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Safeguarding Schiphol Airports accessibility for freight transport

M.C. van der Heijden, A. van Harten, M.J.R. Ebben, Y.A. Saanen, E.C. Valentin & A. Verbraeck

WP-53
Safeguarding Schiphol Airports

accessibility for freight transport

The design of a fully automated underground transport system

with an extensive use of simulation

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Abstract

Automated, underground freight transport should enable sustainable economic growth in the Amsterdam area in the Netherlands. An innovative transport system, which guarantees reliable logistics and which avoids congestion problems, is currently being developed. This logistics system will be highly automated, using AGVs (Automatic Guided Vehicles) for transport and automated loading and unloading equipment. It is unique in its scale, covering a 15-25 km tube system, and in its complexity, using 200-300 small truck size AGVs in a multi-terminal setting. It requires considerable innovations in technology, especially in AGV control and AGV fleet control. Decisions about the implementation of such a system are characterized by a high uncertainty. Object-oriented simulations have been used to get insight in a multitude of design and management options. In this way, we could clarify the relations between logistics system performance and resource capacities, such as the number of docks and parking spaces per terminal and the number of AGVs for various demand scenario’s. Furthermore, we compared several possible layouts, both at the total system and at the terminal level, leading to design optimization. The control structure - e.g. intelligent empty AGV management and intelligent traffic rules - has a noticeable effect on the performance of the system. We showed that the investment costs could be reduced by ±20% by including two-way tube sections in the design, with only a slight, acceptable decrease in logistics performance. The strict use of generic object classes in the simulation provided the flexibility to address the changing user demands during the project. The simulations are advanced to the level that simulated and real objects can be mixed. Simulation control structures are currently used for testing prototype AGVs on a test-site. In this way, the risks of using the new technology can be reduced. Furthermore, the development time of the logistical control systems can be reduced considerably.
Introduction

Need for innovative transport and logistics concepts

The worldwide growth of cargo flows has severe repercussions in terms of traffic congestion problems, especially at and near main traffic hubs, such as airports or harbors. The attractiveness of top industrial areas gives rise to ongoing concentration of activities. In combination with good facilities for transit cargo, arising from a globalization of business activities, this leads to fast increasing in- and outbound transport volumes. The growth percentages in these volumes in the Netherlands can easily surpass those of the GNP by a factor two, i.e. 6 to 8 percent annually. In order to accommodate these increasing flows, the development of new infrastructure has to keep pace. In terms of viable economics, reliable accessibility of a main hub and its surroundings is a key necessity. Realizing sustainable growth is a major challenge, since ground is an extremely scarce commodity around a main hub. Given this core of the growth problem, innovative solutions for extensions of the transport infrastructure should have a high priority. Public and private interests go hand in hand here in a natural way.

Classical solutions such as simply extending the road or rail capacity do not fit well into this picture, because of the lack of suitable space. Use of inland navigation is an option for some product flows, because it is cheap and because the Dutch inland waterways have excess capacity. However, the accessibility and speed are serious drawbacks, especially for time critical products that have to be moved from and/or to urban areas. This forces the government to consider alternatives such as underground construction, focussing on time critical products. Because of this focus, a high level of automation – such as automated transport and loading/unloading – is appropriate. A rather radical innovation with high potential is the use of AGVs in underground tube systems. An in-depth investigation of its merits for reliable logistics service, technical feasibility, environmental benefits and cost performance is worthwhile. Probably, innovative logistics concepts will be necessary as well to make the system to work properly.
The OLS project: a multi-disciplinary approach for integral assessment

The arguments given above were the motivation behind a public/private underground logistics innovation project. In order to provide reliable cargo transport in the Schiphol area near Amsterdam, The Netherlands, an innovative system with free ranging Automatic Guided Vehicles (AGVs) has been designed. This new system is referred to as OLS (the Dutch abbreviation for Underground Logistics System). An impression of the geographical layout is depicted in Figure 1.

Figure 1: Layout of the OLS with terminals at Schiphol Airport (AAS) in the center, Flower Auction Aalsmeer (VBA) at the right and a rail terminal to be constructed in line with the "Zwanenburg" airstrip (RTZ) in the north-east. Restrictions on possible geographical designs stem from existing infrastructure and requirements on connectivity to existing industrial areas and railway infrastructure.

The OLS aims at becoming a reliable logistics system, connecting the transport modes air, rail and road. The system mainly focuses on handling time critical goods, such as air cargo (newspapers, perishables and high-tech spare parts) and flowers. These products can be automatically (un)loaded and transported by AGVs using sophisticated technology and (logistics) control systems.

It is clear that structuring the decision process for realizing an innovative, large-scale system as indicated is a nontrivial matter. The organizational embedding of the decision process is
essential for generating consensus and for supporting the go/no-go decision for the entire project. Almost by nature of public/private partnerships, the organization of such a project is complex, particularly when innovations with considerable technological and financial risks are involved. This project is a joint initiative of the main stakeholders: the airport authority at Schiphol, Dutch Railway, an association of airline companies, representatives of the main industries in the area (especially the world’s largest flower auction at Aalsmeer) and representatives of main cargo shippers and logistics service providers. The Dutch government is represented in the OLS project steering committee and supports the initiative by providing research grants to an independent, coordinating institute (CONNEKT). Several research disciplines cooperate intensively in this project to obtain an integral assessment of this new transportation system, to optimize the system design, and to explore its technological and economic viability. Among these are underground construction technology, AGV and mechatronics technology, automated docking and warehousing technology; information, communication and control technology; logistics, simulation, business, and economics. A point of continuous attention in the project is to involve a user group in the definition of the research questions and the evaluation of the research results.

In this project, more than a hundred researchers and developers of universities, research institutes, customers and business partners are directly involved. The orientation phase of the project has a time-span from November 1997 to December 2000. The total research budget is in the order of 5% of the estimated system construction costs, which is considered to be reasonable given the innovative character of the OLS. As an indication, the total investment will be in the range $250 - $500 million, depending on the system design. If at the end of the orientation phase the technical and economical viability has been proven, a public/private partnership for the system realization will be founded. This partnership will have the infrastructure built and as its owner it will be responsible for its future maintenance. It will rent the system to an exploitation company that operates the AGVs. The goals of the orientation phase are:
• to obtain adequate information for a go/no-go decision for the next phase, where a first part of the system will be constructed,
• to deliver a first optimized system design to the future infrastructure owner,
• to deliver tested AGVs and loading/unloading technology to the system exploitation company,
• to design new control systems and hand these over to the exploitation company,
• to test the prototype AGVs and loading/unloading systems with their control systems at a dedicated test-site.

The system as an extension of current AGV systems

To prepare the go/no-go decision for the system, its potential costs and benefits need to be analyzed. The parameters that affect the cost/benefit ratio such as market size, terminal sizes, number of AGVs, logistics performance, etc. are a necessary ingredient for this analysis. But more is involved. Before an actual go/no-go decision can be taken, the technological feasibility of the system should be ensured. The idea is that risk reduction in a technological sense can best be obtained by first testing the technology for AGVs, loading and unloading docks, ICT systems, networks, and control principles in a prototype setting. This attitude is reinforced by previous experiences with the introduction of analogous systems for container terminals in the Port of Rotterdam. In comparison with the technology used there, several innovative steps are foreseen.

Firstly, it is a matter of scaling. The OLS has a multi-terminal structure where distances between terminals are an order of magnitude 10 larger than in known AGV systems. The same applies to the number of AGVs and the driving times between terminals. This implies that more complex control structures are necessary. An example is that due to the longer distances, good empty car management (pre-positioning of AGVs to anticipate on predicted demand) is much more important than in existing systems. In this respect the OLS is more
similar to certain vehicle and rail wagon fleet management problems, cf. Powell et al [1988], [1998] and Powell [1996].

Secondly, new traffic situations for AGVs will arise. Examples include crossings, access lanes, and two-way tube entrances, which have to be designed for safe operation first. The existing AGV traffic control technology at container terminals is considered to be reliable, but too conservative in its track claiming and safety processes to allow for more flexible, higher speed traffic handling. Therefore, we chose to adapt the TRACES-concept (TRAffic Control Engineering System), a new and intelligent AGV traffic control framework developed by Evers et al [1999]. One of the challenges of the project is to test and improve TRACES in a simulation environment as a step towards implementation in a real AGV system. This is done in cooperation with FROG Navigation Systems, a well-known Dutch AGV control systems producer.

![Image of AGVs and cargo pallets]

**Figure 2.** The OLS is an advanced transport system with Automatic Guided Vehicles (AGVs) and highly automated (un)loading and transit facilities, efficiently connecting road, rail and air transport. This enables a reliable multimodal freight transport system that is ready for the future.

Thirdly, the dimensions of air cargo pallets and flower cars are different from both sea containers and industrial pallets, for which AGVs already exist. Furthermore, the dimensions of the types of goods to be transported with the OLS differ from each other as well. This implies that a new type of AGV for the OLS is required. It should satisfy different
requirements for size, weight, speed, acceleration, etc. Altogether, proof of principle of the new technology is the only acceptable way to realization.

A central role for simulation

Simulation models have been used continuously to act as a common structure to bring together different research groups and to ease communication. For example, simulation has been used for infrastructure design (terminals, docks, track system), the assessment of the corresponding logistics performance, and the testing of new control technology. Terminals and docks have been designed in an iterative process, where technicians and simulation experts closely collaborated. Typical examples of questions that had to be answered with the help of simulation models are:

- How many AGVs and how many docks at terminals are necessary to realize an on time service percentage of 98%?
- How do various system layouts compare in logistics performance?
- Are two-way tube sections feasible for reliable logistics?
- How do AGV throughput times on terminals depend on terminal and dock design, and how can we balance terminal capacity and space requirements optimally?
- How can traffic control guarantee that AGVs move independently at high throughput rates without colliding?
- What is the influence of the logistics control structure on the performance?
- How should battery management be organized?

For this project, one of the challenges was to design the logistics control in such a way, that it can be mapped in a one to one way to the control system used in reality. This is a very tough requirement for the structure of the simulation but it has the tremendous advantage that the simulation models can be used for testing system control in the real system.
Since this is a research and development project in close interaction with other disciplines and a user group, the precise content of the research questions and solution boundaries varied in time. New variants of layouts, characteristics of demand patterns, and alternatives for AGV and dock handling were proposed frequently. Hence flexibility in the simulation model structure was a necessity. Below, we will discuss how this was achieved.

2. Simulation modeling principles

Object-oriented approach

In the context of modeling and simulation, flexibility is enlarged by the ability to quickly construct a great variety of models from a basic set of building blocks, such as variants of terminals, docks, buffers, or tracks. Because of the importance of an appropriate logistics control structure, the same flexibility is required for the building blocks for the various decisions to be taken in the system, such as vehicle routing, traffic rules and order scheduling. Flexibility was achieved by using a strict object-oriented approach based on the TRACES object structure, cf. Evers et al [2000] and Verbraeck et al [1998], and on a general framework for logistics and transport agents and their control, cf. van der Zee [1997]. A key characteristic of the latter modeling framework is the explicit notion of control structures besides the physical processes. A model is constructed from an object library, whose components can be classified as physical objects (e.g. AGV, terminal, dock, parking, track), control objects (e.g. AGV dispatcher, order scheduler, traffic controller, AGV distance controller) and information objects (e.g. distance table, job list). These objects are structured in a hierarchical way. The control objects use the available information to ensure the efficient use of the physical objects (resources).

A basic requirement for a flexible OLS object library is the standardization of communication between objects. As long as the interfaces of the objects remain the same, both the physical objects with their behavior and the corresponding control objects are allowed to change internally in any way, as long as the overall functionality of the object stays the same. This
leads to a powerful object library with reusable objects, which turned out to be a critical factor in the OLS project, where in the orientation and the design phase of the project almost all objects were subject to change over a long period of time.

For sake of robustness as well as extendibility, the project team decided to focus on a local control concept, where physical objects are closely linked to the corresponding information and control. Local control does not necessarily mean a significant loss of logistics performance of the system, conditional on the way the control structures are set up and on an appropriate information exchange between objects. A hierarchical logistics planning and control framework fits perfectly in the object-oriented approach chosen for this project. The TRACES concept for traffic control that was mentioned in the introduction is also based on object orientation and local control.

The local control concept implies that each physical object may have accompanying control objects (managers) and information objects. For example, in the OLS each terminal has a terminal manager that is responsible for demand forecasting, order release, order scheduling and local AGV assignment. The terminal manager only bases its planning decisions and control activities on local terminal information, which is embedded in the terminal information object. When other information is useful to optimize local decisions, this information can be supplied by communicating with other information objects, e.g. empty car information at the network level. Preferably, local controllers communicate with each other via a common global controller, e.g. docks within a terminal communicate via the terminal manager rather than negotiating with each other.

**Bottom-up and top-down**

The range of questions to be covered in the OLS project is very broad, from low-level AGV design, traffic control and distance control to high-level trajectory choice, system dimensioning and AGV allocation to terminals. Constructing one huge model for the OLS,
incorporating all aspects on the most detailed level, is possible, but not practical because of model maintainability and run time requirements. Of course, AGV characteristics like distance control might have a significant impact on the system performance. A clear example that we found is the distance between AGVs required to prevent collisions. This safety distance strongly influences the capacity of tracks for traffic in both directions, so-called two-way tubes. These two-way tubes can be a serious bottleneck. Therefore, we decided to construct two statistically linked simulation models: a network model, constructed from a top-down approach, and a traffic model, constructed from a bottom-up approach. These two models meet at the terminal level.

![Diagram](https://via.placeholder.com/150)

**Figure 3.** Two closely linked models are developed to analyze the OLS. The network model mainly focuses on logistics network control, trajectory choice and logistics performance measurement. The traffic model mainly focuses on traffic control, terminal/dock design, and detailed AGV characteristics. These two models are linked by exchanging key AGV and order characteristics: AGV and order information flows from the network model to the traffic model, while information on the effective driving speed of AGVs and loading/unloading times flow in the other direction.

The network model contains terminals where AGVs drive with a simplified behavior, e.g. instantaneous acceleration and deceleration and no extensive traffic control. The effective driving speed, i.e. the driving speed corrected for detailed AGV-behavior and interactions at crossings and junctions, is derived from the traffic model as a statistical function of the number of AGVs on a terminal. Also, the mutual AGV-distance is controlled at a few critical locations (e.g. terminal entrances and two-way tubes). On the other hand, the terminal in the
traffic model uses arrival patterns of AGVs and loads derived from the network model. In this way, the consistency between both models is guaranteed. First, we will discuss both models and the obtained results in more detail.

3. Top-down: The model for system dimensioning and network control

The primary goals of the network model are to determine the required resource capacities such as the number of AGVs and docks per terminal, to support trajectory choice, and to test different planning and control structures at the terminal and network level. Key input to the simulations are estimates of transport demand for the OLS, derived from Dutch national transport statistics, covering the next 20 years. Volume variations over the day and between days had to be derived, since peaks heavily influence the performance of the system.

Transport jobs for the system are specified by a hard due time at the destination. The main logistics service indicators used are the distribution of throughput times for transport orders and on time service percentages during peak hours on certain days. Furthermore, a large variety of other performance indicators were measured, like resource utilization, buffer occupation, queue sizes of AGVs waiting for terminals and two-way tubes, energy consumption, failure statistics, etc.

Object library

Using the principles from the previous section, an object library has been constructed for the network simulations. Table 1 shows the key physical, information and control objects. Of course, several alternatives have been developed for most object classes. A simulation model can easily be constructed by combining these objects in a consistent way or by replacing one object with another variant. A comparison between alternatives for each of the objects is therefore easily carried out. As discussed in the previous section, a boundary of the network model is the AGV-behavior. Hence the model does not include objects for traffic control and distance control. These aspects and their impact on terminal and dock design are treated in the next section.
Table 1. An object-oriented model library is constructed for the OLS, in which the control structure is explicitly modeled. Decisions on the activities of physical objects are taken by control objects and based on data provided by information objects. This table gives an overview of the key objects in the network simulation model.

Outline of the planning and control structure

As mentioned before, the logistics control structure is based on decentralized control with information exchange between the controllers (managers). Figure 4 describes the process for handling transport orders, together with a number of control issues. To structure the planning and control activities, we classified these as tactical versus operational control on the one hand and as global versus local impact on the other hand.

Regarding the first classification, operational issues cover planning and control activities that may be taken at any point in time, with high frequency, and that imply immediate actions like moving cargo or redirecting AGVs. Tactical planning typically takes place periodically and covers a longer time interval. For example, the empty car manager balances AGV flows every 10-60 minutes, taking into account the known and predicted events within a time horizon of ½-2 hours. These value ranges are appropriate for the OLS under consideration and may be entirely different for other transport systems, depending on travel times between locations and accuracy of demand forecasts.
A second classification has been made for the scope, namely planning and control issues that have a *global* impact (network) versus control issues that have only a *local* impact (terminal, two-way tube, AGV-parking). The local and global controllers communicate with each other in order to tune the effects of local decisions, and thus preventing negative effects of sub-optimization as much as possible.

Figure 4: The network model consists of a core physical process that is managed by related control objects, reflecting the major planning decisions. The control objects can be categorized by system level (local/network) and planning level (operational/tactical).

Next, we constructed several models for the OLS from our model library for answering a large variety of design questions posed by the multidisciplinary project team. In the remainder of this section, we will highlight some of the main results and their impact on the OLS project.
Gain by efficient planning and control

For most control objects, we constructed several alternatives to analyze the impact of differences in planning and control rules. An important and challenging control object is the empty car manager. Depending on known and expected orders, with their priorities, empty AGVs might have to be relocated from terminals with excess AGVs to terminals with an AGV shortage, also depending on the number of full AGVs that are scheduled to arrive at the terminals with an AGV shortage. We developed several control objects for this empty car manager, ranging from a simple First Come First Serve (FCFS) rule via look-ahead rules to more sophisticated scheduling methods. By comparing the performance of the system with these control objects, we could show the impact of additional pre-information about orders and the value of coordination amongst terminals, cf. Van der Heijden et al [2000]. We found that look-ahead rules based on pre-information are preferred, whereas more sophisticated scheduling methods provide additional benefits if the demand patterns strongly fluctuate in time and over origin-destination pairs. Sophisticated methods showed an additional reduction of empty driven distances by 5-10% compared to simple heuristic rules. These results provide input for the decisions about the complexity of the information and control systems to be implemented. More information leads to better logistics performance and fewer resources needed, but it may also require more expensive information systems.

Trajectory choice and the consequences of two-way tubes

One of the major cost items in the construction of an underground transport system is the infrastructure. The first proposed network layout for the OLS (left side of Figure 5) required high investment costs, about $500 million. This is mainly due to the high construction costs of the tubes with a diameter of 5 meters, which cost about $20 million per km excluding facilities for energy, maintenance and safety. As it appeared that the investment costs were too high to ensure economic and social profitability, the question was raised whether two
tubes, one for traffic in each direction, are really required for all links to guarantee the required logistics service levels.

Figure 5. Three main trajectories have been under consideration for the OLS. The two figures above show the preferred trajectory in 1998 (left) and 1999 (right). The most recent variant (2000) with rail terminal at Schiphol is shown in Figure 1. Schiphol Airport is shown in the center, with Flower Auction Aalsmeer on the right and the Rail Terminal in Hoofddorp on the left. The right figure shows the two-way tubes that saved considerable investment costs.

An alternative trajectory (right side of Figure 5) was sketched, and the accompanying investment calculation showed that it could save about $150 million on infrastructure costs. This trajectory includes three two-way tubes on the long distance links, with respective lengths of 2.7 km (Aalsmeer – Schiphol), 2.3 km (Schiphol – Hoofddorp) and 0.75 km (between Schiphol terminals). The driving times through these tubes are up to 7½ minutes for the longest tube. This implies that AGVs at the other side may have to wait for quite some time until they get permission to enter the two-way tube. During that time, AGVs arrive and queue for the tube entrance. The mutual distance between successive AGVs in a convoy that drives through a tube should be at least 21.2 m because of collision prevention in case of an abrupt stop of one of the AGVs in case of an emergency. Because of the distance between AGVs, the convoys tend to be long, and the last AGV of a convoy leaves the tube after quite some time. This boosts the length of the queue of waiting AGVs on the other side of the tube. As a consequence of convoy formation, the terminals face batch arrivals of AGVs,
accumulating to over 100 AGVs in peak hours. Because a limited number of loading/unloading docks is available, AGVs may have to wait for 5-10 minutes before they are handled at the terminal, thereby further increasing throughput times. As a consequence, it could be necessary to increase the terminal capacity to handle the extended peak capacity demand and the number of AGVs because of lost time while waiting for entering the tube and for handling at the terminal. Extended terminals are more expensive, particularly in case of subterranean construction. More AGVs also cost money, take more space, and might lead to further congestion in the system.

Using the object library, we constructed a model for the new trajectory with two-way tubes. We had to extend our library with a physical object for a two-way tube with accompanying information and control object. Especially the design of effective tube control appeared to be a nontrivial task. The simplest solution is a "traffic-light" solution, where the driving direction in the two-way tube is periodically switched. We found this to be an unpractical solution, because the logistics performance was sensitive to the switching frequency and because the number of AGVs per direction changes over the day and may be temporarily asymmetric. Therefore we developed several adaptive rules for two-way tube control, varying from simple rules based on the number of AGVs waiting at each side of the tube via look-ahead rules to dynamic programming based algorithms, focusing on minimizing waiting times (cf. Ebben et al [2000]). Once developed, we could easily test these control rules in our simulation model by replacing the two-way tube control and information objects. Besides, we replaced the empty car manager object with a version that takes into account the throughput time fluctuations resulting from the effects of two-way tubes.

We showed with the simulation study that the new layout is feasible from a logistics perspective. The $150 million can be saved on the investment in construction at the expense of about 15 minutes additional throughput time with 1½ % loss of on time service percentage and 140 additional AGVs (360 instead of 220). As an AGV is estimated to cost $75.000 per
vehicle, the additional investment in AGVs is clearly less than the savings in construction investment, even when considering different depreciation terms (about 10 years for AGVs and 50 years for the infrastructure). We also found that extended terminals at Hoofddorp and Aalsmeer (12 instead of 8 docks each) could reduce throughput times. Furthermore, we recommended to include sufficient waiting space for AGVs at entrances of terminals and two-way tubes in order to prevent congestion. As the queues can accumulate to more than 100 AGVs with an approximate length of 700 meters during peak hours, insufficient space could lead to blocked infrastructure. The civil engineers would not have considered this aspect without our simulation results.

Upgrading the OLS for internal cargo transport at Schiphol

We faced another question concerning trajectory choice in a later project stage. Schiphol Airport wanted to use the OLS more intensively for internal transport between local warehouses of the cargo shippers and logistics service providers. This third trajectory, as depicted in Figure 1, includes 18 mini-terminals without much parking space, see Figure 6.

![Figure 6](image)

*Figure 6. The trajectory designed for internal cargo transportation at Schiphol includes 18 mini-terminals. Such a mini-terminal is not much more than a subterranean branch from the main line with one or two docks and an additional waiting position for an AGV. There is no further parking space.*

Furthermore, the project team considered an alternative location for the rail terminal near the underground passenger rail terminal at Schiphol Airport. Logistical advantages of this
location are the reduction of the length of the link between the rail terminal and Schiphol Airport by about 4 km, and the removal of one two-way tube. On the other hand, the new terminal location is much more expensive, because it has to be constructed underground, and will therefore be built as small as possible with limited space for equipment and buffering.

Once again, we could construct a new model from our object library rather easily. We only had to add a new physical object for the mini-terminals at Schiphol, with corresponding control object to account for the restricted parking space. We also created new information and control objects for modified order scheduling and empty car management, taking into account the limited cargo buffer capacity at the rail terminal. To this end, we roughly modeled the train arrival and departure processes.

We found that the new trajectory reduces throughput times to and from the rail terminal with about 15 minutes, decreases the number of AGVs from 360 to 250, and increases the on time service percentage from 98% to 99%. Considering the facts that (1) this system has to handle more cargo (internal flows on Schiphol Airport) and (2) the OLS has to deal with limited AGV parking space and cargo buffer capacity, this third trajectory is a promising option.

Failure management

An important competitive advantage of the OLS, next to flexibility, is presumed to be reliability. However, resources like AGVs and docks are subject to failures, which may seriously affect system reliability and hence customer service. A logical question from the project team was which failure rate for docks and AGVs would be acceptable, and how to manage failures in the system.

Whereas we could include dock failures very easily in our model, the AGV-failures required serious attention. The location of the failure heavily influences the effect on the logistical performance, and also the type of measure to be taken. An example is an AGV that fails in a
two-way tube, thereby blocking traffic in both directions versus an AGV that fails in a parking spot. We constructed additional objects to handle AGV failures. A recovery vehicle, that is able to drag away a failed AGV, is stationed at several locations in the system. Once an AGV failure is noticed, the AGV failure manager (a new control object) selects the most appropriate recovery vehicle to solve the problem. The route between the location of the recovery vehicle and the failed AGV is cleared by blocking the access to each track on the route. Next the recovery vehicle removes the failed AGV, and the blocks are removed from the tracks as soon as possible so that normal operation can continue. Using this recovery mechanism, we analyzed acceptable failure rates. Besides, we addressed questions about the number and locations of recovery vehicles.

As a key result, we found that dock failures have only little impact on the logistics performance for terminals with multiple docks, whereas AGV failures can have serious consequences. The simulations showed that an AGV failure rate of once per 500 operating hours or less is acceptable. This failure rate was judged to be technically feasible by experts and accepted as a design target. Still, we should realize that AGV failures are a daily issue given the number of AGVs in the system (200-300). Therefore failure management is a task that should be part of the standard operation of the overall OLS control system.

4. Bottom up: The model for terminal design and traffic control

We faced two main challenges regarding the terminal design. The first challenge was to design a traffic control system that is able to control dense traffic in a safe and efficient way. In order to find the best terminal design, a number of alternatives were developed and evaluated by means of simulation. The second challenge was to support terminal design using simulation, taking into account a number of conflicting requirements. For instance, spacious terminals provide AGVs the opportunity to maneuver without hindering each other, which is beneficial to attain short throughput times. On the other hand, the available space is very limited because of existing infrastructure and the high ground prices in the region. A similar
trade-off between space usage and short throughput times is applicable to the rail terminal, where high-speed trains should be loaded and unloaded as fast as possible. Hence space is needed to buffer loads at the platforms.

**Object library**

In parallel with the experiments with network models, object oriented models for terminals, AGV behavior, loading and unloading operations, and traffic control were constructed. The key elements of a terminal are its layout and control system. Analogous to the network simulations, we made a distinction between the physical, information and control objects, see Table 2. Using the objects in our library, it was relatively easy to build alternative terminal layouts.

<table>
<thead>
<tr>
<th>Physical objects</th>
<th>Information objects</th>
<th>Control objects</th>
</tr>
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<tbody>
<tr>
<td>Terminal</td>
<td>Order</td>
<td>Terminal manager</td>
</tr>
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<td>Dock</td>
<td>Script</td>
<td>Order manager</td>
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<td>Parking</td>
<td>Ticket</td>
<td>Empty car manager</td>
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<td>Dock performance measurement</td>
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<td>Dock control</td>
</tr>
<tr>
<td>Cargo</td>
<td>• acceleration, deceleration, status, speed</td>
<td>AGV control</td>
</tr>
<tr>
<td>Cargo storage</td>
<td>histogram, time-way diagram</td>
<td>Semaphore</td>
</tr>
<tr>
<td>AGV driver</td>
<td></td>
<td>Script engine</td>
</tr>
</tbody>
</table>

*Table 2: An object-oriented model library is constructed for the OLS terminal design, in which the control structure is explicitly modeled. Decisions on the activities of physical objects are taken by control objects and based on data provided by information objects. This table gives an overview of the key objects in the terminal simulation model. The library also contains compound physical objects, such as the loop, crossing, parking, and terminal.*

**Outline of the planning and control structure**

The control system that has been designed, has been called TRACES, Traffic Control Engineering System (Evers et al [1999] and Evers et al [2000]). TRACES fulfils the tasks of managing the scarce infrastructure by providing routes to AGVs and by guarding potentially unsafe parts of the infrastructure (e.g. because of collision risk). Analogous to the control systems at the network level, these tasks are decentralized: the AGV executes its script that
contains script statements, describing the route to take and the locations along the route where a conflict might arise. The AGV gets its script from the script dispatcher control object, which has a virtual map of the terminal. When executing its script, the AGV requests access to conflict locations, such as joins or crossings, at local semaphores. If successful, the AGV receives a ticket, which it returns after leaving the conflict location. In Figure 7, this mechanism is depicted.

The scripts can be assigned by the script dispatcher based on a wide range of conditions, such as the density in different areas, the destination of the AGV, information about failures, and the actual status of the AGVs battery. Furthermore intelligence can be added to the scripts as well, so that the AGV can select the least dense route dynamically.

Figure 7: Basic principle of TRACES (Evers et al., [1999]): an AGV reads in its script that, before accessing a conflict location, it has to send a request for a number of tickets to a certain semaphore. This semaphore guards the conflict location. If possible, the semaphore assigns the number of requested tickets to the AGV. Now, the AGV may access the conflict location, such as a join or a crossing. When the AGV has left the conflict location, it returns the tickets to the semaphore. The AGV sends a request for access just before it has to brake for the conflict location, when it would not get permission.
Conquering the conflicting requirements in terminal design

A number of requirements for the terminals were defined, some of them being conflicting. For instance, speed of AGVs versus safety; speed of docking operations versus reliability, and traffic density versus energy use. A large number of criteria had to be taken into account, such as surface of the terminal (m²), possibilities for efficient transshipment to trains, resource utilization (docks, parkings), duration of an AGVs visit, number of loading/unloading operations per hour, etc. In an iterative process with experts on automated transport and transshipment technology, some alternative terminal configurations have been designed, see Figure 8.

To examine the impact of design choices, we focused each time on one or two important requirements, such as small size, fast handling or high reliability. Each terminal concept has been modeled using our simulation library and thoroughly tested using three different types of experiments:

1. **Analysis of terminal capacity**: AGVs arrived continuously at the terminal and we analyzed the speed of operation.

2. **Performance on a peak day at the terminal where the transshipment to the high speed trains should take place.** Two specific characteristics of this load pattern are the dominance of unloading activities by AGVs and the batch arrival and departure of loads because of the train schedule.

3. **Performance on a peak day at the flower auction.** As loading activities dominate, the control rules to park empty AGVs are important.
Figure 8: Four examples of terminal layouts, with their main characteristics. The pictures shown are scaled so the differences in occupied surface can easily be seen. Furthermore each terminal is built out of smaller building blocks, for instance parkings, docks and loops, which are consecutively built out of even smaller building blocks, such as branches, joins and tracks. The more complex blocks have their own traffic control and scripts for the AGVs. This hierarchical way of assembling a terminal out of tested building blocks saved a lot of time in the design process.

The simulation experiments showed that terminal concepts that seemed attractive from a spatial perspective (concept 2 and 3 in Figure 8), perform poorly in terms of transshipment capacity, simply because AGVs cannot reach the docks in time. We found that:

1. The performance of the terminal benefits from limiting the number of AGVs in the terminal. We call this limit the terminal semaphore, because every AGV has to request a ticket for the terminal until the number has depleted.

2. Buffering and parking locations should not interfere with passing traffic.
3. Instead of minimizing the length of tracks, as designers of rail systems do, there should be many tracks in the terminal to be able to spread the vehicles over the available space. This decreases the number of times vehicles have to decelerate for each other. As a result, the average AGV speeds in the terminal increases.

The difference in terminal performance ranges from a maximum of 130 loading and unloading operations per hour in terminal layout 3 to 424 operations in terminal layout 1 with the same number of docks and less surface used.

<table>
<thead>
<tr>
<th>Terminal-concept</th>
<th>Dock performance: AGVs p.h.</th>
<th>Dock performance: operations p.h.</th>
<th>Terminal performance: AGVs p.h.</th>
<th>Time in terminal per AGV (min.)</th>
<th>Surface occupied (m²)</th>
<th>Distance driven in terminal (km)</th>
<th>Number of accelerations &gt;0.5 m/s²</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC1/8 docks</td>
<td>35</td>
<td>53</td>
<td>424</td>
<td>5.5</td>
<td>4480</td>
<td>0.28</td>
<td>10</td>
</tr>
<tr>
<td>TC1/12 docks</td>
<td>27</td>
<td>42</td>
<td>504</td>
<td>5.7</td>
<td>5760</td>
<td>0.34</td>
<td>13</td>
</tr>
<tr>
<td>TC2/10 docks</td>
<td>8</td>
<td>13</td>
<td>130</td>
<td>9.6</td>
<td>5236</td>
<td>0.63</td>
<td>11</td>
</tr>
<tr>
<td>TC3/10 docks</td>
<td>13</td>
<td>20</td>
<td>200</td>
<td>6.8</td>
<td>8492</td>
<td>0.55</td>
<td>8</td>
</tr>
<tr>
<td>TC4/12 docks</td>
<td>21</td>
<td>32</td>
<td>384</td>
<td>8.3</td>
<td>7644</td>
<td>0.62</td>
<td>26</td>
</tr>
</tbody>
</table>

*Table 3: A number of terminal layouts and their performance. The names correspond with the layouts shown in Figure 8. Further we found that in terminal concept 2 and 3 the performance does not strongly depend on longer docking times. Altogether, terminal concept 1 appeared to be most promising, mainly because of the high capacity. Therefore, this terminal concept has been chosen as basis for further development.

**TRACES: Prove as efficient traffic control concept.**

The implementation of TRACES in the terminal simulations has shown that it provides a safe mechanism to route AGVs through a complex infrastructure. Due to its decentralized structure, a new infrastructure including the scripts and semaphores can be constructed rapidly. In complex situations, TRACES allows to include intelligence in the scripts. For example, AGVs can decide which route to take when they arrive at a decision point, so that local congestion can be avoided.
Furthermore we have used semaphores for larger areas as well, such as the terminal. In order to avoid too dense traffic in the terminal, each AGV has to claim a ticket from the terminal semaphore when entering the terminal. In the case that the semaphore has run out of tickets, the AGV has to wait outside, just like in a parking lot. We found that the influence of the terminal semaphore was at least 25% on the number of terminal operations per hour. So the terminal performance improves by avoiding that too many AGVs enter the terminal.

5. Integration, validation and implementation

Simulation as a real-time control system

Because of the scale of the real system and the novelty of technology, it was decided to test the equipment and control framework under laboratory conditions. To this end, a TestSite has been constructed at Delft University of Technology. At this TestSite, ten 1:3 scale AGVs were built, as well as three prototype vehicles (1:1). Furthermore, twelve 1:3 scale docks and 3 prototype docks (1:1) were built to enable the transshipment processes between AGVs and other modes of transport. On the TestSite, the traffic simulation model is used as real-time control system.

Since only a small part of the OLS-system could be implemented at the TestSite, the other part of the system, including physical equipment, had to be simulated. Therefore we linked the simulation to the TestSite control system. When the system runs and a simulated AGV enters the terminal that has been implemented, a real AGV takes the place of the simulated AGV and vice versa.
**Figure 9:** The TestSite in Delft has a 40 x 40 meters concrete floor with around 7000 magnets in a triangular grid for position-finding. At the TestSite 10 AGVs of a scale of 1:3, circa 2 meters long, as well as 3 full-size AGVs can be controlled with the same simulation software that was used in the experiments. Besides there are a number of pieces of loading and unloading equipment that can be arranged flexibly to model a certain kind of terminal. The AGV and dock equipment communicates with the control systems over a wireless network.

The implementation of the OLS at the TestSite has brought the project in a completely new phase. The simulation libraries proved to be able to fulfil an extensive role as a prototype for the real-time control system. The main benefit of this is the reduction of time – a reduction of 9 to 12 months was estimated -- spent with developing the control system, since only small adjustments had to be made to the existing control structure in the simulation model.

The experiments at the TestSite proved to be a necessary step before building the OLS system in reality. Although the software within the physical equipment is almost a copy of the software with which simulations were ran, the real equipment shows all kind of deviations, such as skidding, overshoot or undershoot in curves, and non-functioning sensors. This brings us to the conclusion that right now, tests with physical equipment remain necessary when new technology is transferred from research to the development stage.
Further, we encountered some deviations from the object-oriented fundamentals that had to be corrected. An example is a piece of information on parking places an AGV picked up in our models. In reality, the AGV cannot "read" anything from the physical parking place. Instead, the AGV control should communicate with the parking manager. Hence, the TestSite appeared to be essential to design a robust and intelligent control system.

We conclude that the testing phase, without any consequences for the real system but with nearly the same value in practice, will probably reduce the number of problems during the final implementation significantly.

6. Simulation experiences

As usual in complex design projects with many uncertainties, we faced the problem that the project team needed answers on a very diverse set of questions, while the (simulation) models had not been developed yet. As a solution to this challenge, a strict object orientation and the use of object libraries were key to handling this complexity. To speed up the modeling process, we started with constructing raw versions of the most important objects to give a quick indication of e.g. feasibility and consequences of alternatives. Later on we refined the objects by providing more detail. For example, when the question about the feasibility of the two-way tube system was posed, we first designed a model with simple "traffic light" control, and later on we improved the logistics performance using advanced control objects for two-way tubes. In this way, the object-oriented approach where objects could easily be replaced by other versions proved to be very flexible and powerful. The TestSite results show that the object advantages could be carried as far as exchanging simulated objects with real objects.

The project pressure varied significantly in time and between subprojects. Initially there was less pressure and hence more time to develop the traffic control model, because this is obviously less related to system feasibility. Once properly designed however, we experienced
that the traffic library gave a real boost to the terminal and dock design subproject. Until then, the engineers had been considering a large amount of options without knowing the effect of their options on the main performance indicators. Using simulation, we could quickly distinguish promising terminal and dock designs from designs that seemed to be attractive from a constructional point of view (a compact terminal), but appeared to imply miserable logistics performance. Thereby, the models gave a clear direction to the design process and fostered creativity by the designers. Iterations between designers and simulation modelers were very common in these modeling efforts. During the terminal design experiments, about 40% of the time of the simulation experts was spent on communication and exchanging results with other members of the multidisciplinary design teams.

Furthermore, during the project we experienced a need for information that appeared to be unavailable. Some questions were simply returned to us. A clear example is failure behavior. We had to give indications for the impact of failures on the system performance, but instead of getting an indication for the AGV failure rate, we got the question which failure rate could be acceptable. Again, communicating with experts and showing model results and behavior was the only way to overcome the information shortage. The simulation models and their results had the function of a common reference during these interactions.

Although we are very satisfied with the object-oriented approach, which has proven to yield a very flexible model library, we also experienced that a true object-oriented library is not as easy to construct as theory suggests. When adding objects or modifying our models, we often found additional errors, showing that our library was not as fully object oriented as we expected it to be. And even when we fully complied with the object-oriented approach, we sometimes found that the model did run, but showed low logistics performance. One issue is to design independent control objects, but another issue is to design control objects that are robust to changes in other control objects it has to collaborate with. The latter appeared to be very difficult. Even in an object-oriented approach, adaptation of existing control objects to
cope with changed requirements remained necessary. A proper object-oriented library does not guarantee good logistics performance. Performance is determined by the contents and interaction of objects and not by the library structure.

Last but not least, we found that cooperation in a multidisciplinary project team provides significant benefits in an uncertain development project like the OLS. Still, a multidisciplinary approach remains hard, as experts and scientists sometimes tend to focus on their own area of interest. Because of that, it still occurred that a new design for a part of the system appeared out of the blue. Hence cooperation between a broad variety of experts remains a point of continuous attention for the future. The positive effect of using flexible simulation models as a common reference for the multidisciplinary project team was striking. This can easily be repeated in future complex design projects with a high degree of uncertainty.

7. Conclusions and continuation

Despite the difficulties that we sometimes faced during the project, we can say that our approach appeared to be a fruitful one. The OLS project is a nice example of the way in which simulation tools in combination with operations research methods can support design decisions and facilitate control system design. The object-oriented approach enabled the needed flexibility in answering the many design questions and supported the choice between alternatives in the project. Furthermore, it facilitated mixing virtual (simulation) objects and real (AGV and dock) objects on a TestSite, thereby bridging the gap between simulation and realization.

As a next step in the design process, the control system will be refined and some final questions will be answered, such as the impact of cost-saving terminal modifications and higher AGV speed on certain parts of the trajectory. The project team now works towards realization. Therefore, the attention is currently focused on practical tasks like finalizing the
business plan and organizing a public-private partnership for construction and exploitation.
The aim is to take the go / no-go decision by the end of 2000. Regarding the simulation

group, we now have a powerful library that can be applied to other automated transportation

systems, such as urban underground cargo systems as are currently reviewed for feasibility in

a number of Dutch cities or to automated passenger transportation systems. In this respect, we

also expect new challenges from a possible extension to a multi-modal countrywide system

for freight transport that can prevent Dutch environmental and congestion problems in the 21st
century.

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