean that the logistic resources are used inefficient. The ULS Schiphol is designed to handle peak demands and imbalances in the transportations flows. The resource holon uses the resources efficiently during peak hours. The logistic resources are not fully occupied outside the peak hours. Efficiency should not only be defined as using the logistic resources efficient, but also as being able to handle peak demands of customers. Peak demands are a characteristic of many automated logistic systems. For example, the peak demand on the Tilburg city distribution system is in the morning when the shops have to be supplied and the peak demand on an automated container terminal is when a sea vessel has to be serviced

We may conclude that *holonic control systems are robust*. Robust control systems are able to continue to operate as normal when disturbances occur. The most likely disturbances for the logistic resources were identified and tested, e.g. communication failures and AGV failures. All holons were able to deal with communication failures. The activities of the holons are temporarily stopped when communication is disturbed and resumed when the communication is resolved. The resource holons were able to deal with disturbances in the logistic resources, such as AGV break downs. This was tested by deliberately stopping AGVs and by creating disturbances. Finally, the participants of the group evaluation session concluded that the holonic control system is able to deal with the most likely disturbances of the ULS Schiphol in a failsafe manner.

We may conclude that *holonic control systems are independent of technology, both for hardware and software*. The holons developed for the ULS Schiphol were implemented in different simulation packages to test the independence of software. The resource holons were used to control different types of logistic resources to show the independence of technology in the logistic resources. The AGV holon and Dock holon at the TestSite were able to control different types of AGVs and docks (chapter six) without the need to make modifications to the holonic structure. The holonic control systems were independent of the layout of the transportation network. This is important during the design phase of large scale logistic systems, in which many different layouts of the transportation network have to be studied (chapter four). When control systems are kept independent of the transportation network, they can be used for any possible layout of the transportation network. Finally, the participants of the group evaluation session appreciated that the holonic structure is independent of the technology and software. The chances of a lock-in on a single manufacturer are reduced when control systems are independent of the technology and software.

The holonic structure was successfully used to design control systems for the ULS Schiphol. The strength of the holonic control structure was further proven by the fact that a holonic structure was chosen to be implemented when the construction of the ULS Schiphol will start (Kuik-Onrust 2003).

9.1.6 Modelling of Large Scale Automated Logistic Systems

Modelling large scale automated logistic systems was an important part of our research. Models of automated logistic systems were used as replacements of the real logistic systems. A distinction between conceptual and empirical models is made in the inductive-hypothetic research strategy. Conceptual models set out the definition of a problem situation in broad terms. Conceptual models of a problem situation are characterised by high levels of abstraction and are used to structure perception, representation and reasoning regarding a problem situation. Empirical models result from a specification phase and enable analysis and diagnosis of a problem situation and possible solutions. Different modelling techniques were used to construct the conceptual and the empirical models of the automated logistic systems. Techniques from the Unified Modeling Language were used to construct the conceptual models, e.g. class diagram, sequence diagram and activity diagram. Discrete-event simulation models, emulation models and prototypes were used as empirical models.

Many actors are involved in the design of large scale automated logistic systems. Some of these actors have little experiences in reading diagrams and have little understanding of automated logistic systems. An important requirement for the modelling techniques is that actors with little experiences in reading diagram can easily understand the constructed models. We choose to construct graphical oriented modelling techniques. Especially the animation models proved to be useful. Animation models of the automated logistic systems were made and shown to the actors. The actors found the animations easy to understand and could this way understand the behaviour of automated logistic systems. We observed that the trust of the actors in automated logistic system was increased as the actors got more insight into the system and more understanding of the behaviour of the system through the animation models.

Simulation models, emulation models and prototypes were used to evaluate the designed control systems of the ULS Schiphol. The order holon and resource holons were implemented in a simulation model. The simulated resource holons were able to effectively control the logistic resources. The simulated order holon was able to effectively schedule customer orders. There are some issues on the simulation of holonic control systems that have to be dealt with. The holonic control structures proved to be

communication intensive; many messages were exchanged between and within the holons. The simulation software in our research was able to deal with the large amount of messages, but this resulted in long runtimes of experiments.

Emulation models were made to study the communication between logistic resources and control systems. Emulation models are models in which some functional part of the model is carried by part of the real system. The control system and system-being-controlled are separated within emulation. The simulation software used in our research lacked possibilities for a clear separation between system-being-controlled and control system. This made it hard to construct the simulation models in such a way that they could communicate with other control systems and the automated logistic resources.

The prototypes of the automated logistic resources proved very useful. The prototyping took place in a special laboratory. Prototypes and scale models of AGVs and material handling stations were used and the automated logistic system could be studied in a small scale setting. The prototypes were used to study the behaviour and technical components of the logistic resources under real world circumstances.

9.2 Research

9.2.1 Research Area

The topic of our research was large scale automated logistic systems. Two automated logistic systems were studied during our research. We reflect on our research area in this section.

Our first case study was designing control systems for the Tilburg city distribution system. The Tilburg CDS was an inductive case study. We wanted to explore the phenomena faced when designing control systems for automated logistic systems. The Tilburg CDS will not be a large scale automated logistic system. The number of AGVs and material handling stations will be low and the transport distances will be short. The problems perceived in designing control systems could first be studied on a small scale, which made the explorative process easier. The Tilburg CDS still has the characteristics and functionalities of automated logistic systems. The CDS Tilburg will use Automated Guided vehicles, material handling stations, transportation networks and control systems. The Tilburg CDS has to perform all three primary functions of a logistic system; transport, storage and transfer. It can be concluded that although the Tilburg CDS is a small scale automated logistic system, the case provided good starting points for the development of the support environment.

The second and third case studies were conducted for the Underground Logistic System Schiphol. The developed support environment was applied to design control systems for the ULS Schiphol. The ULS Schiphol will be a large scale automated logistic system. The ULS Schiphol will be larger and more complex than Tilburg CDS. The participants of the group support environment found that the ULS Schiphol is representative for large scale automated logistic systems in general. This suggests that the developed support environment can be used to design control systems for other large scale automated logistic systems besides the ULS Schiphol. It was not clear who the problem owner was in of ULS Schiphol project. The 'Stichtinggroep OLS-ASH' acted as problem owner. The Stichtinggroep OLS-ASH consisted of participants from Amsterdam Airport Schiphol, Bloemenveiling Aalsmeer, Connekt, The Air Transport Association Netherlands, Centrum Ondergronds Bouwen, Railinfrabeheer en Railned. Although most of these organisations are involved in the field of transportation and logistics, none is directly involved with transport of freight between the airport, flower auction and rail terminal. The lack

of a clear problem owner slowed the design process down. It was difficult to make choices in the designs of the logistic system and the control systems. When a clear problem owner is available, the problem owner will enforce the designers to make explicit choices in the design; this way the design process will be kept short (Latour 1996).

The design of Tilburg CDS and the design of ULS Schiphol are characterised by many degrees of freedom, e.g. the layout of the transport network and the characteristics of the logistic resources. Still it was necessary to design adequate control systems for the logistic system. It can be concluded that although there were still many questions on the logistic system that needed to be answered, it was still possible to design adequate control systems.

The TestSite was also used for commercial applications; demonstrations were given to policy makers, transport companies, local and national government. The TestSite made the ULS Schiphol project more concrete, which mobilised decision makers and researchers around the project. Finally, the TestSite could be used as a training facility. Operators could be trained in a safe environment. In a laboratory, such as the TestSite, operators can be trained without disturbing normal operations in the logistic system.

9.2.2 Research Approach

The development of control systems for automated logistic systems is a fairly new and complex area. There is little literature available on the control of automated logistic systems. Most literature that is available is mono-disciplinary and focuses on the technology used for the logistic resources or the infrastructure. It is therefore difficult, or even impossible, to conduct our research in a purely deductive way. The research approach we needed to follow for designing control systems for automated logistic systems should allow multi-disciplinary research and focus on building new theory. An inductive-hypothetic research strategy was chosen to conduct our research. The inductive-hypothetic research strategy proved to be an appropriate strategy for research on designing control systems for large scale automated logistic systems.

9.3 Further Research

Although the research described in this dissertation answered many questions regarding the control of large scale automated logistic systems, new questions arose during our research that need to be answered in further research.

The support environment was applied by a small group of people of which we, the developers of the support environment, were part. The support environment was developed to support all designers in designing control systems. The question remains how useful the support environment is to other designers of control systems. This leads us to our first recommendation.

Recommendation 1

Research the application of the support environment by other designers of control systems for automated logistic systems.

These other designers should be independent of the developers of the support environment. The support environment can be further improved or extended based on the experiences of the other users.

The goal of our research was to develop a support environment to support the design of control systems for automated logistic systems in general. The support environment was used to design control systems for the ULS Schiphol in our research. The ULS Schiphol contains many components that automated logistic systems have in general, such as Automated Guided Vehicles and automated material handling stations. Some aspects of the ULS Schiphol are case specific and can not be found in automated logistic systems in general; like the cargo units that are transported (chapter six). Further research should be focus on the general usability of the support environment.

Recommendation 2

Research the general usability of the support environment by applying it to design control systems for other types of automated logistic systems.

The support environment could be applied to design control systems for other types of automated logistic systems, such as automated warehouses, automated container terminals and automated city distribution systems. The support environment was applied to design control systems for automated freight transport systems. Passenger transport systems are another possible application area. The main difference between freight and passengers is that passengers are active elements and can make decisions on their own during the transport. This is fundamentally the same difference as controlling AGVs and docks (chapter six). The holonic structure does not see any differences between passengers and freight. Freight and passengers are placed outside the holons; representations of freight and passengers are used inside the holons. Passengers that are transported are just logistic resources with a high level of autonomy, as stated in design guideline four. The application of the support environment in a passenger transport system, however, still has to be studied.

Our research ends with a general comment on automation of logistic and transport systems. The field of designing control systems for automated logistic systems is still under development. As we found out during our research there are still some people who fear automated logistic systems, mainly employees that work for logistic service providers. For many the fear of intelligent machines comes not from science fiction but from concerns about job security (Albus & Meystel 2001). The fear of automation has haunted the labour force since the beginning of the Industrial Revolution. Workers of all kind fear that machines might take away their jobs. This popular belief is not supported in practice. Although technological advances make some employees obsolete, the overall productivity growth has always created more jobs than that were lost (Albus & Meystel 2001).

*Where is the number of our dead? Edward the Duke of York,
the Earl of Suffolk, Sir Richard Ketly,
Davy Gam, esquire; None else of name.
W. Shakespeare*

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Summary

Freight transport and goods distribution are essential and inevitable components of economic activities and development. The volume of transported goods is growing constantly. This growth is not without negative consequences. A great challenge lies in balancing the positive and the negative impacts of the growth of freight transport. Freight transport for shorter distances, such as goods distribution in highly populated urban areas, is mainly carried out today using traditional road transport. The vehicles used, e.g. lorries and vans, have large negative impacts on the local environment. In response to this several initiatives have been taken to reduce the negative impacts of goods distribution in urban areas. Most of these initiatives focus on the current way of distributing goods. Although these initiatives have helped to guide the growth of goods distribution in good directions, we argue that the way in which the growth is currently facilitated is not sustainable. Sustainable initiatives are needed that are environmentally sound and economically efficient. We focus on an alternative for goods distribution that is expected to be sustainable; large scale automated logistic systems.

Automated Logistic Systems

Large scale automated logistic systems will use large numbers of automated logistic resources, such as Automated Guided Vehicles and material handling stations. The travel distances will be long and many (un)loading points will be used. Although automated logistic systems are seen as promising alternatives to facilitate the growth of goods distribution little is known of such systems. No implementations of large scale automated logistic systems are available at the time of our research. Some comparable systems are already operational, such as the automated container terminals at the ports of Rotterdam and Hamburg. There is a number of issues that hinder the implementation of large scale automated systems, e.g. economic issues, organizational issues, technological issues and control issues. We try to solve a number of the issues regarding the control systems and the technology of automated logistic systems. Dealing with these issues should make it easier to develop and to implement large scale automated logistic systems.

Research Objective

The control systems of logistic systems are complex. The control systems have to control many concurrent processes, have to react to inputs within strict time windows, have to operate in a distributed setting, have to work with large sets of heterogeneous data and have to be able to control large numbers of heterogeneous logistic resources. Designing control systems for large scale automated logistic systems is a complex activity. The technology is new and not yet proven in practice, many actors are involved and designers drawn from different disciplines have to cooperate. We want to support designers in the complex engineering process of control systems for automated logistic systems. The central research objective is formulated as:

'Develop a support environment that helps designers in developing control systems for large scale automated logistic systems.'

Four research questions are formulated to reach the research objective.

1. What are the generic characteristics of large scale automated logistic systems?
2. What concepts can be used for controlling large scale automated logistic systems?
3. What should a support environment for designing control systems for large scale automated logistic systems look like?
4. How can large scale automated logistic systems and their control systems be evaluated before implementation?

Research Approach

We chose to use the inductive hypothetical research strategy to answer our research questions and reach our research objective. The inductive hypothetical research strategy is useful in emerging research fields for which little theory is available. The inductive hypothetical research strategy starts with identifying a number of initial theories. These theories are used to study a number of problem situations in the first step. Descriptive empirical models are used to describe the relevant aspects of the problem situations. The descriptive empirical models are abstracted into a descriptive conceptual model in the second step. The descriptive conceptual model represents the essential and generic elements of the problem area under investigation and gives indications for possible solutions. A theory is constructed to solve some of the observed problems in the third step. The constructed theory is presented in a prescriptive conceptual model. The prescriptive conceptual model is still an abstraction of the specific areas of interest, but it explicitly defines how to address the perceived problems. The prescriptive conceptual model is implemented in a number of practical situations in the fourth step. The result of this step is a set of alternatives that provides solutions for the original identified problems and is presented in prescriptive empirical models. The developed theory is evaluated by comparing the descriptive empirical models to the prescriptive empirical models in the fifth step.

Theoretical Background

A literature review is conducted to identify a number of initial theories to study the problem area under investigation. Control is the use of control actions by a control system to promote the preferred behaviour of a system-being-controlled. Two control paradigms are distinguished within control systems theory; open loop and closed loop control. An open loop control system utilises an actuating device to control a system-being-controlled directly without using feedback. An open loop control system simply assumes that the control actions are effective. Closed loop control systems measure the systems-being-controlled and compare the actual measurements with desired values. Based on the differences between the actual values and desired values control actions are taken. Two basic types of closed loop control systems exist; feedback and feed forward. Feedback control produces reactive control; control actions are taken when the deviation between the measured values and the desired values exceeds a certain level. Feed forward control produces proactive or anticipatory control; the measurements are used to predict what control actions need to be taken to prevent differences between the measured and desired values in the future.

Traditionally, logistic control systems have hierarchical structures. The basic strategy of hierarchical systems is to divide complex decisions into a number of smaller decisions with less complexity. A number of disadvantages of hierarchical structures can be found in the literature. Hierarchical systems

are rigid and static; modifications are hard and costly and hierarchical systems cannot cope effectively with disturbances. These drawbacks of hierarchical control have led to the development of heterarchical control structures. Heterarchical control is a flat control structure composed of independent agents without centralised, or explicit direct control. Heterarchical control solves a number of the drawbacks of hierarchical control, but has its own drawbacks; the large number of interactions between the agents. The interactions result in complex systems and behaviour that is difficult to understand, predict and control. The disadvantages of hierarchical and heterarchical control have led to the combination of hierarchical and heterarchical control. Holons combine the advantages of hierarchical and heterarchical control, while disregarding any disadvantages. Holons are autonomous self reliant units with a high degree of independence. Holons have a dual tendency to preserve their individuality as quasi autonomous wholes and to function as integrated parts of larger wholes. Holons can make decisions on their own without consulting higher levels of control; simultaneously holons are subject to higher levels of control. The combination of hierarchical and heterarchical control makes holons stable forms that survive disturbances.

Inductive Case Study: Tilburg City Distribution System

An inductive case study is carried out to get a better understanding of designing control systems for automated logistic systems. The design of the Tilburg City Distribution System is chosen as our inductive case study. The supply of goods to shops in the inner city of Tilburg is problematic. The lorries used for goods distribution cause many inconveniences to the local inhabitants. The inconveniences and high logistic costs are causing the inner city of Tilburg to lose its attraction for shoppers and are reducing the quality of life of local inhabitants. The city counsel decided to study the possibilities of an underground city distribution system to solve the problems. The Tilburg CDS will consist of a distribution centre at the railway station that can be easily reached by lorries and trains. Freight will be transported to the distribution centre and transferred onto Automated Guided Vehicles that will use an underground transportation network to deliver freight to the inner city.

The following learning points can be taken from the inductive case study. First, the design of control systems received little attention in the design process of the Tilburg CDS. A structured approach was not followed in the design and most decisions were taken on an ad hoc basis. Second, designing automated logistic systems is a complex activity. The design space is large and characterized by many degrees of freedom. Third, automated logistic systems will be constructed in phases. The logistic system will be extended and the level of automation will increase in each phase. Fourth, the available transportation network and space are critical logistic resources. The transportation networks are separated from other traffic, which is costly to achieve. The transportation networks are kept to a minimum to reduce investment costs. Finally, little is known regarding the exact technical specifications of the automated logistic resources. Some characteristics have been decided, e.g. speed and size. The simulation model used in the design process of the Tilburg CDS did not take technical aspects and communication into account at an adequate level. Many assumptions were made on the technical aspects and communication which led to unrealistic models. The technical specifications have to be taken into account since they strongly influence the control systems and the performance of the logistic system. These learning points have to be addressed in our support environment.

Support Environment

We develop a support environment to help designers in developing control systems. The support environment has two functions. First, it can be used as a foundation for developing control systems. Second, the support environment provides a basis for the evaluation of control systems. The support environment consists of three parts. The first part is a generic structure for control systems. The second part contains a number of design guidelines. The third part consists of recommendations for support facilities to evaluate the designed control systems and logistic resources before their implementation.

Support Environment Part One: Holonic Structure

The first part of the support environment consists of a holonic structure for control systems. Three types of holons are identified.

- *Order holons* are the interfaces between the customers and the logistic system. Order holons are responsible for scheduling customer orders and have to decide which resource holons are contacted to perform logistic services.
- *Resource holons* are responsible for scheduling and controlling the execution of the logistic services provided by a set of logistic resources, e.g. AGVs and material handling stations.
- *Load holons* are responsible for controlling the cargo units that are transported, handled and stored. The primary function of a load holon is to provide information services to order holons and resource holons.

Large scale automated logistic systems will be controlled by several holons of each type. The holons are autonomous and have to cooperate to perform logistic services for customers. Holons cannot force other holons to cooperate, because of the autonomy the holonic structure offers.

Support Environment Part Two: Design Guidelines

The second part of the support environment consists of design guidelines that can be followed when designing holonic control systems. The design guidelines are formulated in such a way that they facilitate the holonic structure of control systems. The design guidelines focus on the holonic structure and communication within holonic control systems.

The first design guideline states that resource holons have a layered structure. Three layers are identified; resource management, resource control and resource representation. Each layer offers its own functionalities and uses its own technologies. The management layer is responsible for controlling entire sets of logistic resources. The control layers are responsible for controlling one specific logistic resource. The resource representation is a model, or representation, of the logistic resource that is controlled. The actual physical resources are placed outside the resource holons. The second design guideline states that holonic control systems are hybrid structures that combine a hierarchical structure in a distributed setting. The resource holons have hierarchical layered structures. The holons are distributed in the sense that the responsibilities for control are divided over several points. The third design guideline formulates that holonic control consists of two separated interacting process; scheduling and real-time control. Scheduling is the process of developing a schedule to perform logistic services for customers. The order holon and resource holons have to cooperate to develop the schedules. The created schedules become contracts between the order holon and the resource holons. Real-time control is focused on controlling the execution of the schedules. The resource holons are responsible for the real-time control of executing

the schedules. The fourth design guideline states that the physical logistic resources are placed outside the resource holons. The resource holons contain models, or representations, of the logistic resources. This way the resource holons remain independent of the technology used in the physical resources. The logistic resources have a high degree of autonomy and are responsible for controlling many of their own activities. The fifth design guideline formulates that communication in holonic control systems is asynchronous. Asynchronous communication allows continuous uninterrupted processes; the control processes and physical processes are decoupled. The sixth design guideline states that communication has a command/event based structure in holonic control systems. Control systems send commands to the systems-being-controlled to perform logistic services. Systems-being-controlled send event notifications to the control systems on the progress of the execution of the logistic services. The seventh and final design guideline states that the asynchronous command/event based communication is implemented through information services. The information services are based on a publish/subscribe mechanism. The holons need to subscribe to the information services that provide the information they need.

Support Environment Part Three: Support Facilities for Evaluation

The third part of our support environment consist of the recommendations for the support facilities that can be used to evaluate the designed holonic control systems and the logistic resources before implementation. The support environment recommends using a combination of simulation, emulation and prototypes to evaluate the resource holons and the logistic resources. Simulation models of the resource holons are used to control simulated, emulated and prototype logistic resources. Each type of model offers its own specific advantages and is used to study specific aspects of the logistic system. Simulation models offer a safe environment to study the system faster than real-time. Emulation models are used to study the communication within the automated logistic system. Prototypes are used to study the technical aspects of the logistic resources. It is important that a consistent interface is constructed between the resource holon and the various models of the logistic resources. This way the resource holons can be developed once and used to control all three types of models of the logistic resources.

The support environment is evaluated using two case studies and a group evaluation session. The case studies are focused on the design of a future large scale automated logistic; the Underground Logistic System Schiphol. The ULS Schiphol will use AGVs and automated material handling systems to transport cargo units between the Flower Auction Aalsmeer, Rail Terminal Hoofddorp and Amsterdam Airport Schiphol.

Evaluation of the Resource Holons

The technical usability of the resources holons is evaluated in the first case study. The holonic structure is used to develop an AGV holon and a Dock holon to control AGVs and docks designed for the ULS Schiphol. A special laboratory, called the Connekt TestSite, is used for the case study. The TestSite is equipped with prototype AGVs and docks that are designed for the ULS Schiphol. Simulation models of the AGV holon and Dock holon are used to control simulation models, emulation models and prototypes of the AGVs and docks at the TestSite. The AGV holon and Dock holon follow the holonic structure and design guidelines prescribed by the support environment. The results of the first case study are that the resource holons are able to control the different types of logistic resources at the TestSite. The resource holons are scalable for the limitations of the TestSite and are able to control all the logistic resources available. The resource holons are extendable and adaptable. The resource holons are able to deal with changes in the system without modifications to the structure of the holons, e.g. new destinations, new

routes and new types of logistic resources can be added. The resource holons are robust and able to deal with the most likely disturbances within automated logistic systems, e.g. equipment break downs and communication failures. The resource holons prove to be independent of the technology and software. The AGV holon is able to control different types of AGVs from different manufacturers. The AGV holon is also designed to be used with any type of software, this is tested by implementing the AGV holon in different simulation packages. Finally, the AGV holon and the Dock holon are independent of the transportation network. Any layout of the transportation network can be controlled by the resource holons.

An important aspect in the evaluation of the resource holons is the synchronisation of the resource holons and the models of the logistic resources. Synchronisation has two aspects, time and place. Synchronisation of time is aimed at synchronising the simulation clock to the internal clock of the logistic resources. Synchronisation of place is aimed at synchronising the position and orientation of physical resources and the simulated resources. Special events are introduced for the synchronisation of place.

Evaluation of the Order Holon

The support environment is applied to design a customer order management system for the ULS Schiphol in the second case study. A Holonic Order Management System (HOMS) is developed to schedule customer requests and maintenance to the logistic resources.

The order holon and different resource holons have to cooperate to match the demand and the supply of logistics services. Customer requests arrive at the order holon. The order holon sends sub-requests to the resource holons to carry out the logistic services. The resource holon can create sub-offers to perform the requested logistic service. The order holon chooses the best sub-offers and joins them into an offer for the customer. The resource holons aim at optimising the schedules of the set of logistic resources they control. The order holon tries to optimise the entire logistic system.

The HOMS is responsible for scheduling maintenance to logistic resources. The technology that will be used in the ULS Schiphol has not yet been proven in practice. High levels of failures are expected in the start-up phases. Regular maintenance to the logistic resources will be needed to minimise the disturbances caused by failures. A Maintenance holon is responsible for scheduling maintenance to the logistic resources. The Maintenance holon needs to cooperate with the resource holons to schedule maintenance.

Simulation models are used to evaluate the HOMS. Emulation models and prototypes are not used, since the HOMS is less complex regarding the technology used than the resource holons in the first case study. Different scenarios are studied that represent possible 'to-be' situations of the ULS Schiphol. The scenarios differ on the number of holons used. The number of order holons and resource holons is changed in the experiments to study the possibilities for competition within the HOMS. The first possibility is that several order holons are operational in the same logistic system. Several order holons have to compete for the services provided by the same set of logistic resources. The second possibility is that several resource holons are competing in the same logistic system. Several resource holons can create sub-offers for the order holon and the order holon chooses the best sub-offers. The most important conclusion from the experiments is that the HOMS is able to facilitate competing order holons and resource holons. This is important for the long term use of the HOMS in the ULS Schiphol. The HOMS treats competing holons equally and does not give priority to certain holons. The best sub-offers and

sub-requests are chosen by the holons. Second, the efficiency of the logistic resources seems low at first sight. The utilisation of the resource seems low, however, the ULS Schiphol is scaled to handle peak demands. The logistic resources are used efficiently during peak demands. Outside the peak demands the resources are used less efficiently. The Maintenance holon and resource holons schedule maintenance to the logistic resources outside the peak hours. Finally, the HOMS is communication intensive, especially when competing order holons and resource holons are used. Many messages have to be exchanged in the holonic scheduling process between the order holons and resource holons. Special attention has to be given to communication when the HOMS will be implemented for the ULS Schiphol.

Group Evaluation Session

The final evaluation is carried out in a group evaluation session. The support environment and the application of the support environment are presented to a group of experts. The experts are all involved in designing automated logistic and transport systems. The experts are not involved in the development of the support environment to ensure an independent evaluation. The support environment is presented to and discussed with the experts. The experts evaluate the support environment by studying how well the support environment meets a number of requirements for logistic control systems. The requirements are identified by the experts and derived from our inductive case study. The experts find the holonic structure adaptable and extendable for the ULS Schiphol. The holonic structure can facilitate the most likely changes and extensions without modifications to the structure of the holons. The experts find the holonic structure to be scalable within the limits of the ULS Schiphol. The experts find the holonic structure to be robust and able to deal with the most likely disturbances to the logistic resources and communication. Finally, the experts find that the holonic structure has an open structure. New holons and other control systems can easily be added to the holonic structure as long as they comply to the communication protocol prescribed by the support environment.

We end our research by pointing to possible directions for further research. The first direction is for other designers of control systems to apply the support environment to design control systems for automated logistic systems. The second possible direction is to investigate the general usability of the support environment by using the support environment to design control systems for other types of automated logistic systems, for example automated container terminals, automated warehouses and automated passenger transport systems.

Samenvatting

Vrachtransport en distributie van goederen is een essentieel onderdeel van economische activiteiten en economische ontwikkeling. Het volume van vervoerde vracht groeit continu. Deze toename is niet zonder negatieve gevolgen. Een grote uitdaging ligt in het balanceren van de positieve en negatieve gevolgen van deze groei van het vrachtransport. Vrachtransport voor kleinere afstanden zoals stedelijke distributie wordt hoofdzakelijk uitgevoerd door traditionele wegvoertuigen. Deze voertuigen zoals vrachtwagens en bestelbussen hebben grote negatieve gevolgen voor de directe omgeving. Verschillende initiatieven zijn ondernomen om de negatieve gevolgen te verminderen. Deze initiatieven richten zich op de huidige manier van vrachtransport en zijn niet duurzaam. Duurzame initiatieven zijn noodzakelijk die zowel milieuvriendelijk als economisch rendabel zijn. Wij richten ons op een initiatief voor vrachtransport waarvan verwacht wordt dat het een duurzame ontwikkeling is.

Grootschalige geautomatiseerde transportsystemen

Geautomatiseerde transportsystemen gebruiken geautomatiseerde logistieke 'resources' zoals Automatisch Geleide Voertuigen en geautomatiseerde overslagstations. De reisafstanden zijn lang, veel overslagpunten worden gebruikt en veel logistieke resources worden gebruikt. Ook al worden grootschalige geautomatiseerde transportsystemen gezien als veelbelovende duurzame initiatieven om de groei van het vrachtverkeer in goede banen te leiden, is er weinig bekend over zulke systemen. Er zijn geen implementaties beschikbaar op dit moment. Wel bestaan vergelijkbare systemen zoals geautomatiseerde containerterminals in de havens van Rotterdam en Hamburg. Een aantal obstakels verhindert de implementatie van geautomatiseerde transportsystemen zoals economische onzekerheden, veranderingen in de betrokken organisaties, technische uitdagingen en moeilijkheden rondom de besturingssystemen. Wij proberen een aantal obstakels op het gebied van de besturingssystemen en de techniek weg te nemen met ons onderzoek. Op deze manier moet het makkelijker worden voor actoren om geautomatiseerde transportsystemen te ontwerpen en te implementeren.

Onderzoeksdoelstelling

Besturingssystemen voor transportsystemen zijn complex. Dergelijke besturingssystemen moeten veel gelijktijdige processen besturen, moeten opereren in gedistribueerde omgevingen, moeten reageren in korte tijdspannes, moeten omgaan met heterogene datasets en moeten veel logistieke resources besturen. Het ontwerpen van besturingssystemen voor grootschalige transportsystemen is een complexe activiteit. De technologie is nieuw en heeft zich nog niet bewezen in de praktijk en actoren van verschillende disciplines moeten samenwerken in het ontwerpproces. Wij willen ontwerpers ondersteunen in het complexe ontwerpproces van besturingssystemen voor grootschalige geautomatiseerde transportsystemen. De onderzoeksdoelstelling is geformuleerd als:

'Het ontwikkelen van een ontwerpomgeving die ontwerpers ondersteunt in het ontwikkelen van besturingssystemen voor grootschalige geautomatiseerde transportsystemen.'

Vier onderzoeksvragen zijn geformuleerd om ons onderzoeksdoel te bereiken.

1. Wat zijn de generieke eigenschappen van grootschalige geautomatiseerde transportsystemen?
2. Welke concepten kunnen worden gebruikt voor het besturen van grootschalige geautomatiseerde transportsystemen?
3. Hoe moet een ontwerpomgeving voor het ontwerpen van besturingsystemen er uit zien?
4. Hoe kunnen grootschalige geautomatiseerde transportsystemen en de bijbehorende besturingssystemen worden geëvalueerd voordat zij worden geïmplementeerd?

Onderzoeksaanpak

We kiezen om volgens een inductief-hypothetische onderzoeksstrategie te werk te gaan. Deze strategie is bijzonder geschikt voor opkomende onderzoeksgebieden waar weinig theorie beschikbaar is. De strategie bestaat uit vijf stappen en begint met het identificeren van initiële theorieën. Deze theorieën worden gebruikt om een aantal probleemsituaties te bestuderen in de eerste stap. Descriptieve empirische modellen worden gebruikt om de relevante aspecten van de probleemsituatie te beschrijven. De descriptieve empirische modellen worden vertaald in descriptieve conceptuele modellen in de tweede stap, die de essentiële en generieke aspecten van de probleemsituatie en mogelijke oplossingsrichtingen weergeven. Een theorie wordt geconstrueerd in de derde stap om een aantal van geobserveerde problemen op te lossen. De theorie wordt gepresenteerd in de vorm van een prescriptieve conceptueel model. Het prescriptieve conceptuele model wordt toegepast in een aantal probleemsituaties in de vierde stap. Het resultaat is een verzameling van alternatieven die oplossingen geven voor de oorspronkelijk geïdentificeerde problemen en wordt gepresenteerd in prescriptieve empirische modellen. De ontwikkelde theorie wordt geëvalueerd door het vergelijken van de descriptieve empirische modellen en de prescriptieve empirische modellen in de vijfde stap.

Theoretische achtergrond

Een literatuuronderzoek is uitgevoerd om de initiële theorieën te identificeren die het begin vormen van ons onderzoek. Besturing is het gebruik van besturingsmaatregelen door een besturingssysteem om het gewenste gedrag van een systeem dat bestuurd wordt te bewerkstelligen. Twee besturingsparadigma's worden onderscheiden in de besturingstheorie; open-loop en closed-loop besturing. Een open-loop besturingssysteem gebruikt een mechaniek om een systeem te besturen zonder terugkoppeling en gaat ervan uit dat de besturingsmaatregelen effectief zijn. In closed-loop besturing worden metingen gedaan in het bestuurd systeem waarbij besturingsmaatregelen worden genomen op basis van de verschillen tussen doelstellingen en waarnemingen. Twee soorten closed-loop besturingssystemen zijn mogelijk; feedback en feedforward. Feedback besturing is reactief; besturingsmaatregelen worden genomen als de afwijking tussen de doelstellingen en waarnemingen een bepaalde grens overschrijden. Feedforward besturing is pro-actief; waarnemingen worden gebruikt om te voorspellen welke besturingsmaatregelen nodig zijn om afwijkingen in de toekomst te voorkomen. Logistieke besturingssystemen hebben traditioneel een hiërarchische opbouw. Complexe besturingsbeslissingen worden verdeeld in een aantal minder complexe beslissingen. Hiërarchische structuren hebben een aantal nadelen. Hiërarchische systemen zijn star en statisch; veranderingen zijn moeilijk om te implementeren en het effectief omgaan met verstoringen is moeilijk. Deze nadelen hebben geleid tot de ontwikkeling van heterarchische besturingssystemen. Heterarchische besturing is een platte structuur die uit een aantal onafhankelijke agenten bestaat zonder directe of expliciete besturing. Heterarchische besturing heeft echter zijn eigen

nadeel namelijk de vele interacties tussen de agenten. De vele interacties leiden tot complexe systemen die moeilijk te begrijpen, voorspellen en te besturen zijn. De nadelen van hiërarchische en heterarchische besturingssystemen hebben geleid tot de combinatie van beide. Holonen proberen de voordelen van beide paradigma te combineren en tegelijkertijd de nadelen weg te laten. Holonen zijn autonome systemen met een hoge mate van onafhankelijkheid. Holonen hebben de gecombineerde eigenschap om aan de ene kant hun individualiteit te behouden (heterarchie) en aan de andere kant deel uit te maken van een groter geïntegreerd geheel (hiërarchie). Deze eigenschappen maken holonen tot stabiele systemen die goed kunnen omgaan met verstoringen.

Inductieve case studie: stadsdistributiesysteem Tilburg

Een inductieve case studie is uitgevoerd om een beter begrip te krijgen van het ontwerpen van besturingssystemen voor geautomatiseerde transportsystemen. Het ontwerpproces van het stadsdistributiesysteem Tilburg is gekozen als onderwerp van de inductieve case studie. Het bevoorraden van de winkels in de binnenstad van Tilburg is problematisch. De vrachtwagens veroorzaken veel overlast voor de lokale bewoners. De overlast en hoge logistieke kosten zorgen ervoor dat de binnenstad van Tilburg zijn aantrekkingskracht voor winkelende mensen en omwonenden verliest. De gemeente Tilburg heeft besloten om de mogelijkheden van een geautomatiseerd ondergronds transportsysteem te bestuderen. Het stadsdistributiesysteem Tilburg zal bestaan uit een terminal naast het station die gemakkelijk bereikbaar is voor treinen en vrachtwagens. Goederen worden op de terminal overgeslagen op AGVs die door een ondergronds transportnetwerk de goederen afleveren in de binnenstad.

De volgende leerpunten kunnen worden meegenomen uit de inductieve case studie. Ten eerste, de besturingssystemen krijgen weinig aandacht in het ontwerp van het stadsdistributiesysteem Tilburg. Er is geen gestructureerde aanpak gevolgd en beslissingen zijn op ad-hoc basis genomen. Ten tweede, het ontwerpen van geautomatiseerde transportsystemen is een complexe activiteit. De ontwerpruimte is groot en wordt gekenmerkt door vele vrijheidsgraden. Ten derde, geautomatiseerde transportsystemen worden in fasen geconstrueerd. Het transportsysteem wordt uitgebreid en het niveau van automatisering neemt toe in iedere fase. Ten vierde, het beschikbare transportnetwerk en de ruimte zijn kritieke logistieke resources in het systeem. De transportnetwerken zijn gescheiden van het overige verkeer en deze scheiding is kostbaar om te realiseren. Het transportnetwerk wordt daarom zo minimaal mogelijk gehouden. Tenslotte is er weinig bekend over de exacte technische specificaties van de geautomatiseerde logistieke resources. Vooral op het gebied van de technische specificaties en communicatie worden veel vereenvoudigen gedaan in het ontwerpproces. Dit leidt tot onrealistische uitgangspunten in het verdere verloop van het ontwerpproces. De technische specificaties en communicatie moeten worden meegenomen, omdat deze de prestaties van het transportsysteem sterk beïnvloeden. Deze leerpunten vormen de beginpunten voor de ontwerpomgeving.

Ontwerpomgeving

We ontwikkelen een ontwerpomgeving om ontwerpers van logistieke besturingssystemen te ondersteunen. De ontwerpomgeving heeft twee functies. Ten eerste vormt de ontwerpomgeving een basis voor het ontwerpproces. Ten tweede vormt de ontwerpomgeving een basis voor het evalueren van besturingssystemen. De ontwerpomgeving bestaat uit drie delen: een holonische structuur voor besturingssystemen, een aantal ontwerprichtlijnen welke kunnen worden gevolgd tijdens het ontwerpproces en ondersteunende faciliteiten voor de evaluatie van besturingssystemen.

Deel een van de ontwerpomgeving: holonische structuur

Het eerste deel van onze ontwerpomgeving is een holonische structuur voor besturingssystemen. Drie holonen worden onderscheiden:

- *Order holonen* zijn de raakvlakken tussen de klanten en het transportsysteem. Order holonen zijn verantwoordelijk voor het plannen van de klantopdrachten en beslissen welke resource holonen worden aangesproken voor het uitvoeren van logistieke diensten.
- *Resource holonen* zijn verantwoordelijk voor het plannen en besturen van de logistieke resources, zoals AGVs en overslagstations.
- *Load holonen* zijn verantwoordelijk voor het besturen van de goederen die worden getransporteerd, opgeslagen en overgeslagen. De belangrijkste taak van load holonen is andere holonen van informatie voorzien betreffende de goederen die moeten worden vervoerd.

In holonische besturingssystemen voor grootschalige geautomatiseerde transportsystemen zijn alle drie typen holonen vertegenwoordigd. De holonen zijn autonoom en moeten met elkaar samenwerken voor het uitvoeren van logistieke diensten. De holonen kunnen door de autonomie die de individuele holonen hebben samenwerking niet afdwingen.

Deel twee van de ontwerpomgeving: ontwerprichtlijnen

Het tweede deel van de ontwerpomgeving bestaat uit een zevental ontwerprichtlijnen die ontwerpers kunnen volgen tijdens het ontwerpproces. De ontwerprichtlijnen richten zich op de holonische structuur en communicatie.

De eerste ontwerprichtlijn zegt dat de resource holonen een gelaagde structuur hebben. Drie lagen worden onderscheiden; resource management, resource control en resource representatie. Resource management is verantwoordelijk voor het besturen van een verzameling logistieke resources. Resource control is verantwoordelijk voor het besturen van een enkele specifieke logistieke resource. Een resource representatie is een model van een logistieke resource. De tweede ontwerprichtlijn zegt dat holonische besturingssystemen een hiërarchische en decentrale structuur combineren. De resource holonen zijn hiërarchisch opgebouwd volgens ontwerprichtlijn een. De holonen zijn gedistribueerd; de verantwoordelijkheden voor besturing zijn verdeeld over verschillende punten. De derde ontwerprichtlijn zegt dat holonische besturing uit twee interacterende processen bestaat; plannen en uitvoeren. Planning is het proces van het maken van planningen die moeten worden uitgevoerd om logistieke diensten voor klanten uit te kunnen voeren. De order holonen en resource holonen moet met elkaar samenwerken om planningen te maken. De planningen worden contracten tussen de order holonen en resource holonen. Besturing is het uitvoeren van de planningen tot een succesvol einde. De resource holonen zijn verantwoordelijk voor uitvoeren van de planningen. De vierde ontwerprichtlijn stelt dat de logistieke resources buiten de resource holonen worden geplaatst. De resource holonen bevatten representaties van de logistieke resources. Het gebruik van representaties maakt de resource holonen onafhankelijk van de techniek in de fysieke resources. De logistieke resources hebben een hoge mate van autonomie en zijn zelf verantwoordelijk voor het besturen van deel van hun activiteiten. De vijfde en zesde ontwerprichtlijnen stellen dat de communicatie in de holonische structuur een opdracht/gebeurtenis structuur heeft en asynchroon is. Besturingssystemen sturen opdrachten of besturingsmaatregelen naar de logistieke resources. De resources sturen notificaties terug van de gebeurtenissen tijdens het uitvoeren van de opdrachten. Asynchrone communicatie ontkoppelt de

besturingsprocessen en uitvoerende processen. Op deze manier kunnen besturingsprocessen en uitvoerende processen onafhankelijk van elkaar worden uitgevoerd. De zevende en laatste ontwerprichtlijn stelt dat de communicatie wordt geïmplementeerd in informatiediensten die gebaseerd zijn op een publicatie/registratie mechanisme. De holonen moeten zich registreren bij de informatiediensten die de informatie publiceren die zij nodig hebben.

Deel drie van de ontwerpomgeving: ondersteuningsfaciliteiten voor evaluatie

Het derde en laatste deel van de ontwerpomgeving bestaat uit de ondersteunende faciliteiten voor het evalueren van de ontworpen besturingssystemen voordat zij worden geïmplementeerd. De ontwerpomgeving schrijft een combinatie van simulatie, emulatie en prototypen voor om de resource holonen te evalueren. Simulatiemodellen van de resource holonen worden gebruikt voor het besturen van gesimuleerde logistieke resources, geëmulerde logistieke resources en prototypen van de logistieke resources. Elke type model heeft specifieke voordelen voor het bestuderen van de besturingssystemen voor grootschalige transportsystemen. Simulatie biedt een omgeving die veilig is en waarin experimenten snel kunnen worden uitgevoerd. Emulatie biedt mogelijkheden voor het bestuderen van de communicatie. Prototypen worden gebruikt voor het bestuderen van de technische aspecten van de logistieke resources.

Het is belangrijk dat een consistente koppeling tussen de verschillende typen modellen wordt gebruikt. Op deze manier kan de gesimuleerde resource holon eenmalig worden ontwikkeld en worden hergebruikt voor het besturen van alle typen modellen van de logistieke resources.

De ontwerpomgeving wordt geëvalueerd in twee case studies en een groepevaluatie. Het centrale onderwerp van de evaluatie is het ontwerp van een toekomstig grootschalige ondergronds transportsysteem; het Ondergronds Logistiek Systeem Schiphol. Het OLS Schiphol zal AGVs en geautomatiseerde overslagstations gebruiken om vracht te vervoeren tussen Schiphol, bloemenveiling Aalsmeer en een toekomstige railterminal bij Hoofddorp.

Evaluatie van de resource holonen

De technische bruikbaarheid van de resource holonen wordt als eerste geëvalueerd. De ontwerpomgeving wordt gebruikt voor het ontwerpen van twee resource holonen, een AGV holon en een Overslag holon, voor het besturen van AGVs en overslagstations in een speciaal laboratorium, de Connekt TestSite. De TestSite is voorzien van prototypen AGVs en overslagstations ontwikkeld voor het OLS Schiphol. Simulatiemodellen van de AGV holon en de Overslag holon worden gebruikt voor het besturen van simulatiemodellen, emulatiemodellen en prototypen van de logistieke resources.

Het belangrijkste resultaat van de eerste evaluatie is dat de holonische structuur in staat is om effectief en efficiënt geautomatiseerde logistieke systemen te besturen. De resource holonen zijn schaalbaar binnen de grenzen van de TestSite en in staat om alle aanwezige resources te besturen. De resource holonen zijn uit te breiden en aan te passen. De resource holonen kunnen met de belangrijkste verwachte veranderingen in het OLS Schiphol omgaan zonder dat aanpassingen nodig zijn in de structuur van de holonen. Verschillende wijzigingen die kunnen voorkomen zijn getest zoals nieuwe bestemmingen, nieuwe en aangepaste routes en nieuwe logistieke resources. De resource holonen zijn robuust en in staat om te gaan met de meest voorkomende verstoringen in het OLS Schiphol zoals technische mankementen in de resources en fouten in de communicatie. De resource holonen zijn onafhankelijk van de technologie en software. De AGV holon is geïmplementeerd in verschillende simulatiepakketten en

gebruikt om AGVs van verschillende fabrikanten te besturen. Tenslotte zijn de resource holonen onafhankelijk van het transportnetwerk. Iedere inrichting van het transportnetwerk kan worden bestuurd door de holonen.

Een belangrijk onderdeel van de evaluatie is het synchroniseren van de resource holonen en de modellen van de logistieke resources. Twee soorten synchronisatie worden onderscheiden; tijd en plaats. Synchronisatie van tijd is gericht op het synchroniseren van de simulatieklok en de interne klokken van de logistieke resources. Synchronisatie van plaats is gericht op het synchroniseren van de plaats en de oriëntatie van de logistieke resources en de representaties daarvan in de resource holonen.

Evaluatie van de order holon

In de tweede case studie is de ontwerpomgeving gebruikt voor het ontwerpen van een managementsysteem voor het afhandelen van klantopdrachten. Een Holonisch Opdracht Management Systeem (HOMS) is ontwikkeld voor het plannen van klantopdrachten en onderhoud aan de logistieke resources.

De order holon en verschillende resource holonen moeten samenwerken om de vraag naar en het aanbod van logistieke diensten te koppelen. Klantopdrachten arriveren bij de order holonen. De order holonen sturen deelopdrachten naar de resource holonen voor het uitvoeren van diensten. De resource holonen creëren deelaanbiedingen gebaseerd op de deelopdrachten. De order holon koppelt de deelaanbiedingen van de resource holonen en stuurt een aanbieding naar klant. De klant bepaald vervolgens of de aanbieding wordt geaccepteerd of afgewezen. De resource holonen proberen hun planningen zo efficiënt mogelijk te maken voor de verzameling resources die zij besturen. De order holonen proberen de planningen van het totale logistieke systeem zo efficiënt mogelijk te maken.

De HOMS is ook verantwoordelijk voor het plannen van onderhoud aan de logistieke resources. Het OLS Schiphol gebruikt nieuw ontworpen logistieke resources, die nog niet volledig in de praktijk getest zijn. De verwachting is dat de resources met veel verstoringen te maken zullen hebben, zeker in het begin van de operationele fasen. Regulier onderhoud is noodzakelijk om de gevolgen van de verstoringen te minimaliseren. Een onderhoud holon is ontwikkeld die in samenwerking met de andere resource holonen het onderhoud aanstuurt.

Simulatiemodellen van het HOMS worden gebruikt voor de evaluatie. Emulatiemodellen en prototypen zijn niet gebruikt, omdat de technische vraagstukken minder relevant zijn. Verschillende scenario's worden gebruikt die mogelijke 'to-be' situaties van het OLS Schiphol voorstellen. De scenario's verschillen op het aantal order holonen en resource holonen, dat wordt gebruikt in de holonische structuur. Dit om de mogelijkheden van concurrerende order holonen en resource holonen te bestuderen. Een eerste mogelijkheid is de aanwezigheid van concurrerende order holonen binnen een logistiek systeem. De order holonen concurreren om de diensten die geleverd worden door dezelfde resource holonen. De order holon die de beste deelopdrachten stuurt zal worden gekozen door de resource holonen. Een tweede mogelijkheid is concurrentie tussen resource holonen. Meerdere resource holonen concurreren voor het uitvoeren van dezelfde deelopdrachten van dezelfde order holon. De order holon kiest de beste deelaanbieding van de resource holonen. Tenslotte is een combinatie van concurrerende order holonen en concurrerende resource holonen mogelijk in een logistiek systeem.

De belangrijkste conclusie van de tweede evaluatie is dat de HOMS concurrerende order holonen en concurrerende resource holonen kan faciliteren, wat belangrijk is voor het OLS Schiphol op een langere termijn. De HOMS behandelt de concurrerende holonen gelijkwaardig en geeft geen voorkeur aan specifieke holonen. Verder lijkt de bezetting van de logistieke resources laag op het eerste gezicht. Het OLS Schiphol is ontworpen om piekbelastingen tijdens spitsuren aan te kunnen. Binnen de spitsuren ligt de bezetting van de logistieke resources hoger dan buiten de spitsuren. De tijd buiten de spitsuren wordt door de onderhoud holon gebruikt voor het inplannen van onderhoud. Op deze manier kunnen de logistieke resources binnen de spitsuren efficiënter gebruikt worden. Tenslotte is de HOMS communicatie-intensief vooral als concurrerende order holonen en concurrerende resource holonen worden gebruikt. Veel berichten moeten worden uitgewisseld tussen de order holonen en resource holonen voor het inroosteren van de logistieke diensten.

Groepsevaluatie

Tijdens de laatste evaluatie is de ontwerpomgeving aan een groep experts gepresenteerd. De experts zijn allemaal betrokken bij het ontwerpen van geautomatiseerde transportsystemen. De experts zijn om een onafhankelijke evaluatie te bewerkstelligen niet direct betrokken bij het ontwikkelen van de ontwerpomgeving. De ontwerpomgeving is gepresenteerd en bediscussieerd met de experts. De experts vergelijken de ontwerpomgeving met hun verwachtingen en ervaringen op het gebied van geautomatiseerde transportsystemen. De experts vinden dat de ontwerpomgeving aanpasbaar en uitbreidbaar is binnen de grenzen van het OLS Schiphol. De holonische structuur kan de verwachte aanpassingen implementeren zonder aanpassingen in de structuur van de holonen. De experts vinden de holonische structuur schaalbaar binnen de grenzen van het OLS Schiphol. De holonische structuur is robuust en kan omgaan met de belangrijkste verwachte verstoringen in de techniek en communicatie. Tenslotte vinden de experts dat de holonische structuur een open karakter heeft, nieuwe holonen en andere besturingssystemen kunnen makkelijk worden toegevoegd zolang zij maar voldoen aan de voorgeschreven communicatieprotocollen.

Ons onderzoek eindigt met mogelijke richtingen voor verder onderzoek. Een eerste richting is het toepassen van de ontwerpomgeving door andere ontwerpers van besturingssystemen van geautomatiseerde transportsystemen. In ons onderzoek is de ontwerpomgeving alleen toegepast door onderzoekers die betrokken zijn bij het ontwikkelen van de ontwerpomgeving. Een tweede richting is het gebruik van de ontwerpomgeving voor het ontwerpen van besturingssystemen voor andere soorten geautomatiseerde transportsystemen, zoals geautomatiseerde containerterminals, geautomatiseerde distributiecentra en geautomatiseerde transportsystemen voor personenvervoer.

Appendix. Participants of the Group Evaluation Session

A group evaluation session was carried out to evaluate the usability of the support environment (chapter eight). Mr. A. Verbraeck acted as facilitator and did not actively participate in the group evaluation session. Some of the experts were contacted after the group expert session to further elaborate their evaluation of the support environment.

Table 1: Participants of group evaluation session

<i>Participant</i>	<i>Organisation</i>
Mr. R. Jager	FROG Navigation Systems
Mr. J. van Putte	FROG Navigation Systems
Mr. R. de Vos Burchart	FROG Navigation Systems
Mr. B-J. Pielage	Delft University of Technology \ TRAIL
Mr. A. Verbraeck (facilitator)	Delft University of Technology \ TRAIL
Mr. J. Katgerman	RUPS
Mr. N. van Hylckama-Vlieg	TNO Automotive
Mr. L. Kusters	TNO Automotive
Mr. J. Ploeg	TNO Automotive
Mr. F. Terheijden	Imtech
Mr. H. Bosma	Bostec b.v. Technology Management
Mr. R. Groenveld	Structon
Mr. D. Buitenhek	Connekt

Curriculum Vitae

Corné Versteegt was born on November 26th 1972 in Woerden, the Netherlands. In 1994 he graduated from the 'Christelijk Lyceum' in Gouda. He studied at the Faculty of Technology, Policy and Management at Delft University of Technology from 1994 to 1998. He specialised in logistic control and supply chain management. His masters' thesis project, conducted at the 'Dutch Organisation for Applied Physics (TNO)', focused on management information systems to support research on supply chain management.

His research has been published in several articles and books and has been presented at international conferences in the Netherlands, Belgium, Germany, United Kingdom, United States of America, Australia, Singapore and Japan. Furthermore, Corné presented his research to many international visitors in Delft. During his project he developed and managed a number of courses, related mostly to logistics and simulation. He developed an advanced course on simulation of logistic systems for students at Delft University of Technology. He supervised several students in their masters' thesis project. In 2002 Corné received a prize in the SWOV research proposal contest for young researchers for research on traffic safety. Corné taught courses at the Haagse Hogeschool, the Open Universiteit and the University of Melbourne besides his work at Delft University of Technology. He gave guest lectures for international companies and universities. Currently, Corné works as senior systems engineer at NCIM (Nederlands Centrum voor Interim Management, www.ncim.nl). He works on projects in health care, logistics and transportation.

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Da steh' ich nun, ich armer Tor!
Und bin so klug als wie zuvor;
Heiße Magister, heiße Doktor gar
Und ziehe schon an die zehen Jahr
Herauf, herab und quer und krumm
Meine Schüler an der Nase herum-
Und sehe, daß wir nichts wissen können!

Johann Wolfgang von Goethe

RHC