Conceptual Design of Automated Freight Transport Systems

Methodology and Practice

Ben-Jaap Pielage
Conceptual Design of Automated Freight Transport Systems

Methodology and Practice

Proefschrift

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Preface

Designing is a challenging activity. Creating things, solving problems is something I have always found interesting. As a young child, playing with wooden building blocks was one of my favourite activities. As I grew older the building blocks got more complicated and gradually I was able to define and create my own building blocks. It all started with practice and eventually led to theory, as is often the case in science. This thesis on the conceptual design of automated freight transport systems presents both, methodology and practice. It is a product of my experiences and research to date.

Although writing a thesis is something you have to do on your own, many more people are involved. My special thanks goes to Joan Rijsenbrij, who inspired and encouraged me throughout my research and with whom I share the interest in this subject, and Gabriel Lodewijks, also a valued supervisor, who guided me in bringing the necessary structure to this thesis. I further wish to thank: Joop Evers, who first introduced me to the OLS project and the idea of writing a thesis; Arjan van Binsbergen and Johan Visser, for showing me that it is possible to combine project work with writing a thesis; André Loos and all other members of TRAIL Research School, who supported me with the many projects throughout the years and ultimately with the realization of this thesis; Jan Katgerman and many others within the OLS project, with whom it was a pleasure to work; and all my colleagues at Delft University, who provided the environment within which I was able to do this research. Last but not least I would like to thank those close to me: my father, mother, family and friends for their support especially towards the end; and Krista with whom I share fond memories. Knowing I left out many names, I would like to thank all those who have supported me in writing this thesis. It has been a challenging experience.

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1 Introduction

This thesis deals with the conceptual design of automated freight transport systems. The first two sections of this chapter define and describe automated freight transport systems and conceptual design in general. The following sections then describe the general problem statement for this thesis, provide an introduction to the underground logistic system project (known as OLS), formulate the goal and scope of the thesis and finally outline the structure of this thesis.

1.1 Automated freight transport systems

What are automated freight transport systems? The dictionary defines a system as “a set of connecting things or parts forming a complex whole, in particular a set of things working together as parts of a mechanism or an interconnecting network” [Oxford Dictionary, 1998]. Transport is defined as to “take or carry people or goods from one place to another by means of a vehicle, aircraft or ship” [Oxford Dictionary, 1998]. Finally, to automate is to “convert a process or facility to be operated by largely automatic equipment”, automatic being “a device or process working by itself with little or no direct human control” [Oxford Dictionary, 1998].

Automated freight transport systems can therefore be defined as:

“A set of interacting elements, working together to take goods from one place to another with little or no direct human control”.

This definition, although formally correct, says little about what automated freight transport systems in practice really look like. To get an impression, an example of an operational automated freight transport system is shown in Figure 1-1; the automated container terminal of Europe Container Terminals (ECT) in the port of Rotterdam.
At this automated container terminal, a container is lifted out of the ship by a manually operated Quay Crane (QC), and placed on an Automated Guided Vehicle (AGV) already available under the crane. Here the fully automated freight transport system takes over. The AGV drives to a stacking area and positions itself under an Automated Stacking Crane (ASC). From this interchange area, the container is lifted from the AGV and placed into the stack (storage area). No manual control is required for this process. For loading the vessel, the process is of course reversed.

In terms of the before given definition, the interacting elements are the QC, AGV and ASC, the goods are containers, and the one place is the ship and the other place in this case is the stack. The highly automated control system makes the elements work together without any direct human control.

Typical characteristics of such automated freight transport systems are: they are complex and often new systems; they take a long time to develop; they have a long lifecycle; they require large investments (often including public money); and they can
have a great impact on their environment. Although there are some inspiring operational examples to be found, two of which are presented in Chapter 2, automated freight transport systems are still in their earlier stages of development. The typical characteristics of automated freight transport systems are discussed in more detail in Chapter 2.

1.2 Conceptual design

The conceptual design phase is a phase in the total lifecycle of a system. The conceptual design phase is one of the first and one of the most important phases in the development of a system, as the decisions made in the conceptual design phase influence all subsequent phases and the total system costs. Figure 1-2 positions conceptual design as a phase in the total lifecycle of a system.

![Figure 1-2 Conceptual design as a phase in the total lifecycle of a system](image)

The first ideas for the system are developed in the initiation phase, together with the initial problem statement and goal. In essence, the conceptual design phase then starts with a problem for which a solution or concept must be found. This concept can then be further detailed, built and put into operation in the subsequent detailed design, construction and operation phases. The system is finally taken out of operation in the retirement phase.

As automated freight transport systems in general have a long lifecycle, require large investments, and can have a great impact on their environment, it is even more
important to pay due attention to the conceptual design phase. The conceptual design phase and the conceptual design process are discussed in more detail in Chapters 3 and 4.

### 1.3 General problem statement

The conceptual design of automated freight transport systems is a complicated matter.

Firstly, the conceptual design of automated freight transport systems is complex because it involves many qualified people of different disciplines. Civil engineering, mechanical engineering, electrical engineering, information and communication technology are only a few of the disciplines that have to work together as a multidisciplinary team.

Secondly, different interested parties each have their own objectives, which are often not yet clearly defined at the beginning of the conceptual design phase. Apart from the financial and economical aspects often put forward by the financers or owners of an automated freight transport system, there are service and performance requirements which are important to the (future) customers or users of the system. Environmental aspects are also becoming more important, as society is demanding efficient sustainable transport systems for the future. The conceptual design phase has to take into account all these different objectives.

Thirdly, the conceptual design of automated freight transport systems is a relative new field. There is little experience with the conceptual design of automated freight transport systems, and there are no standard components, elements or building blocks from which a system can be built. Automated freight transportation systems are often newly developed systems, with new elements and/or new methods for handling and control.

Although people have been designing for many years, and many design methods and techniques have been developed for different fields of engineering, there is no design approach for the conceptual design of automated freight transport systems. The lack of such a design approach became apparent during the design process of a new
automated underground freight transport system (the so-called OLS). This observation formed the main motivation for this thesis.

1.4 The OLS project

OLS is the acronym for “Ondergronds Logistiek Systeem” or “Underground Logistic System”. The goal of the OLS project is to transport flowers and other time-critical cargo through an automated underground transport system between the flower auction in Aalsmeer, Amsterdam Airport Schiphol (AAS) and a railway terminal near Hoofddorp. The OLS should create an undisturbed link between the flower auction at Aalsmeer, AAS and the rest of Europe by means of an international network of high-speed freight trains through the rail terminal at Hoofddorp. An overview of the envisaged layout of the OLS system is presented in Figure 1-3.

![Figure 1-3 The OLS project, overview of the area](image)

The project started in 1995 with a feasibility scan, which was completed in January 1996. The general conclusion was that an OLS could make an important contribution
to improve the accessibility of the Schiphol area and to reduce the pressure on the environment. Several alternative concepts were generated for vehicles, material handling, routing/infrastructure, terminal layout and process control. After some years of developing and testing different concepts, the project was put on hold in 2002 to wait for better economic times. The conceptual design of OLS terminals is used as a case study for this thesis, and presented in Chapter 5.

1.5 Goal and scope of the thesis

The goal of this research project was to develop an approach for the conceptual design of automated freight transport systems and to use this approach in the OLS project. In this large scale project, a useful design approach was required to support the conceptual design of this complex new system. The OLS project, also being a research and development project, proved an ideal environment for developing the new design approach.

This research focuses on the conceptual design of automated freight transport systems and takes an engineering point of view. Although other fields are also important to develop and operate an automated freight transport system, such as economics, business or law, engineering is leading when considering the actual designing of such a system. The developed approach integrates a Systems Engineering approach, acknowledging the complexity of an automated freight transport system, and an Engineering Design approach focusing more on how to actually design a new product or system. In addition to these scientific considerations, the practical implementation also plays an important part in this thesis. The practical use of the design approach is demonstrated in the OLS case study.

1.6 Structure of the thesis

The main structure of this thesis is shown in Figure 1-4. In Chapter 2, the typical characteristics of automated freight transport systems (AFTS’s) are discussed in more detail.
Chapter 3 presents a literature survey on design models and methods potentially useful for the conceptual design of automated freight transport systems. Chapter 4 presents the design approach developed for the conceptual design of automated freight transport systems. Chapter 5 presents the conceptual designing of OLS terminals as a case study. Chapter 6 contains the conclusions of this thesis.

Figure 1-4 Structure of this thesis
2 Characteristics of Automated Freight Transport Systems

This chapter discusses the typical characteristics of Automated Freight Transport Systems (AFTS’s). The first section (2.1) presents two illustrative examples of operational AFTS’s. The following sections then discuss in a more general manner, the typical layers, elements and functions of an automated freight transport system (2.2), the main reasons for developing an AFTS (2.3) and the main issues important for the design of an AFTS (2.4). Section 2.5 presents the summary and conclusions.

2.1 Operational examples of automated freight transport systems

The typical characteristics of AFTS’s can best be derived from an analysis of existing operational systems. This section presents two illustrative examples of operational automated freight transport systems: the automated container terminal of Europe Container Terminals (ECT) in the port of Rotterdam and the automated baggage handling system at Amsterdam Airport Schiphol (AAS).

2.1.1 Automated container terminals of ECT in Rotterdam

The first automated container terminal of ECT, called the Delta Sea-Land Terminal, was developed between 1989 and 1992 and is in operation since 1993. This terminal was developed exclusively for the shipping company Sea-Land. Evolving from this first terminal, two successive terminals were built called the Delta Dedicated East and the Delta Dedicated West. These were taken into operation in respectively 1996 and 1999 [Driel & de Goey, 2000]. All three terminals are still in use today and serve many different shipping companies. Although each terminal was developed using the experiences, insights and knowledge available at that time, the general concept developed for the first terminal is basically unchanged. An illustrative overview of the Delta Dedicated East (DDE) terminal is shown in Figure 2-1. Distinguished are the sections: (i) container vessels, (ii) quay cranes, (iii) quay transport, (iv) stack and (v) landside.
System and Process
The primary process of the container terminal is to unload a container vessel (i) and transport the containers from the quay crane (ii) to a storage area or stack (iv) and from there to the connecting transport mode, either the road, rail or barge (landside, section v), or to a different deep-sea vessel (transhipment). Automated Guided Vehicles (AGV’s) are used to transport the containers between the quay cranes and the stack (iii). The AGV system and stacking system are the two fully automated sub-systems within the terminal. The automated processes are discussed in more detail in the next paragraph. A flow scheme of the ECT container terminal is shown in Figure 2-2, presenting the flow of containers within the terminal and the main sub-systems within the system.
The following description focuses on the automated processes of the terminal (shaded areas in Figure 2-2). After a container is lifted out of the ship by a manually operated Quay Crane (QC), it is placed on an Automated Guided Vehicle (AGV) already available under the crane (see also Figure 2-3 left). Here the fully automated freight transport system takes over. The AGV drives to the stacking area and positions itself under the also fully Automated Stacking Crane (ASC, see Figure 2-3 right). From this interchange area, the container is lifted from the AGV and placed in the stack (storage area). No manual control is needed for this process. For loading the vessel, the process is of course reversed.

There are clear boundaries between the automated system and the manually operated system. On the quayside, this border is formed by the handling of the container on/off the AGV by the crane driver. On the landside, the border lays on the landside interchange area of the stack. Here the containers handled by the ASC are put down on (or picked up from) the ground. At ECT, manned straddle carriers pick up the
containers and bring these to the connecting transport mode. The automated transport system consists of two main (sub-)systems, being the transport system between the QC and the stack and the stacking system itself.

![Figure 2-3 Loading container on AGV (left) & AGV at ASC (right) (Photos by courtesy of ECT)](image)

**Novelty and complexity**

Two visible complex new elements of the automated freight transport system are the AGV and ASC. These pieces of equipment, complex systems in their own, were newly developed for the automated container terminal at ECT. They are however, only a part of the total system. The development of the automated container terminal did not only involve the development of equipment, but also the development of the required process control system and infrastructure. The newly developed process control system had to physically control the equipment and synchronize their actions. It had to prevent dead locks, avoid collisions between the equipment and deal with the sequencing problems. Developing the software for controlling the process was one of the most challenging aspects. New infrastructure was developed to support the equipment (e.g. special rail tracks for the ASC’s and pavement for AGV’s), and also to provide facilities such as cables for electricity, transponders and induction wires for guiding the AGV’s and other facilities for the wireless communication network (Wireless Local Area Network -WLAN). The introduction of this automated freight transport system also required a different operational organization. Although the system is highly automated, there are still people necessary for supervising the automated operation, maintenance and management of the systems. As this was a new and complex system, the restructuring of the operational organization and training of
personnel were also important aspects for the management to consider. The system required an intensive cooperation between the IT-experts, maintenance department and operational management [Rijsenbrij, 1994].

**Motivation**

Main reasons for ECT to develop the automated terminal were cost control and increase of performance and service flexibility under the varying load conditions. Sea-Land, initially preferring a very expensive and space consuming “on wheels” concept using chassis, eventually agreed to this most advanced mode of operation with automatic vehicles and stacking cranes. Although the shipping company also liked this “show-case facility”, the cost advantages and increase in performance proved the deciding factors [Driel & de Goey, 2000].

Even in low labour cost situations, where the investment in automated concepts has a longer pay-back period, there are other driving forces for an automated approach, such as damage control, area utilization and ability to deal with last minute changes [Dobner & Rijsenbrij, 2003]. Another important benefit of automation is safety, not only because of the reduction of accidents among personnel, but also for the cargo being handled, as there are less people involved with the physical handling [Wormmeeester, 2000]. The experience in the industry has shown that an early investment in automation, including the related process re-design, finally resulted in substantial cost savings and better response to the market [Dobner & Rijsenbrij, 2003].

**Design**

The conceptual design of the first automated terminal took about 3 years. This was followed by the detailed design phase from 1988 to 1990, the prototyping from 1989 to 1991, a pilot plant operation from 1990 to 1992, and a commissioning period from mid 1992 to mid 1993 [Rijsenbrij, 2000]. During these long periods of time, many new elements were developed, tested and then integrated into a very novel and complex system. The introduction of a large number of new custom-made elements all at the same time, combined with the high level of automation of all these elements and the development of a new overall process control system able to deliver the service/performance required by the client (in this case Sea Land), caused many difficulties. ECT, apart from being the terminal operator, also performed the task of
system integrator. Integrating all the different elements proved to be a challenging task, not only because of the start-up and interface problems of the components, but also because of the many parties involved (e.g. subcontractors, shipping lines, transportation companies) and the different development times required for the different major components [Rijsenbrij, 2000]. In general, developing a new terminal concept with enough flexibility to deal with the stochastic processes, with many last minute changes, varying call sizes, and at the same time providing the desired service not only to seagoing vessels, but also to the other connection transport modes, and all this for reasonable costs, proved to be a major challenge. Although there were considerable difficulties with the development of this first automated terminal, the concept eventually proved itself, and was copied for the second and third automated terminal at ECT in later years. Another automated container terminal recently opened in Hamburg Germany is taking the automation even further, as now the loading and unloading of trucks at the landside also has been partly automated. The general concept of the terminal handling system, using AGV’s and ASC’s has however not changed.

2.1.2 Automated baggage handling at Amsterdam Airport Schiphol

The newly developed automated baggage handling system at Amsterdam Airport Schiphol (AAS) is another example of an operational automated freight transport system. This project started in 1998, and the system has been in operation since 2002 [Broekman, 2003]. It connects to the existing baggage handling systems, located in the basement of the Schiphol terminal buildings, and transports the baggage to and from the D-pier, where most international flights of KLM and its partners arrive and depart. The new system transports each bag separately, using Destination Coded Vehicles (DCV’s) and is also known as Bagtrax (the name given by the developer of the system, Vanderlande Industries). Figure 2-4 presents an overview of the baggage handling system at Amsterdam Airport Schiphol. The new Hold Baggage Screening (HBS) system screens all the baggage coming from the check-in counter destined for the D-pier.
System and process
A flow scheme of the baggage handling system, comparable to the flow scheme presented for the ECT container terminal, is presented in Figure 2-5. The most important sub-systems here are: the Tug and Dolly system, the Conveyor Belt systems, and the Bagtrax system. The tugs and dollies are used to transport the baggage to and from the airplanes. The conveyor belts (so-called laterals) between the Tug and Dolly system and Bagtrax system are used to buffer the baggage temporarily and to feed bags into the Bagtrax system or retrieve bags from the Bagtrax system.
The Bagtrax system is used as the main transport and sorting system. The Early Baggage Storage (EBS) system is used to store transfer-baggage with long connection times, but can also be used for baggage which is checked in very early. A conventional conveyor belt system is used as an interface with the passengers, both at the check-in desks and at the baggage reclaim area.

The Bagtrax system is used for transfer-baggage and baggage checked-in at the check-in counter. All baggage from airside to landside (baggage with AAS as final destination) is transported by tugs and dollies directly to the baggage reclaim area.

The EBS system is only used to store so called “cold” baggage, with several hours waiting time before departure. The “hot” baggage is transported directly to its required destination.

![Figure 2-5 Flow scheme for new baggage handling system at Schiphol](image-url)

The main process of the automated baggage handling system is discussed in more detail below, followed by some of its characteristics. The process is described, starting at the check-in counter.
After the baggage has been checked-in and labelled at the KLM check-in desk, it is transported by a belt conveyor to a restricted baggage handling area in the basement. Here, the label attached to the baggage is scanned and the baggage itself is weighed and screened using X-ray. Baggage destined for the D-pier, where most European international flights of KLM and its partners arrive and depart, is transferred onto a Standard Baggage Tray (SBT) which is positioned on a cart, as shown in Figure 2-6 (left). The cart runs on an aluminium track (Figure 2-6 middle). The cart is driven by linear induction motors positioned between the tracks, which can drive the carts up to a speed of 6 m/s. Depending on the departure time of the flight, the baggage is either transported directly to its destination at the pier or temporarily stored in the Early Baggage Storage (EBS). At the EBS, the SBT is lifted from the cart and placed into the EBS using an Automated Storage and Retrieval System (AS/RS) as shown in Figure 2-6 (right). The EBS does not only store baggage that has been checked in early, but stores transfer-baggage with long connection times as well. In fact, most of the baggage handled in the EBS is transfer-baggage.

<table>
<thead>
<tr>
<th>Loading baggage</th>
<th>Transport</th>
<th>EBS AS/RS</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Loading baggage" /></td>
<td><img src="image2.png" alt="Transport" /></td>
<td><img src="image3.png" alt="EBS AS/RS" /></td>
</tr>
</tbody>
</table>

**Figure 2-6 Images Bagtrax Transport System I (Photos by courtesy of Vanderlande Industries)**

If the baggage is wanted at the D-pier, the SBT is retrieved from the EBS and again placed on a cart (Figure 2-7 left). The cart then transports the baggage to its destination, where the baggage is unloaded as shown in Figure 2-7 middle. The baggage is thus collected on a conveyor belt (lateral), ready to be handled manually into a baggage cart or Unit Load Device (ULD). The connecting transport to the airplane is done in a conventional manner with tugs and dollies. The conveyor belt thus connects the manual part of the system with the fully automated part of the
system, both for feeding baggage into the system and for collecting baggage from the system. Figure 2-7 right shows how transfer baggage is handled manually from the ULD’s onto the belt conveyor.

<table>
<thead>
<tr>
<th>Placing SBT on cart</th>
<th>Unloading baggage</th>
<th>Transfer Baggage</th>
</tr>
</thead>
</table>

**Figure 2-7 Images Bagtrax Transport System II (Photos by courtesy of Vanderlande Industries)**

In order to meet the performance and reliability requirements, the transport system was split into two independent parallel sub-systems with separate tracks, power supplies, motors, control system etc. Furthermore, the EBS was built as a full redundant random access storage system, where each position in the stack can be reached by two independent stacker cranes. The total system counts 650 carts, 3650 SBT’s, 3000 EBS slots, 5 kilometres of track and has a peak handling capacity of 6,000 bags/hour.

**Novelty and complexity**

Although the type of cargo and its handling are very different when compared to e.g. container transport, this automated baggage handling system also clearly reflects the novelty and complexity which are so characteristic for automated freight transport systems. In this case, new elements developed were e.g. the Standard Baggage Trays (SBT’s) and the special carts to carry these. The complexity however, lies more in the combination of all the different elements into one new system and the integration of this system with the already existing baggage handling system at AAS. The development of the process control system proved to be one of the major challenges for this project [Broekman, 2003].
Motivation
The reason for developing this automated transport system was not only the need for higher transport speed and handling capacity of the system, but also the higher traceability and reliability of the system. The reduction of mishandled bags should ultimately result in a lower cost per bag handled [Broekman, 2003]. Lately, security is becoming a more important issue in air transport, a trend that stimulates further implementation of highly automated baggage handling systems as human interference is limited.

Design
As with the development of the automated container terminals of ECT, the development of this automated baggage handling system for Schiphol took a long period of time. The first ideas for Bagtrax date back to before 1989. After developing and testing the first concepts in the early 1990’s, Vanderlande Industries developed a full scale test track at their own facility to further test and demonstrate the system. In 1993 the inhouse developments were completed and in 1994 a first smaller system was developed for Oslo. This system became operational in 1998, four years after the project started. A second system developed for Zurich has been in operation since 2000. The system developed for Schiphol is the third system developed by Vanderlande Industries, but still took 4 years to develop, a period of time very much needed according to Vanderlande’s project manager [Broekman, 2003].

In this respect it is interesting to briefly discuss the problems encountered with the development of a similar baggage handling system for Denver International Airport (DIA). Mainly due to complications with the baggage handling system, the airport opened sixteen months behind schedule in February 1995 instead of in October 1993 as was initially planned, costing all parties involved a significant amount of money.
Many of the problems stem from the fact that, despite the central importance of the automated baggage system, its design was largely an afterthought [Neufville, 1994]. The baggage handling system was detailed well after the construction of the airport was underway and started only about two years before the airport was to open.
Part of the problem was the already completed design of the infrastructure; the tunnels designated to accommodate the baggage handling system were constructed before the baggage handling system itself was designed. As baggage handling is an important aspect of airport operation, the architectural and civil design of the airport should have
been done in cooperation with the design of the baggage handling system right from the start of the project. Furthermore, the novelty and complexity of the system proved problematic. Apart from the highly visible mechanical problems with the equipment, such as the jamming of carts and the misalignment of conveyor belts and carts, the overall control of the system proved difficult to manage. Line balancing (getting the empty carts at the proper place at the proper time) was a major problem, and one of the main reasons for the lack of performance (capacity) [Neufville, 1994].

Learning from the Denver case and from the systems developed in Oslo and Zurich, the AAS system was developed with special attention to advanced product development and testing (Factory Acceptance Test), and computer simulation to test the total performance of the system before it was installed. This proved very successful and greatly reduced the problems encountered and time needed at the Site Acceptance Tests (SAT). In fact, the testing and acceptance of the control system at maximum capacity was done by computer simulation [Broekman, 2003]. Furthermore, attention was paid to the phasing and management of the project, as this also was an area of concern in the Denver case. During the development of the Denver system, many things were changed without considering the full consequences for the whole system. Ideally one should not change the design once the design phase has been finished. However, due to problems encountered in a later phase or changing circumstances, modifications are sometimes necessary. During the development of the AAS system, the requirements of KLM and AAS also changed because of outside events. Dealing with these changes and coming to reasonable agreements with the parties involved (in terms of time, money and quality) were important aspects of project management [Broekman, 2003].

Another lesson learnt from the Denver Case is to consider all aspects or layers of a system during the design phase. The conceptual design phase of such a system should include the equipment and the control system as well as the required infrastructure. The next section (2.2) discusses these layers in more detail.

The Denver case also shows that it is very risky to fully rely on a newly developed complex automated freight transport system. Within an operational environment, one should always consider alternatives and backup systems.
2.2 Layers, elements and functions of AFTS’s

By analyzing different existing automated freight transport systems; several characteristic layers, elements and functions can be distinguished. This section presents a layer model characteristic for automated freight transport systems and discusses the different types of elements or sub-systems generally found in AFTS’s. The functions of these layers and elements are also discussed in this section, together with their structuring capabilities and application for the conceptual design of automated freight transport systems.

2.2.1 Layer model for AFTS’s

By modelling an automated freight transport system using layers, a structure can be presented where each layer facilitates or serves the layers above and needs the layers below. Inspired by the layer schemes discussed by [Schaafsma et al., 2001], the following layer model is presented for automated freight transport systems. (See Figure 2-8)

```
Transport Market

Operational Organization

Control system

Equipment

Infrastructure
```

*Figure 2-8 Layer model for AFTS*

Reading the layer model from top to bottom; the operational organization, which operates in a larger transport market, needs the control system to control the equipment, which in turn requires the underlying infrastructure. Starting at the bottom layer; the infrastructure supports or facilitates the layers above, the equipment serves
the control system, which in turn serves the operational organization fulfilling the service demands from the market.

The layer model allows for a functionally oriented structuring of an automated freight transport system, as also found in other descriptions of transport systems [Schaafsma et al., 2001] & [Binsbergen & Visser, 2001]. A common distinction made, when describing the organization of transport, is between the functions of: carrier (e.g. train, automobile, airplane etc.), facility provider (rail, road or airport) and planner/controller (often an agency which controls to some extent the actions of carriers or providers of facilities) [Morlok, 1978]. These functions can be linked with respectively equipment, infrastructure and control in the layer model as presented in Figure 2-8. The four layers of an AFTS and their main functions are shown in Figure 2-9.

Although this functional structuring with layers is often used to organize and structure operational transport systems, such as the current road and in some cases the rail transport systems, it may not always be the best structure or sub-division for the conceptual design of automated freight transport systems. As discussed in the previous section, it is important to integrate all the layers in the conceptual design phase. The Denver case shows the adverse consequences of not considering the equipment and control system, as well as the required infrastructure in an integrated manner during the conceptual design phase. So, although it is important to distinguish
and consider the different layers of AFTS’s during the conceptual design phase, it is perhaps not the best functional structure to be used for structuring the conceptual design of such a system. The functional structuring of AFTS’s is discussed in more detail in the next sections (2.2.2 & 2.2.3).

2.2.2 Typical elements of AFTS’s

Apart from structuring automated freight transport system by using layers, as discussed in the previous section, AFTS’s can also be represented as being subdivided in different types of elements or sub-systems with different functions. This section discusses several of these typical elements or sub-systems of AFTS’s, using the same examples discussed in Section 2.1.

For the automated container terminals of ECT (see Figure 2-1 and Figure 2-2) the following elements or sub-systems are distinguished:

- Quay cranes.
- Quay transport / AGV.
- Stack.
- Straddle carrier.

For each element or sub-system, main functions can be defined. The main elements or sub-systems of the ECT container terminals with their main functions are presented in Figure 2-10.

<table>
<thead>
<tr>
<th>Element / sub-system</th>
<th>Main Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quay crane system</td>
<td>Handling / Loading-Unloading</td>
</tr>
<tr>
<td>AGV system</td>
<td>Transport</td>
</tr>
<tr>
<td>Stack system</td>
<td>Storage &amp; Handling</td>
</tr>
<tr>
<td>Straddle carrier system</td>
<td>Transport &amp; Handling</td>
</tr>
</tbody>
</table>

Figure 2-10 Main elements and functions of ECT Container terminals
For the automated baggage handling at AAS (see Figure 2-4 and Figure 2-5) the following elements or sub-systems are distinguished:

- Tugs and Dollies.
- Conveyor belts.
- Bagtrax.
- EBS.
- Conveyor belts.

The main elements or sub-systems of the baggage handling system at AAS with their main functions are presented in Figure 2-11.

<table>
<thead>
<tr>
<th>Element / sub-system</th>
<th>Main function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tug and dolly system</td>
<td>Transport</td>
</tr>
<tr>
<td>Conveyor belt system</td>
<td>Transport &amp; Buffer</td>
</tr>
<tr>
<td>Bagtrax system</td>
<td>Transport &amp; Handling</td>
</tr>
<tr>
<td>EBS system</td>
<td>Storage &amp; Handling</td>
</tr>
<tr>
<td>Conveyor belt system</td>
<td>Transport &amp; Buffer</td>
</tr>
</tbody>
</table>

Figure 2-11 Main elements and functions of Baggage handling system at AAS

As demonstrated above, several different functions of automated freight transport systems can be defined by analyzing similar existing systems. This is a technique often used for designing products or systems. The different type of elements or sub-systems within the system, with their specific functions, can often be regarded as separate systems themselves. Various possible solutions or concepts can then be developed to fulfil that specific function. As such this type of functional structuring can help to structure the conceptual design process. The next section (2.2.3) discusses the functional structuring in more detail.

2.2.3 Functional structuring of AFTS’s

There are different ways to functionally structure automated freight transport systems, as already demonstrated in the previous sections (2.2.1 and 2.2.2).
The main functions defined for the layer model (Figure 2-9) were: Management, Planning & Control, Carrier and Support. The main functions defined for the different elements or sub-systems distinguished for both, the container terminal (Figure 2-10) and the baggage handling system (Figure 2-11) were: Transport, Handling, Storage and Buffer. These main functions can be sub-divided further in sub-functions, sub-sub-functions and so forth. Such functional structuring can help to sub-divide complex large-scale automated freight transport systems into more manageable smaller sub-systems.

For the conceptual design of automated freight transport systems, the functional structuring using layers is probably not the most suitable, as already discussed in Section 2.2.1. Layers should be considered in a more integrated manner during the conceptual design phase. For the conceptual design of automated freight transport systems, a functional structure is preferred which allows for a sub-division into sub-systems which can be regarded as separate systems themselves, as discussed in Section 2.2.2. The functional structures derived from analyzing the existing AFTS’s allow for such a sub-division. The sub-systems, with their specific functions, can be regarded as separate systems for which possible solutions or concepts can be developed. This kind of functional structuring furthermore allows for a better integration of the different layers.

In this thesis, no general applicable functional structure for the conceptual design of automated freight transport systems is defined. Although the functions defined in this section can be seen as characteristic for AFTS’s, several other functions can be defined. The functions defined can vary from system to system and from person to person, depending on a person’s perspective or background. Functional structuring can aid the conceptual design of automated freight transport systems, but must not be applied or interpreted too strictly. Analyzing existing similar systems and focusing on characteristic functions can help to structure the conceptual design process and deal with its complexity. However, one should take care not to limit oneself to functional structures derived only from other already existing systems, but also consider other possibilities. As such, developing a functional structure is in itself part of the conceptual design process. The use of functions for the conceptual design of automated freight transport systems is further discussed in Chapters 4 and 5.
2.3 Motivations for developing AFTS’s

General reasons for automating production facilities are: to increase labour productivity; to reduce labour costs; to mitigate the effects of labour shortages; to reduce or eliminate routine manual tasks; to improve worker safety; to improve product quality; to reduce manufacturing lead time; and to accomplish processes that cannot be done manually and to avoid the high costs of not automating [Groover, 2001]. Although the main reasons for developing an automated freight transport system may differ and can vary per project, costs, performance and safety or security are important recurring issues in both examples discussed in Section 2.1. In general it is a combination of these issues, which initiates the development of an AFTS.

For ECT, long term cost control was one of the major reasons to consider automation. Automation not only reduced labour costs, but also reduced costs related to damage and loss of equipment and cargo on the terminal. Furthermore, automation would provide a constant and reliable service 24 hours a day, 7 days a week. The cost savings, not only for ECT but also for Sea-Land, combined with the improvement in service, proved decisive for developing the first automated terminal at ECT. The advantages eventually proved themselves and ECT continued to develop a similar second and third automated terminal in the following years.

Although cost reduction is always important, improving performance can be an even greater motivator for developing an AFTS. For AAS, and even more so for KLM, performance (apart from costs) was the main reason for developing the automated baggage handling system. Not only the higher transport speed and capacity of the system, but also the improved traceability of baggage and reduction of mishandled baggage were the main motivators for developing the automated system. As baggage handling is an important part of the operation at any airport, and many bags are handled every year, performance and costs are both important aspects to consider.

Safety and security are becoming more important aspects in the transportation industry and can influence the development of automated freight transport systems. Automation will reduce the number of people required to physically handle the cargo, thus improving the safety and security of the system. Automation will not only reduce
the number of accidents among personnel, but also helps to secure the cargo being transported. For containers, but even more so for air cargo, security is becoming a very important aspect.

2.4 Design issues of AFTS’s

Designing an automated freight transport system is a challenging task. Apart from considering the different layers, elements and functions already discussed in Section 2.2, the following aspects should also be taken into account when designing AFTS’s:

- The long time span required for the design and development of such a system, and the many changes that will take place during this period.
- The various parties involved or interested in the project and their sometimes unclear or conflicting requirements or objectives.
- The many different disciplines and types of people required for designing such new and complex systems.
- The special attention required for the process control of such fully automated systems.

One of the lessons learnt from past projects is that the design and development of AFTS’s takes a long time. For the first automated container terminal at ECT, the conceptual design alone took about 3 years. This was followed by another 3 years for detailing, prototyping and a first pilot phase before the system was taken into operation. The development of the automated baggage handling system at Schiphol also took a long time. The system at Schiphol was built only after several years of in house development and testing and several successful smaller projects. Many of the problems encountered at Denver airport were due to the tight schedule and late start of the design of the baggage handling system. Recognizing that the successful implementation and operation of a novel, complex automated baggage handling system is difficult, and is likely to take a long time, provides the basis for avoiding the problems with automated systems [Neufville, 1994].

During these long periods of time, things are bound to change. Some changes come from within the project, as insights change during the development of the system, while others come from outside the project, due to external developments. Changes
took place during the development of the automated container terminal at ECT as well as during the development of the automated baggage handling systems at Schiphol and Denver. Dealing with these changes is an important aspect of designing automated freight transport systems.

The various parties involved or interested in the project all have their own requirements or objectives. At the beginning of the project, during the conceptual design phase, the objectives can often be unclear, as parties involved do not yet fully know what to expect. This may also be one of the reasons for changes to occur during the conceptual design phase, as discussed in the previous paragraph. Furthermore, the parties involved will have different and possibly conflicting objectives. Characteristic is the balancing between cost (prime objective of the owner/operator of the system) and performance (prime objective of the client of the system). For instance, designing and dimensioning a system on the peak capacity required by the client is very expensive, especially for systems which have a very variable load pattern, as is the case with the AFTS’s described in this chapter. On the other hand, designing and dimensioning the system on e.g. maximum utilization or average load will often greatly reduce the performance of the system under peak loads. Defining clear objectives and criteria for evaluating the different possible options or concepts is an important aspect in the conceptual design phase.

The design of an automated freight transport system involves many different disciplines and many different types of people. An integrated approach is needed, taking into account the infrastructure, equipment, control system and operational organization. This requires e.g. generalists to keep the general overview of the project, but also various specialists to design and develop the many different, often new, elements of the system. Apart from distinguishing between different disciplines, such as Civil Engineering, Mechanical Engineering, Electrical Engineering and ICT, one should also distinguish between different types of people, such as generalists vs. specialists or problem-focused people vs. solution-focused people. Furthermore, it is important to involve the right people at the right time. In this respect it is also important to recognize that not all layers or elements of a system have the same development time. This has often lead to problems in the past, as layers or element
with the longest development times (e.g. infrastructure) were detailed and developed before the other layers or elements were considered.

Finally, the process control system requires special attention when designing such highly automated systems. Integrating and controlling all the different elements in such a way that the whole system delivers the required performance proved challenging for both, the automated container terminals and the automated baggage handling systems discussed in Section 2.1. Developing and testing the control system at an early phase in the project using computer simulation proved essential. As such, computer simulations should be seen as an integral part of the conceptual design process (see e.g. [Saanen, 2004]).

All these aspects should be considered for the conceptual design of AFTS’s and are further discussed in the Chapters 3, 4 and 5.

2.5 Summary and Conclusions

The automated container terminals of ECT in the port of Rotterdam and the automated baggage handling system at Amsterdam Airport Schiphol have been presented as operational examples of automated freight transport systems (AFTS’s). The main processes, novelties and complexities, reasons for development and most important design issues have been discussed. Although these two automated transport systems differ as they handle very different types of cargo, they also have much in common. The more common aspects have been discussed in a more general manner as “characteristics” of AFTS’s.

Characteristics of automated freight transport systems are:

- The novelty and complexity of the system.
- The high investments costs.
- The long lifecycle of the system.
- The long development time and the many changes that will take place during that period.
• The many different parties involved and their sometimes unclear or conflicting objectives.
• The balancing between cost and performance as main criteria.
• The many different disciplines and types of people involved.
• The special attention required for controlling such a highly automated system.
• The four typical layers to be integrated in the conceptual design phase: Infrastructure, Equipment, Control systems and Operational organization.
• The functional structuring of a system, using functions such as Transport, Handling and Storage, which allow for a sub-division into sub-systems that can be regarded as systems themselves and which furthermore allow for an integration of the four layers per sub-system.

A design approach for the conceptual design of automated freight transport systems should reflect on the characteristics discussed in this chapter. These characteristics have therefore been used to guide the literature survey on design methodology presented in the next chapter, and to formulate the criteria eventually used to evaluate the design models.

Three main aspects are defined in order to sub-divide the different type of criteria:

A. Project Structure, focusing on how the models help to structure a large complex project.
B. Design Process, focusing on how the models represent the actual design process.
C. Multi-X, focusing on how the models show the multiple layers, disciplines, types of people and stakeholders involved in the conceptual design of automated freight transport systems.

These main aspects are discussed further in Section 3.3.
3 Literature Survey on Design Methodology

This chapter presents the results of a literature search into the state of the art of design methodology, possibly relevant for the conceptual design of automated freight transport systems. The literature research was done to present the state of the art and to investigate whether or not (parts of) current existing models could be used for the conceptual design of automated freight transport systems.

When focusing on the design of new and complex technical systems such as AFTS’s, two interesting fields of study can be distinguished in literature: Systems Engineering (SE) and Engineering Design (ED). Models developed in both fields are discussed in Sections 3.1 and 3.2. The models are evaluated in Section 3.3 by using evaluation matrices. Section 3.4 presents the summary and conclusions.

3.1 Systems Engineering Models

Systems Engineering (SE) deals with the engineering of complex systems. SE considers the system as a whole rather than focussing on the individual components, and often takes a broader perspective, contemplating the whole lifecycle of a system. SE enables a more structured development of a system.

It is difficult to pinpoint the exact origin of systems engineering. One can for instance think of many ancient examples, such as the construction of the pyramids in Egypt or the development of the extensive water networks by the Romans, which would have required a systematic approach to develop. Systems engineering as a way of thinking or ”systems thinking”, is therefore not new and can be traced back many centuries. The expression “Systems Engineering” however is more modern, and is believed by most authors to originate around the Second World War.

One of the first organizations that used the term Systems Engineering was probably the Bell Telephone Company [Hall, 1962]. In his early publication, Arthur D. Hall introduced Systems Engineering as a methodology for developing complex systems.
Hall, at that time working for Bell Telephone Laboratories Incorporated, used the development of a radio relay system as a case study, to illustrate the SE process for developing a large-scale communications network in the USA.

Although most textbooks on SE refer to [Hall, 1962] as one of the first publications on SE, early developments in the military and space sector are also mentioned when discussing the history of SE. The race to space and the race to develop missiles with nuclear warheads, are seen as main reasons for SE to evolve as a branch of engineering during the late 1950’s in the USA [INCOSE, 1998]. A number of military standards were developed to help the engineering of these complex systems. An early publication is [MIL-STD-499, 1969], which was issued in 1969 to assist the government as well as the contractors in supporting the defence acquisition programs. A more recent publication by the Department of Defense [DoD, 2001] discusses some of the experiences gained during the last decennia of SE practices in the military. The National Aeronautics and Space Administration (NASA) in the USA developed a Systems Engineering Handbook as a reference work for systems engineers within NASA. It provides a generic description of systems engineering as it should be applied within NASA, with many NASA specific elements [NASA, 1995].

The International Council on Systems Engineering (INCOSE), also developed a SE Handbook. Although there is a clear relation between INCOSE and the DoD, INCOSE takes a broader perspective considering governmental as well as commercial applications. INCOSE was founded in 1990 to develop, nurture and enhance the interdisciplinary approach and means to enable the realization of successful systems [INCOSE, 1998]. INCOSE publishes several works on SE, including their quarterly journal, proceedings of their annual conference as well as an SE Handbook [INCOSE, 1998]. Furthermore, INCOSE is also involved in the development of SE standards such as [EIA 632, 1998] and [IEEE 1220, 1998]. More information can be found on their website (www.INCOSE.org).

Apart from the publications by institutes discussed above, there are many other works on SE such as, [Royce, 1970] who introduced a waterfall model for software engineering and [Boehm, 1988] who developed a spiral model for software development. Andrew Sage has published an interesting textbook on system
management for information technology and software engineering [Sage, 1995]. Other publications focusing more on SE and management are for instance [Blanchard, 1998] and [Stevens et al., 1998]. Another well-known publication is from [Checkland, 1981] in which he proposed a so-called soft systems methodology opposed to what he calls the hard systems methodology, although both are found to be conceptually similar [Sage et al., 2000]. There are many more publications on SE. A comprehensive overview of Systems Engineering literature and other related systems theory studies is presented by [Sage et al., 2000].

It is neither practical nor desirable to discuss all models developed within the field of SE in this thesis. This section (3.1) is therefore limited to the most well-known models found in literature. Although other models may differ on certain details or perhaps focus more on a specific aspect, they are mostly similar to the SE models discussed in this chapter. In this research no other models have been found in literature, which better represent the total development of a system. In all, it is fair to say that a representative overview is shown of the state of the art of the models developed within the field of SE. Section 3.1.1 first presents some of the matrix models developed by Hall. Section 3.1.2 then presents two different spiral models and Section 3.1.3 presents two different waterfall models. The V-process model is discussed in Section 3.1.4, and the models developed by the DoD and INCOSE are presented in Section 3.1.5.

### 3.1.1 Matrix models by Hall

The structuring of the SE process using a matrix, with phases and steps, can be traced back to [Hall, 1962]. Phases provide the main structure of the process in the time dimension, while steps (or elements of the fine structure [Hall, 1962]) are exercised in every phase. The Systems Engineering Activity Matrix introduced by Hall is presented in Figure 3-1. The phases are presented vertically and the steps horizontally, every box representing an activity. The phases again show the time sequence of activities covering the whole lifecycle of a system, while the steps show the logical sequence of activities to be taken in every phase.
Figure 3-1 Activity Matrix [Hall, 1989]

The Hall activity matrix provides a plain and simple structuring and visualization of the SE process. It presents all the activities in a straightforward manner (e.g. $A_{16}$ are activities in the decision making step 6 in the program planning phase 1). However, the model suggests a very linear approach, all activities presented as following one after the other. It does not show the iterative character of the design process, nor does it allow for any other relation or dependency to be shown between the steps, phases or activities as this would rapidly make the model unreadable. Although the model does not represent the actual design process, it does allow for a clear structuring using phases and steps and clearly reflects the many different activities to be performed during the development of a complex system. The activity matrix developed by Hall is one of the first models which presented the whole lifecycle of a system and clearly distinguished between phases and steps, and as such is an important first model to discuss.

Apart from the 2D matrix shown in Figure 3-1, Hall also developed a 3D matrix including the different professions required to develop a system. This matrix is presented in Figure 3-2.
The comments made for the 2D matrix also apply for this 3D matrix. However, an often-heard comment on models of the design process is that they do not include people. This 3D matrix presented by Hall clearly presents professions (disciplines), making it possible for professionals to position themselves within the project (e.g. I am a lawyer, working in the system development phase of the project, and busy with the decision making step, see Figure 3-2). As such, this 3D model is helpful. It shows the grandeur and different dimensions typical for a large and complex project. It also emphasizes the many different disciplines necessary to develop such a complex system. However, similar to the 2D activity matrix, it does not represent the actual design process as no relations or interactions can be shown between the phases and steps in the model, as this would rapidly make the model unreadable.
3.1.2 Spiral models

In addition to the rather straightforward matrix models discussed in Section 3.1.1, spiral models have been introduced to better emphasize the “dynamics” in the SE process. Based on his activity matrix, Hall developed a spiral model to better emphasize the iteration and convergence of the SE process (see Figure 3-3) [Hall, 1989].

The spiral model shows the series of one-way connecting activities (a_{11}, a_{12} etc.) also used in the activity matrix, spiralling inwards towards the centre. This represents the convergence of the SE process. Feed-forward and feed-back connections (arrows) are added, permitting any activity to follow any other activity in any possible sequence, thus indicating that the design process is an iterative process. The seven steps, which are repeated in every phase, are presented along the outside of the spiral. Each cycle, starting from the outside and travelling inwards, represents a phase.
Although this spiral model better presents the convergence and iteration as characteristics for the design process, it does not improve the comprehensiveness or clarity of structure that was presented by the activity matrix. The spiral model however can be used to emphasize a certain aspect, in this case the convergence of the design process.

A different spiral model by [Boehm, 1988] for the development of software is presented in Figure 3-4. Here the emphasis was on visualizing the increase in cost during the development process instead of the convergence.

![Figure 3-4 Spiral model by [Boehm, 1988]](image)

This spiral model starts in the centre and spirals outwards. The length of the radius measures the cost of the project. To enhance legibility, the spiral is not drawn to scale. This model stresses a risk driven approach. To minimise risk, a prototype is made in
every cycle. On each cycle, sufficient risks are to be removed in order to proceed to the next cycle.

Summarizing, spiral models can be used to emphasize and visualize certain aspects within a cyclic process, such as convergence or cost increase. They are also useful to visualize the repetition of logical steps during each phase. Although they better visualize certain aspects characteristic for the design process than the matrix models, they are still not very useful for structuring and guiding the total design process.

3.1.3 Waterfall models

The term "waterfall model" was introduced by [Royce, 1970]. He developed the model presented in Figure 3-5 (left) for developing software. Since then, many other waterfall models have been developed. For instance, [Sage et al., 2000] developed a waterfall model containing seven phases with feedback loops as shown in Figure 3-5 (right).

![Figure 3-5 Waterfall models by [Royce, 1970] (left) & [Sage et al., 2000] (right)](image)

Waterfall models are often used in practice as they present a clear and simple sequential structuring. This makes them ideal for presenting sequential phases but less
useful for presenting iterative steps. Although the notion of iteration can be introduced using the feedback loops as shown in Figure 3-5 (right), the waterfall model primarily suggests an ongoing motion (down the waterfall). As such, waterfall models are considered useful for presenting sequential phases (preferably without the feedback loops), but less appropriate for presenting iterative steps.

### 3.1.4 V-process model

The V process model presents the phases in a V shape, emphasizing the decomposition sequence of the first half towards a lower and more detailed level, followed by the integration sequence of the second half. A V-process model by [Sage, 1995] is presented in Figure 3-6. The phases used by Sage in the V model are similar to those presented in his waterfall model but adapted to software design. The different horizontal levels indicate different levels of detail requiring different perspectives. Sage indicates three different perspectives, being that of customers (top level), system architects (mid level) and programmers (bottom level) and characterizes these perspectives as being dominantly purposeful, structural and functional.

![Figure 3-6 V process model for software design by [Sage, 1995]](image-url)
The horizontal relations present an interesting extra relation between the otherwise sequential phases. The V-process model suggests an interrelation between two different phases, separated in time, which require the same perspectives. This is an interesting model as it reveals some of the difficulties encountered with developing AFTS’s. First of all, as an AFTS has such a long development time, it is difficult to involve the same people or types of people with the same perspectives in both, the first half of the project as well as the second half of the project. It is therefore essential to document and complete each phase in such a manner that the information and knowledge, needed as input in a later phase, is available.

Furthermore it is noted that combined with the complexity and high costs of developing an AFTS, it is very difficult to go back in time to for instance the conceptual design phase and repeat all subsequent phases, when faced with a problem in the integration and testing phase of a project. In other words, although there may be certain logical interrelations between different phases (horizontal arrow in Figure 3-6) based on the content of a certain phase, or the types of people involved in a certain phase, phases primarily have a sequential relation following the V with the one way arrow in Figure 3-6. The horizontal interrelations should therefore not be interpreted as possible interactions between phases within a certain time domain. Iteration is a notion that applies to steps within a phase but not to phases themselves. It is therefore essential to acknowledge that the conceptual design phase is one of the first and probably one of the most important phases in the development of an automated freight transport system. Decisions made in the conceptual design phase will influence all subsequent phases and cannot be changed easily in a later phase.

Apart from leading to the discussion above on phases and their interrelation, the V-model is also interesting because it shows that different perspectives or types of people are needed for different phases in a project. This too is an important aspect to take into account for the conceptual design of an AFTS, as this is also true for the different steps within the conceptual design phase.

3.1.5 Models by Department of Defense USA & INCOSE

Two expert organizations on Systems Engineering are the Department of Defense (DoD) in the USA and the International Council On Systems Engineering (INCOSE). As discussed in the introduction of this section, the US military were among the first
to develop and apply SE starting in the late 1950’s, which makes their experience very valuable. INCOSE is a younger organization founded in 1990 with members from many different fields, providing a broad common platform for Systems Engineering. Both organizations have developed a model of the Systems Engineering process, which are discussed below.

**DoD Model**

A model of the SE process developed by the DoD is shown in Figure 3-7. The process input consists primarily of consumer needs, objectives, requirements and project constraints. Three fundamental steps are defined: Requirements Analysis, Functional Analysis & Allocation and Design Synthesis. Also, three feedback loops are used: Requirements Loop, Design Loop and Verification. A fourth element, System Analysis and Control, is presented as a separate element in the model interacting with all three steps. The Process output depends on the level of development (phase), but in general the output is any data that describes the product configuration or the process, necessary to develop that product [DoD, 2001].

![Figure 3-7 Systems Engineering process by [DoD, 2001]](image)
The model clearly presents Requirements Analysis, Functional Analysis/Allocation and Synthesis as three logical steps, which can be repeated in different phases. The phases used by the DoD are not presented in this model of the SE process, but are shown separately in Figure 3-8. Although the steps are presented by using a waterfall-like model (a representation not recommended for presenting steps as argued in Section 3.1.3), the iterative characteristic of the SE process is represented in the model by the various feedback loops. Although the fourth element (System Analysis and Control) is presented as a separate element in the model, part of this element (System Analysis) can be seen as a fourth step in the process, logically placed under the synthesis step where the system is “put together”. Trade-off studies and selecting the best concept(s) can be seen as part of this fourth step. The “control” or management part is indeed a more general aspect which can be projected “above” the logical steps as a coordinating element. The DoD focuses more on defining the requirements and functions than on the actual design (synthesis) of a system. This is acknowledged by the DoD and is also reflected in their model of the SE process by their choice of steps and in the representation of the phases for what they refer to as the DoD acquisition process. The phases defined by the DoD are presented in Figure 3-8. Conceptual design can be recognized in their “Concept and Technology development” phase, also referred to as “Pre-systems Acquisition”. Milestone B marks the end of the concept and technology development phase. The decision to enter into the concept and technology development phase is made formally at milestone A.

![Figure 3-8 Phases for DoD acquisition process [DoD, 2001]](image-url)
The DoD has a vast experience with developing complex systems and the SE process. As such, it is interesting to discuss some of their own considerations. The DoD states that although the SE process has produced a series of ever increasing capable and reliable systems since the 1960s, the problem now is that in too many cases the process is overlaid with ever increasing levels of control, reports and reviews [DoD, 2001]. The result is that the cycle time required to produce systems has increased to unacceptable levels, even as technology lifecycles have decreased. The fact is that, in too many cases, they are producing excellent systems, but systems that take too long to produce, cost too much, and are often outdated when they are finally produced [DoD, 2001]. One of the more important lessons to be learnt here is that the SE process should be tailored to the specific needs of the program. However, the DoD also states that there is a substantial risk when ignoring elements of the process. Before one decides to skip phases, eliminate reviews, or take other actions that appear to deliver shortened schedules and less cost, one must ensure that those decisions are appropriate for the risk that characterizes the program. One can for instance take more risks when developing a vehicle to travel over land compared to developing a vehicle to travel into space, as the consequences of a failure and the possibilities for recovery are very different.

**INCOSE Model**

A model of the SE process developed by INCOSE is presented in Figure 3-9. They state that SE is basically an iterative process starting at the top level (system level) and propagating downward through a series of steps. Figure 3-9 suggests a circular motion with six steps (starting at the top left turning clockwise) and different levels of detail or development. When interpreting the levels as phases, this representation of the Systems Engineering process is, at first sight, comparable with the spiral models discussed earlier. However, this model has some inconsistencies. First of all the numbers of levels behind each step are not equal, which should be the case if they are to represent phases (as the same steps are repeated in every phase). Furthermore, the logical sequence of the steps is not always clear. For instance, a concept can be analyzed (top right step) only after it has been designed (bottom right step). Although this model is fundamentally less correct when compared to previous models because of the reasons mentioned above, the expressions used in this model are more general and modern compared to the terminology used by Hall. Basic steps that can be
distinguished are: Analysis, Definition, Design, Production, Delivery and Tradeoffs (although the model does not show tradeoffs as a separate step). The phases are not all clearly represented in the model, however some can be recognized, e.g. Conceptual-Preliminary-Detailed design, Production & Delivery-Installation-Operation-Disposal.

Figure 3-9 Systems Engineering process by [INCOSE, 1998]

A better representation of phases is presented in Figure 3-10 [INCOSE, 1998]. This figure shows a structured comparison of program phases for five different organizations. This comparison shows that all programs are fundamentally similar in that they move from the project initiation phase through the system concept phase, further to the development phase, production phase and operational phase etc. (see bottom time line Figure 3-10). Milestones, typical control gates in Figure 3-10, are set for all the phases. A typical control gate recognized in all the programs, is that of system concept approval, marking the end of the conceptual design phase. Generally the conceptual design phase, the focus of this study, is placed after the initiation phase and before the detailed design phase.
3.2 Engineering Design Models

Engineering Design (ED) models focus more on the actual design process of technical products. As with SE, it is difficult to determine the precise origin of ED. The systematic design of technical products as such, can be traced back to for instance Leonardo da Vinci. Most current literature on ED however refers to the German developments in the 1960’s and 1970’s when discussing the development and history of ED models. This section discusses the most important models.
Several early works on ED have been published by the “Verein Deutscher Ingenieure” (VDI). The VDI published Guidelines VDI 2222 in 1977 and VDI 2221 in 1985 in which they present a systematic approach to design. Their aim was to develop a systematic approach for the design of technical systems and products, to be generally applicable in practice [VDI 2221, 1985]. The general approach towards design developed by the VDI, can be called a consensus model [Cross & Roozenburg, 1992] as it converges the early (mainly) German developments in ED. Reference is made to [VDI 2221, 1985] for the many (mainly) German references and names of committee members involved in the development of the VDI approach. The general approach towards design, as well as some of the other models developed by the VDI, are discussed in Section 3.2.1.

Another important work of reference for ED has been published by Pahl & Beitz, who published their first German edition of “Konstruktionslehre” in 1977, which has been updated and modified several times. A recent publication, containing many references and presenting the state of the art on ED is [Pahl & Beitz, 1999]. Pahl & Beitz give an extensive overview of both, historical and current literature on design methodology. Although they focus on German developments, especially for the historical overview, developments outside Germany are also discussed. Pahl and Beitz state that, although the various methods described in literature are strongly influenced by their author’s specialist fields, they resemble one another far more closely than the various concepts and terms would suggest. Pahl & Beitz do not claim to have developed a theory of design that will have the final word on the subject, but they simply try to combine various methods in a coherent and practicable way. The ED model developed by Pahl & Beitz is comparable with the so-called consensus model developed by the VDI, but is somewhat more detailed and specific for the field of mechanical engineering. Section 3.2.2 discusses the model developed by Pahl & Beitz.

Apart from Pahl & Beitz, there are several other textbooks which present models comparable to the consensus model, such as [Hubka & Eder, 1988], [Kroonenburg & Siers, 1998], [French, 1985] and [Pugh, 1991], although not all these models are as detailed and precise [Cross & Roozenburg, 1992]. There are however also other models of the design process which differ from the engineering design models discussed above. An excellent paper comparing the models developed in engineering
with the models developed in architecture is presented by [Cross & Roozenburg, 1992]. They discuss the positive and negative features of both types of models and argue to reintegrate the different types of models, building on the strengths of each. Both authors present their own models as attempts to develop such an integrated model. The models developed by Roozenburg & Eekels and Cross are discussed in Sections 3.2.4 and 3.2.3 respectively.

3.2.1 VDI Model

The general approach of the “Verein Deutscher Ingenieure” (VDI) towards design is presented in Figure 3-11. This model presents the engineering design process as a sequence of seven stages, correspondingly producing seven results. The stages can be grouped into design phases, the names and numbers depending on the project or field of application. Phases often used are: Clarification of the task (I), conceptual design (II), embodiment design (III) and detailed design (IV) [VDI 2221, 1985]. This VDI model does not distinguish between phases and steps as clearly as the models presented in the Systems Engineering section. The VDI model emphasizes the time dimension, not clearly presenting the logical steps that take place in every phase. This could be the reason why the logical steps are sometimes overlooked by its users and critics [Cross & Roozenburg, 1992]. Although the steps are not clearly shown, they are discussed by the authors. They emphasize that the seven stages can be further subdivided into additional steps, depending on the complexity of the task. The stages introduced by the VDI are however not the same as phases. Certain stages in the model in fact resemble steps. One could state that, although phases and steps are mentioned and described by the VDI, they are not clearly represented in the model. The terms used for the stages are furthermore not clearly distinguishable as either phases or steps. The stages defined by the VDI are perhaps more a combination or mixture of phases and steps. This is considered one of the weaker aspects of the model. Stages however do help to structure the design process by specifying intermediate results. The authors further note that the stages do not necessarily follow rigidly one after the other. They are often carried out iteratively, returning to preceding ones, thus achieving a step-by-step optimization. It is however unclear in the figure how this iterative process works and which elements of the model are included. As discussed earlier in Section 3.1, iteration is a notion that applies to steps
within a phase, but not to phases themselves. In this respect it is unclear whether stages, being neither phases nor steps, should or should not be part of an iterative process.

**Figure 3-11 VDI model for the Engineering design process [VDI 2221, 1985]**
Apart from modelling the ED process using stages, the VDI suggest sub-dividing a complex overall problem into sub-problems. This makes it easier to find a solution, and also makes it possible to break down the problem solving process into parallel paths. This structuring of the problem by decomposition is shown in Figure 3-12. The overall problem is divided into sub-problems for which sub-solutions are found which are then integrated or combined into an overall solution (reading from top to bottom). The figure however, also illustrates the fundamental systematic approach of structuring a system into sub-systems and system elements (starting at the bottom going up). Such a structuring promotes the recognition of sub-problems, the discipline to proceed systematically, the development of alternative solutions, the adoption of familiar and well-tried sub-solutions, and the introduction of a rationally organized division of labour [VDI 2221, 1985]. As a comment, it should be noted that it is also important to keep the overall overview, as sub-division can lead to sub-optimization.

![Figure 3-12 Decomposition model, structuring the problem and system [VDI 2221, 1985]](image)

Finally, the VDI discusses divergence and convergence as an important characteristic of the design process. In each phase alternative solutions can be considered. Working out all variants in all phases, would lead to an explosion of the number of possibilities
to study. On the other hand, restricting oneself to one track only within the network of possibilities is dangerous, because then the better or best alternatives may be overlooked. One is therefore urged to diverge and converge in each phase. This important methodical principle is visualized in Figure 3-13 [VDI 2222, 1977].

Figure 3-13 Divergence and convergence [VDI 2222, 1977]
This model clearly presents the divergence and convergence in different phases of the design process. In every phase, alternatives or variants can be thought up (divergence) after which choices have to be made to come to one total solution (convergence). The model also clearly represents the conceptual design phase starting with the overall function at the top, and ending with a selected concept variant at the bottom. The reasoning from function to sub-functions, for which alternative solution principles are developed (building blocks) which are then used to build system concepts, is clearly presented in the model.

In general these models developed by the VDI are considered useful for structuring the design process. Although their model of the ED process does not clearly distinguish between phases and steps, their models do enhance the general understanding of the design process and so help to unravel and structure it.

### 3.2.2 Pahl & Beitz

Pahl & Beitz present their model of the design process as being developed from the VDI model [Pahl & Beitz, 1999]. While the aim of the VDI was to develop a generally applicable approach to design, Pahl & Beitz focused more on mechanical engineering. The model developed by Pahl & Beitz is presented in Figure 3-14.

Although this model does resemble the VDI model, it better presents the steps within the phases. Focusing on the conceptual design phase, the following steps can be distinguished:

- Identify essential problems.
- Establish function structures.
- Search for working principles and working structures.
- Combine and firm up into conceptual variants.
- Evaluate against technical and economical criteria.
Market, company, economy

Plan and clarify the task:
- Analyze the market and the company situation
- Find and select product ideas
- Formulate a product proposal
- Elaborate a requirements list

Requirements list
- (Design specification)

Develop the principle solution:
- Identify essential problems
- Establish function structures
- Search for working principles and working structures
- Combine and firm up into conceptual variants
- Evaluate against technical and economical criteria

Concept
- (Principle solution)

Develop the construction structure:
- Preliminary form design, material selection and calculation
- Select the best preliminary layouts
- Refine and improve layouts
- Evaluate against technical and economical criteria

Preliminary layout

Define the construction structure:
- Eliminate weak spots
- Check for errors, disturbing influences and minimum cost
- Prepare the preliminary parts list and production and assembly documents

Definitive layout

Upgrade and improve

Information: Adapt the requirements list

Optimisation of the principle

Conceptual design

Embodiment design

Detail design

Optimisation of the production

Optimisation of the layout, forms and materials

Upgrade and improve

Product documentation

Solution

Figure 3-14 Design process according to [Pahl & Beitz, 1999]
Both the VDI and Pahl & Beitz use so-called stages in their models. As discussed in the previous section (3.2.1), the VDI stages were not clearly distinguishable as either phases or steps, which was considered a weaker aspect of the VDI model. For the Pahl & Beitz model however, stages more resemble phases. In fact three of the four phases in Figure 3-14 coincide with a certain stage. For example, the conceptual design phase coincides with the second stage of the model. With steps defined for each stage and stages comparing with phases, the Pahl & Beitz model could also be considered a model consisting of phases and steps.

In this respect it is again interesting to discuss iteration in relation to steps and phases (or in this case stages). Pahl & Beitz stress the importance of taking all steps presented in the conceptual design phase, but also admit that it is not always possible to draw clear borders between the phases and that it is not always possible to avoid backtracking. As discussed earlier, iteration is a notion that applies to steps within a phase, but not to phases themselves. Although phases are basically sequential, it is sometimes necessary to return to a previous phase. For instance, when a system or sub-system does not comply with the expected performance at the beginning of the operational phase, it could be necessary to go back to previous phases to find the origin of the problem. This is called backtracking, and should not be confused with iteration. With backtracking one tries to retrace ones steps to find the origin of the problem, with iteration one repeats two or more steps in order to improve the results. As such, backtracking is a notion that can be applied to phases.

The models by both the VDI and Pahl & Beitz suggest that it is possible to go back to previous phases and repeat the whole process. Although this may be possible for less complex products or systems, it is very difficult for developing automated freight transport systems both for costs reasons and because of the long development times, as also discussed in Section 3.1.4.

### 3.2.3 Cross

A model for the product design process developed by [Cross, 2000] is presented in Figure 3-15. He distinguishes 7 stages between the overall problem and the overall solution. Furthermore he assumes a symmetrical relationship between problem and solution and between sub-problems and sub-solutions, represented by the two way horizontal arrows.
The seven stages presented by Cross can be interpreted as logical steps rather than temporal phases, although the distinction between steps and phases is not clearly made, just as with the VDI model. More interesting however, are the clearly indicated interrelations between problem and solution. The model conveys that the process is not one way, from problem to solution through the 7 stages, but that there are important interrelations between the problem(s) and solution(s). This model shows that contemplating possible solutions often helps to clarify the problem, and reflecting on similar past (sub-)problems and their (sub-)solutions supports the establishing of functions and setting of requirements. It is important to acknowledge this interaction between problem and solution when designing systems. Just as the VDI, Cross distinguishes between the overall problem and sub-problems and between sub-solutions and overall solution. His model however, better emphasizes the interrelation between overall problem and overall solution. This model stimulates one to think about possible solutions in order to help formulate the problem. This in contrast to the so-called top down approaches, which encourages one to think from function to form or from abstract to concrete or from problem to solution.

The model presents “improving details” as a last step in the design process. Although this is often seen in design procedures stemming from practice, theoretically it is not entirely correct. Improving details, when interpreted as a process comparable with
“optimization”, should be seen as an iterative process. Although some models present an iterative process as a step to emphasize its importance, such as “optimization” by Hall or “improving details” by Cross, iteration should not be considered a step in itself but rather a process containing two or more steps. Furthermore, “detailing” can be seen as part of a whole different phase: the detailed design phase. Detailing or detailed design is a process in itself, often with the same logical steps as required for the conceptual design phase. Detailing often also involves understanding the (detailed) problems, generating different possible solutions and evaluating the different possibilities in order to choose the best detailed solution. Theoretically, detailing is therefore a phase in itself rather than a last step of the conceptual design phase. In practice however, one often sees detailing activities at the end of the conceptual design phase. This is often necessary in order to assess the technological and sometimes economical feasibility of a concept. Especially when developing new systems, with new elements, it is important to consider the new and most critical elements in more detail in order to reduce uncertainties about e.g. the functioning of the system and the operation and maintenance costs.

Although it is fundamentally not correct to present detailing as a step in the conceptual design phase, detailing is sometimes needed in order to properly evaluate a concept. This aspect can be represented in the theoretical models by letting the end of the conceptual design phase and the beginning of the detailed design phase overlap.

### 3.2.4 Roozenburg & Eekels

Roozenburg & Eekels have developed a model that they call “the basic design cycle”. They present their basic design cycle as a most basic fundamental model of the design process. They state that, someone who has claimed to have solved a design problem has gone through this cycle at least once [Roozenburg & Eekels, 1998]. Roozenburg & Eekels formulate that designing should be seen as a specific form of problem solving and that the core of designing is reasoning from goal (the function) to means (the design). They state that, as with problem solving in general, it is initially uncertain what means (which design) is most effective and that designing is in essence a trial-and-error process that consists of a sequence of empirical cycles, in which the knowledge of the problem as well as the solution increases spirally. Their basic design cycle is presented in Figure 3-16.
The point of departure in product design is always the function of the new product, that is, the intended behaviour in the widest sense. In the analysis step the designer forms an idea of the problems around a new product idea and formulates the criteria that the solution should meet, first broadly and in later iterations more accurately and completely.

The second step is the generation of a provisional design proposal. The word "Synthesis" means the combining of separate things, ideas, etc., into a complete whole. However, a good design is seldom merely a collection of solutions to sub-problems; it is an integral solution, which makes sub-problems disappear. Synthesis is the least tangible of all steps as it contains "human creativity". It is the crucial step, but comes out well only if it is supported by and implemented in the other steps. Hence, the result is called a provisional design.

Simulation is forming an image of the behaviour and properties of the designed product by reasoning and/or testing models, preceding the actual manufacturing and use of the product. Simulations lead to "expectations" about the actual properties of the product.

Evaluation is establishing the value or quality of the provisional design. To do so, the expected properties are compared with the desired properties in the design specifications (Criteria).

Then follows the decision: Continue—that is to say, elaborate the design proposal or, if it is the final design, manufacture it. Or try again and generate a better design proposal (to do better in a second, third or tenth iteration). A feedback of experience could also lead to the (re-) formulation of the problem and criteria.

Although Roozenburg & Eekels focus on product design, they present their basic cycle of design to be true for all design problems. Indeed, the five steps they define can be seen as the most basic logical steps to be taken in every phase of the design process (phases are not represented in the model). The iterative characteristic of the design process is also clearly and correctly represented by the feedback loop, indicating that iteration is a repetitive process involving two or more steps. As such, the model developed by Roozenburg & Eekels is one of the most fundamentally correct models for representing the design process. Furthermore, it most clearly presents the formulation of criteria as important part of the analysis step.
However, the model suggests this cycle is performed for a single design. The synthesis step produces one provisional design, which is then simulated and evaluated, after which a decision is made to either accept this design or repeat the process to improve it, or find a different design. Although this “trial-and-error” approach could work for relatively simple products with shorter development times, a more systematic parallel approach is required for the conceptual design of AFTS’s. In this respect it is considered better to develop different concepts parallel to one another, simulate and evaluate these alternative concepts and then choose the most suitable concept. In this parallel process, iteration of course remains possible.

3.3 Evaluation of the SE & ED models

This section evaluates the System Engineering and Engineering Design models discussed in the previous two Sections 3.1 and 3.2, using evaluation matrices. An evaluation matrix is presented for each of the main aspects introduced in Chapter 2. This evaluation is not an exercise to select the best existing model, but rather to graphically reflect (in matrix form) which criteria are represented in which models. The criteria developed for evaluating the SE and ED model are discussed first in Section 3.3.1, after which several evaluation matrices are presented in Section 3.3.2.

3.3.1 Evaluation criteria

The criteria for evaluating the different SE and ED model have been derived from the characteristics of automated freight transport systems discussed in Chapter 2, and from the literature survey discussed in this chapter. All criteria are presented below. The criteria have been sub-divided into three groups, introduced in Chapter 2, focusing on the following main aspects:

A. Project Structure, focusing on how the models help to structure a large complex project.
B. Design Process, focusing on how the models represent the actual design process.
C. Multi-X, focusing on how the models show the multiple layers, disciplines, types of people and stakeholders involved in the conceptual design of automated freight transport systems.
A. Criteria for the main aspect Project Structure

A1 Use of phases for the main project structure
Phases should be used for the main structuring of complex projects. Phases structure the development of a system in the time dimension, making it possible to plan a project and to control its progress. The use of phases for the main structuring of a project has been discussed throughout this chapter.

A2 Present phases primarily in a linear / sequential relation
The phases should be represented as being primarily sequential. The long developments times, the complexity and the high costs of developing an AFTS, all discussed as characteristics in Chapter 2, make it very difficult to constantly go back in time to repeat phases. As discussed in Sections 3.1.4 and 3.2.2, iteration is a notion that applies to steps within a phase, but not to phases themselves.

A3 Clearly distinguish between phases and other elements
Phases should be clearly presented in the model and not be obscured by or confused with other types of elements within the models such as steps. As phases form the main structure of a project, they should be clearly recognized and distinguished.

A4 Clearly present Conceptual Design as a phase
As discussed in Chapters 1, 2 and 3, Conceptual Design is one of the first and most important phases in the lifecycle of a system and should be presented as a separate phase. Decisions made in the conceptual design phase will influence all subsequent phases and cannot be changed easily in a later phase.

A5 Represent the total lifecycle of a system
The total lifecycle of a system should be represented in the model. Although the focus here is on the conceptual design phase, the other phases in the lifecycle should also be presented. It can be important for instance, to consider the conditions or possibilities for retirement of a system during the conceptual design phase.
A6  Present milestones at the end of every phase
Milestones should be presented at the end of each phase to mark a point in time. At this point in time all documentation should be completed and a decision should be made whether to continue with the next phase.

B. Criteria for the main aspect Design Process

B1  Use of steps to present design process
Within the conceptual design phase, as within all other phases, several logical steps can be defined. These steps help to structure the conceptual design phase in a logical way and form the basis for presenting the conceptual design process.

B2  Present design as an iterative process
The design process is an iterative process and should be presented as such. As opposed to phases, which are primarily sequential, steps can be repeated many times during the design process.

B3  Present steps in logical sequence
Although steps can be repeated several times during the design process, they should have a logical sequence. One can for instance analyze or simulate a certain concept only after the concept itself has been designed.

B4  Present fundamentally correct steps
The steps used for the presentation of the design process should be fundamentally correct. Optimization for instance is not a step, but rather a repetitive process in itself containing two or more steps, as also discussed in Section 3.2.3

B5  Include step(s) for analyzing the problem
In essence, the conceptual design phase starts with a problem for which a solution must be found. One of the first steps of the conceptual design process should be to analyze the problem.

B6  Include step(s) for developing possible solutions
After analyzing the problem, a logical step is to develop possible solutions for that problem. This is also referred to as the most creative step of the design
process.

B7 Include step(s) for analyzing possible solutions
After developing possible solutions, these solutions should be analyzed e.g. by simulations or prototyping in order to determine their value.

B8 Include step(s) for evaluating and selecting a solution
Using the simulation results, the possible solutions or concepts can be compared and the most suitable concept can be selected. This is done in the evaluation and selection step.

B9 Show divergence & convergence in the design process
Divergence and convergence have been discussed in Section 3.2.1 as important characteristics of the design process. In every phase, alternative solutions should be developed (divergence) after which choices have to be made to come to one selected solution (convergence). Both divergence and convergence should be presented as part of the conceptual design process.

B10 Show decomposition & integration in the design process
Decomposing or sub-dividing e.g. a problem into sub-problems or a system into sub-systems helps to structure the design process and to deal with its complexity, as also discussed in Sections 2.2.3 and 3.2.1. A total solution or system concept can then be developed by again integrating or combining the different sub-solutions or sub-systems. Decomposition and integration is typical for developing complex systems, such as AFTS’s, and should therefore be reflected in the model.

B11 Show the relations between problem and solution
A design process basically starts with a problem for which a solution must be found. However, as discussed in Section 3.2.3, there are important interrelations between problem and solution. For example, contemplating possible solutions can often help to clarify and better define the problem. The relations between problem and solution should be presented in a model of the design process.
B12 Show the parallel development of concepts

As discussed for criterion 9 (divergence & convergence), alternative solutions or concepts should be developed during the conceptual design phase. Although these concepts could be developed one after the other, it is preferred to develop these concepts parallel to one another, as also discussed in Sections 3.2.4.

C. Criteria for the main aspect Multi-X

C1 Present different layers

Characteristic for automated freight transport systems are the layers: Infrastructure, Equipment, Control System and Operational Organization. Although the different layers require different development times and therefore could be considered sequentially, they are interdependent and should all be integrated in the conceptual design phase, as also discussed in Section 2.2.1. A model for the conceptual design of automated freight transport systems should therefore present these multiple layers.

C2 Present different disciplines needed for development

As discussed in Chapter 2, the conceptual design of AFTS’s requires many different disciplines. Civil Engineering, Mechanical Engineering, Electrical Engineering and ICT are only some of the disciplines, which have to work together to design a system. This multi-disciplinary characteristic should be presented in the model.

C3 Present different types of people needed for development

Apart from distinguishing between the different disciplines, one should also distinguish between the different types of people needed, as discussed in Section 2.4. For example, one can distinguish between generalists and specialists or between problem focused people and solution focused people. Furthermore, as discussed in Section 3.1.4, different types of people are needed for the different phases in a project and for the different steps in a phase. This should be presented in the model.

C4 Present different stakeholders, with different objectives

The different parties involved or interested in the project all have their own
requirements or objectives. This too is typical for the conceptual design of automated freight transports systems as discussed in Chapter 2 and should be reflected in the model.

### 3.3.2 Evaluation matrices

An evaluation matrix is presented for each of the main aspects discussed in Section 3.3.1. The models are evaluated using the criteria defined for each main aspect. This is an evaluation using plus (+) and minus (-) qualifications. A (+) indicates the specific criterion is represented in the model, a (-) indicates it is not represented in the model and a (-/+) indicates the characteristic can be recognized in the model, although not clearly, correctly or explicitly. This is not an exercise to select the best model, but rather to graphically represent which criteria are reflected in which models. As such it is a qualitative evaluation. The evaluation matrices for the main aspects Project Structure, Design Process and Multi-X are presented in respectively Figure 3-17, Figure 3-18 and Figure 3-19.

The models are evaluated using and A, B, C or D classification, presented in the last column of each matrix. Classification A indicates that most of the criteria are represented (75 to 100% plusses); classification B indicates that many of the criteria are represented (50 to 75% plusses); classification C indicates that several of the criteria are represented (25 to 50% plusses); and classification D indicates that little or no criteria are represented (0 to 25% plusses). The total number of plusses divided by the total number of criteria produces the percentage for each model. The -/+ is counted as half a plus. Again, the letters and percentages are not introduced as a quantitative measure to rank the models, but rather as an indication how many of the criteria are represented in the model. An overview of the evaluation is presented in the summary and conclusions (Section 3.4).

#### A. Project Structure evaluation matrix

The criteria defined in Section 3.3.1 for evaluating how the models help to structure a large complex project are:

1. Use of phases for the main project structure.
2. Present phases primarily in a linear / sequential relation.
3. Clearly distinguish between phases and other elements.
4. Clearly present Conceptual Design as a phase.
5. Represent the total lifecycle of a system.
6. Present milestones at the end of every phase.

The evaluation matrix for the main aspect Project Structure is presented in Figure 3-17.

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Figure 3-17 Evaluation matrix for the Project Structure

The evaluation is clarified below.

**System Engineering models**

**Matrix models by Hall (Section 3.1.1)**

Both the activity matrix and the 3D matrix by Hall help to clearly structure complex projects by using phases for the main structuring and steps for the fine structuring, to be completed in every phase. The models also suggest a very linear approach. Furthermore, the phases represent the total lifecycle of a system. However, conceptual
design is not presented as a separate phase and milestones are not presented at the end of every phase.

**Spiral models (Section 3.1.2)**

The spiral model by Hall does not help to structure a project as clearly as his matrix type models, even when using the same elements (the phases, steps and activities defined by Hall in his matrix models are also used in his spiral model). The phases are not clearly defined or distinguishable and therefore the total lifecycle is also not clearly represented. The model does present the phases as sequential, although this also is less clear. Conceptual design is not presented as a phase and milestones area again not used at the end of every phase.

The spiral model by Boehm emphasizes the increase in cost with every cycle and stresses a risk driven approach, resolving the risk in every cycle. Although every cycle could be regarded as a phase in the development of a system, and every quadrant as a step to be completed in every phase, this would not lead to a very consistent or correct model. For example, the last step in the last phase in the model by Boehm (Figure 3-4 bottom right quadrant) would then contain elements named “detailed design”, “integration and test” and “implementation” which themselves should be phases in the development of a system and not elements of the last steps of the last phase. So, although phases can be recognized in the model, they are not presented very clearly or correctly. The spiral model does suggest a sequential relation, but again not clearly for phases. As discussed, the distinction between phases and other elements is not clearly made. Furthermore, the model does not present: conceptual design as phase, the total lifecycle of a system and milestones at the end of every phase.

**Waterfall models (Section 3.1.3)**

Both models by Royce and Sage, define phases and suggest a one-way flow (down the waterfall). However, Sage suggests a more iterative process by introducing feedback loop. Phases are the only elements defined in both models and are therefore clearly distinguishable. Conceptual design is defined as a phase by Sage, but not by Royce. Not all phases are defined and some of the phases defined are not clear or logical. For example, “retirement” is not included as a phase in the lifecycle of a system in either
model, and “maintenance” defined by Royce as a last phase in a system lifecycle is not a logical phase. Furthermore, neither model presents milestones.

**V-process model (Section 3.1.4)**
As with the waterfall models, the V-process model by Sage presents phases in a primarily sequential relation, although the elements here follow a V-shape instead of a waterfall. However, the additional horizontal arrows drawn between the phases could obscure this primarily sequential relation. Furthermore, the V-process model lacks the simplicity and straightforward clarity of the waterfall model, although the phases used by Sage here are similar to the phases used in his waterfall model. The phases are therefore less clearly distinguishable. Similar to the waterfall model by Sage, the V-process model presents conceptual design as a phase, does not fully represent the total lifecycle of a system and does not present milestones at the end of every phase.

**DoD models (Section 3.1.5)**
The DoD clearly distinguishes between phases, for the main structuring of a project in the time dimension, and steps to be completed within the different phases. The DoD SE process model focuses on these steps to be taken within a phase and not on the phases themselves. This SE process model (Figure 3-7) therefore does not reflect any of the criteria defined for this main aspect: Project Structure.
However, the DoD model presenting phases (Figure 3-8) reflects nearly all criteria. The Phases model presents phases for the main project structure, presents the phases as sequential, clearly distinguishes phases from other elements and uses milestones at the end of every phase. Although, conceptual design can be recognized in their model and the different phases in a systems lifecycle are presented, this could have been done more explicit.

**INCOSE models (Section 3.1.5)**
The model on Comparison of Phases presented by INCOSE also reflects nearly all criteria fully. Phases are used for the main project structure, phases are presented as sequential, phases are the only elements discussed and therefore clearly distinguished, Conceptual Design is presented as a phase, and milestones are presented at the end of every phase. Only the retirement or disposal of a system should have been represented more clearly as part of the total lifecycle of a system.
Although INCOSE clearly distinguishes between phases and other elements, as shown by their Comparison of Phases discussed above, this is not clearly shown in their SE process model. In fact the INCOSE SE process model has several flaws or inconsistencies, as also discussed in Section 3.1.5. In contrast to the DoD SE process model, which clearly focuses on the steps to be taken within a phase, the INCOSE SE process model attempts to integrate different aspects. However, their SE process model does not clearly present phases for the main project structure, and certainly does not present them as primarily sequential. Furthermore, the distinction between phases and steps is not very clear. Although Conceptual Design as such can be recognized in the model, it is again not clearly presented as a phase. The total lifecycle of a system is also not clearly presented and milestones are not included in the model.

**Engineering Design models**

**VDI models (Section 3.2.1)**

Although the VDI ED process model does introduce several phases alongside their model, they are not used for the main structure. The main focus for the VDI is on stages. Their stages are neither clearly phases nor steps, but rather a combination of the two. The model does not clearly distinguish between phases and steps. Although the phases suggest a sequential relation, feedback loops are also introduced in the model making it possible to return to previous stages and therefore also to previous phases. Conceptual design is presented as a phase, but the lifecycle of a system is not sufficiently shown and milestones are not introduced at the end of each phase.

Apart from the ED process model, the VDI have developed the Decomposition model and the Divergence and Convergence model. The Decomposition model focuses on a certain aspect of the design process and does not reflect any of the criteria defined for evaluation this main aspect Project Structure. The Divergence and Convergence model does reflect several of the criteria. Although the phases presented in this model are similar to the phases presented in the ED process model, here the phases could be regarded as forming the main structure. The phases are presented as sequential. However, the phases are still not clearly distinguished from the other elements in the model. Conceptual design is again presented as a phase, the total lifecycle is not sufficiently shown and milestones are not used.
Pahl & Beitz model (Section 3.2.2)

Both, the VDI ED process model and the model developed by Pahl & Beitz use stages for the main structure. However, for the Pahl & Beitz model, the stages better compare with phases, and steps are defined in every stage. Therefore, the Pahl & Beitz model could be considered a model consisting of phases and steps. As such phases are used for the main structuring of a project and a clear distinction can be made between phases and steps. The phases are presented as primarily sequential. However, similar to the VDI model, feedback loops are introduced for the stages, suggesting it is possible to return to previous stages or phases and repeat the whole process in order to improve the result. As discussed in Section 3.2.2, iteration is a notion that should apply to steps within a phase, but not to phases themselves. Furthermore, as with the VDI model, Conceptual design is presented as a phase, the total lifecycle of a system in not sufficiently presented and milestones are not presented at the end of every phase.

Cross model (Section 3.2.3)

The model developed by Cross presents several different stages, which can be interpreted as logical steps rather than phases in time. As such, the model represents the design process rather than the structuring of a project. None of the criteria defined for the Project Structure are presented in this model.

Roozenburg & Eekels model (Section 3.2.4)

The basic design cycle developed by Roozenburg & Eekels focuses on the actual design process and does not reflect any of the criteria defined for evaluating the Project Structure.

B. Design Process evaluation matrix

The criteria defined in Section 3.3.1 for evaluating how the models represent the actual design process are:

1. Use of steps to present design process.
2. Present design as an iterative process.
3. Present steps in logical sequence.
4. Present fundamentally correct steps.
5. Include step(s) for analyzing the problem.
6. Include step(s) for developing possible solutions.
7. Include step(s) for analyzing possible solutions.
8. Include step(s) for evaluating and selecting a solution.
9. Show divergence & convergence in the design process.
10. Show decomposition & integration in the design process.
11. Show the relations between problem and solution.
12. Show the parallel development of concepts.

The evaluation matrix for the main aspect Design Process is presented in Figure 3-18.

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Figure 3-18 Evaluation matrix for the Design Process

The evaluation is clarified below.

**System Engineering models**

**Matrix models by Hall (Section 3.1.1)**

The Matrix models by Hall clearly present steps to be completed in every phase. However, the models suggest a very linear approach and do not show the iterative
character of the design process. The steps as defined in both models do have a logical sequence, but are not always fundamentally correct (e.g. optimization is defined as a step). Steps for: analyzing the problem, developing possible solutions, analyzing possible solutions and evaluating and selecting a solution have all been included in the matrix models. The matrix models do not show: divergence & convergence, decomposition & integration or the relations between problem and solution. The models do allow for a parallel development of alternative concepts in their systems synthesis step but do not clearly show it.

**Spiral models (Section 3.1.2)**

The steps defined by Hall in the matrix models are also used in his spiral model. The evaluation is similar, except for criteria 2 and 9. The spiral model by Hall does reflect the iterative nature of the design process by adding feedback loops. Furthermore, convergence is shown in the model, although not as part of the divergence and convergence normally found within a phase, but as convergence of the whole SE process.

The Spiral model by Boehm does contain elements that could be interpreted as steps, but does not do so very clearly or correctly, as discussed in the previous evaluation for the project structure. Iteration is not presented in the model. As steps have not been defined clearly or correctly, it is difficult to determine whether the steps have a logical sequence. Should one regard the quadrants as steps, then the steps would not be fundamentally correct. Although no clear steps have been defined for analyzing the problem, developing solutions, analyzing possible solutions or evaluating and selecting a solution, similar expressions can be found in the model. The model does not show: divergence & convergence, decomposition & integration and relations between problem and solution. Although the model allows for parallel development of concepts, it is not clearly shown.

**Waterfall models (Section 3.1.3)**

Both waterfall models by Royce and Sage, present phases rather than steps. Although Sage introduces the notion of iteration by presenting feedback loops, this is done for phases and not for steps. Apart from the inappropriate introduction of iteration by Sage, none of the criteria defined for evaluating the design process are reflected in the waterfall models by Royce and Sage. Waterfall models in general suggest a one-way
flow (down the waterfall) and are better used for presenting the sequential phases in a project, rather than the iterative steps of the design process.

**V-process model (Section 3.1.4)**
The V-process model by Sage also presents phases rather than steps. Although the model emphasizes the decomposition sequence down the first (left) half of the V-shape, followed by the integration sequence up the second (right) half, this is done for phases and not for steps. Apart from this representation of decomposition and integration, none of the criteria defined are represented in the model.

**DoD models (Section 3.1.5)**
The DoD present the SE process as three steps to be performed within a phase. Feedback loops are included to present the iterative character of the process. The steps presented, have a logical sequence and are fundamentally correct. The steps focus more on the acquisition of a system than on the actual design itself. However, steps for analyzing the problem (requirements analysis) and developing possible solutions (design synthesis) are clearly presented in the model. Although analyzing possible solutions is not clearly defined as a separate step in the model, the expression “system analysis” is mentioned in the model and could be regarded as a step, as discussed in Section 3.1.5. A step for evaluating and selecting a solution was not found in the model. Furthermore, the SE process model does not show: divergence & convergence, decomposition & integration, any relation between problems and solutions or the parallel development of concepts.
The DoD Phases model focuses on phases and the main structuring of a project. None of the criteria defined for evaluating how a model reflects the actual design process are presented in the DoD Phases model.

**INCOSE models (Section 3.1.5)**
The INCOSE SE process model presents six cyclic steps and several levels, which could be interpreted as phases. There are however some flaws or inconsistencies in the model, as also discussed in Section 3.1.5. Although steps are used in the model and iteration is presented, the steps do not have a logical sequence and not all steps are clearly defined. It is therefore difficult to determine whether all steps are fundamentally correct. Although their sequence is not always logical, steps can be
distinguished for analyzing the problem (Mission analysis), developing possible solutions (Design) and analyzing possible solutions (Concept Analysis). An evaluation and selection step is not included in the model, but can be recognized in the model by the expression “Tradeoff” in the centre of the model. The SE process model does not show: divergence & convergence, decomposition & integration, any relation between problem and solution or the parallel development of concepts.

The INCOSE Comparison of Phases model again focuses on phases and does not reflect any of the criteria defined for evaluating the design process.

**Engineering Design models**

**VDI models (Section 3.2.1)**

The VDI model of the ED process focuses on stages and does not clearly distinguish between phases or steps, as also discussed in section in Section 3.2.1. Feedback loops are added between the stages. However, as stages are not clearly steps or phases but rather a combination of the two, this does not clearly reflect the iterative design process with steps that can be repeated several times within a certain phase. As steps are not clearly presented in the model, it is difficult to evaluate their logical sequence or whether they are fundamentally correct. The stages that are presented do have a logical sequence and seem fundamentally correct. Although not all stages are clearly steps, some stages can be compared with steps, e.g. analyzing the problem (Stage 1: Clarify and Define the Task) and Developing possible solutions (Stage 3: Search for solution principles and their combinations). Comparable stages for analyzing possible solutions or evaluating and selecting a solution are not found in the model. Furthermore, the VDI ED process model does not show: divergence & convergence, decomposition & integration, any relation between problem and solution or the parallel development of concepts.

The Decomposition model developed by the VDI clearly shows the decomposition and integration in the design process as this model was developed to show exactly that. Furthermore, the model presents a relation between problem and solution, although not as clearly as e.g. the model developed by Cross. However, none of the other criteria defined to evaluate the design process are reflected in this model.

The Divergence and Convergence model developed by the VDI obviously reflects the divergence and convergence of the design process. Furthermore, the model clearly reflects the decomposition and integration in the design process and the parallel
development of concepts. The model does not show any relation between problem and solution, nor does it present an iterative process. Although several steps can be recognized in this model, they are not clearly presented as steps. Similarly to their ED process model, it is therefore difficult to determine whether steps have a logical sequence or are fundamentally correct. Compared to the ED process model, here the evaluation and selection of a concept is better reflected. Furthermore, the development of possible solutions can still be recognized in the model. The model does not show the analyzing of the problem or the analyzing of possible solutions.

**Pahl & Beitz model (Section 3.2.2)**

Compared to the VDI ED process model, the model by Pahl & Beitz better presents the steps within a phase, although the basic structures of the models are comparable. The notion of iteration is again introduced through feedback loops, but again not as an iterative process with two or more steps within a phase, but rather as an upgrade and improvement process that can involve two or even more phases. The steps that can be distinguished as part of the conceptual design phase do have a logical sequence and are fundamentally correct. Steps are included for: analyzing the problem (Identify essential problems), developing possible solutions (Search for working principles and working structures & Combine and firm up into conceptual variants) and for evaluating and selecting a possible solution (Evaluated against technical and economical criteria). A separate step for analyzing possible solutions is not included in the model. Furthermore, the model does not show: divergence & convergence, decomposition & integration or any relation between problem and solution. Although a parallel development of concepts is suggested, it is not clearly presented in the model.

**Cross model (Section 3.2.3)**

Like the VDI and Pahl & Beitz, Cross also uses stages to present the design process. However, here most of the stages can be interpreted as steps rather than phases. Steps can therefore be distinguished in the model although not always clearly. The model does suggest that the stages can be repeated several times and are part of an iterative process. However, this is less clear or explicit compared to models with e.g. feedback loops. Although not all stages are clearly steps, they do have a logical sequence. Some stages are however fundamentally not correct as steps (e.g. improving details), as also
discussed in Section 3.2.3. Stages that can be recognized as steps are: clarifying objectives (analyzing the problem), generating alternatives (developing possible solutions) and evaluating alternatives (evaluating and selecting a solution). No specific stage was defined for analyzing possible solutions. The model does not show divergence & convergence. The model does reflect the decomposition and integration in the design process, but not as clearly as the VDI Decomposition and Divergence & Convergence models. However, this model does clearly show the relations between problem and solution. A parallel development of concepts is suggested but not clearly shown in the model.

**Roozenburg & Eekels model (Section 3.2.4)**

The model by Roozenburg & Eekels clearly uses steps to present the design process. They introduce iteration as a repetition of steps by using feedback loops. The steps have a logical sequence and are all fundamentally correct. Steps are included for: analyzing the problem (Analysis), developing possible solutions (Synthesis), analyzing possible solutions (Simulation) and evaluating and selecting a solution (Evaluation & Decision). The model does not show: divergence & convergence, decomposition & integration, the relations between problem and solution or the parallel development of concepts.

**C. Multi-X evaluation matrix**

The criteria defined in Section 3.3.1 for evaluating how the models show the multiple layers, disciplines, types of people and stakeholders, are:

1. Present different layers.
2. Present different disciplines needed for development.
3. Present different types of people needed for development.
4. Present different stakeholders, with different objectives.

The evaluation matrix for the main aspect Multi-X is presented in Figure 3-19.
### Criteria

<table>
<thead>
<tr>
<th>Models</th>
<th>1</th>
<th>2</th>
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*Figure 3-19 Evaluation matrix for Multi-X*

The evaluation is clarified below.

Only two of the SE models do reflect a certain criterion. The 3D matrix by Hall (Section 3.1.1) presents the different professions or disciplines involved in developing a complex system. However, as with the phases and steps presented in Hall’s matrix models, the required interaction or relation between the disciplines is not shown. The V-process model by Sage (Section 3.1.4) presents the different perspectives or types of people needed in different phases of a project. The different layers, characteristic for AFTS’s, and the different stakeholders with their different objectives are not presented in any of the SE models. The ED models do not present any Multi-X criteria.
3.4 Summary and Conclusions

This literature survey on design methodology, relevant for the conceptual design of automated freight transport systems, has produced several interesting models. Various System Engineering (SE) and Engineering Design (ED) models have been discussed and evaluated in this chapter. An overview of the evaluation of the models in relation to the different criteria defined for each of the three main aspects is presented in Figure 3-20. This overview matrix is a compilation of the evaluation matrices for the main aspects Project Structure (Figure 3-17), Design Process (Figure 3-18) and Multi-X (Figure 3-19). The classifications A, B, C and D, reflect the number of criteria represented in the models. A indicates that most of the criteria are represented, B indicated that many of the criteria are represented, C indicates that several of the criteria are represented and D indicates that little or no criteria are represented in the model.

<table>
<thead>
<tr>
<th>Main aspects ⇒ Models</th>
<th>Project Structure</th>
<th>Design Process</th>
<th>Multi-X</th>
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<tr>
<td><strong>SE models</strong></td>
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<td>Roozenburg &amp; Eckels model</td>
<td>D</td>
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Figure 3-20 Evaluation overview matrix
From Figure 3-20 it can be concluded that none of the models satisfy all criteria and none of the models fully integrate all three main aspects (no model has an A for all three main aspects).

It should be noted that this evaluation is not an exercise to select the best model, but rather to graphically reflect (in matrix form) which criteria are represented in a certain model (Figure 3-17, Figure 3-18 and Figure 3-19) and then to show in an overview how many of the criteria are represented for each of the three main aspects (Figure 3-20). The main aim of this evaluation has been to show that none of the existing models satisfy all criteria.

It also should be noted that the letters in Figure 3-20, are not a measure for the quality of a particular model, but simply a measure for the number of criteria represented in that model. A model with a low score (D) is not necessarily a poor model.

In general it is concluded that, although all models present a number of interesting and/or useful items for the conceptual design of AFTS’s, not one integrates all aspects. The aim in the next chapter is to develop a design approach, which fulfils all criteria.
4  A Design Approach for the Conceptual Design of Automated Freight Transport Systems

This chapter presents a new design approach for the conceptual design of automated freight transport systems. The development of this design approach is presented, using the same three main aspects introduced in Chapter 2 and further discussed in Chapter 3: Project Structure, Design Process and Multi-X. Section 4.1 further clarifies how the design approach has been developed. Sections 4.2, 4.3 and 4.4 then present the specific models developed for respectively the Project Structure, Design Process and Multi-X aspects. Section 4.5 presents the integrated design approach, which has been developed by integrating the models for the three main aspects. Section 4.6 presents the summary and conclusions.

4.1  The development of the design approach

A design approach was developed, which helps to structure a project, presents the design process, and reflects the multiple layers, disciplines, types of people and stakeholders involved in and required for the conceptual design of automated freight transport systems. The goal was to develop a design approach, which fulfils all criteria for all three main aspects (see Section 3.3.1). The development of this integrated design approach is presented in Figure 4-1.

By further analyzing the criteria together with the models that best present these criteria, a design approach has been developed which fulfils all criteria important for the conceptual design of automated freight transport systems. Many of the useful elements of the different SE and ED models presented in Chapter 3 have been integrated in the design approach.
4.2 Project Structure

The main aspect Project Structure focuses on the main structuring of large complex projects. The criteria defined in Section 3.3.1 for evaluating the project structure were:

1. Use of phases for the main project structure.
2. Present phases primarily in a linear / sequential relation.
3. Clearly distinguish between phases and other elements.
4. Clearly present Conceptual Design as a phase.
5. Represent the total lifecycle of a system.
6. Present milestones at the end of every phase.

Using these criteria, and the SE and ED models that best present these criteria, a new model has been developed for the main structuring of large complex projects. In this respect, reference is made to Figure 3-17, which presents the evaluation matrix for the Project Structure in Chapter 3. Elements of the existing SE and ED models that best represent the criteria have been integrated in the new model shown in Figure 4-2.
The six criteria mentioned above, which were instrumental for the development of the new model, are discussed in more detail below.

Criterion 1. Use of phases for the main project structure.
Phases are used for the main structuring of a project. Phases structure the development of a system in the time dimension, making it possible to plan a project. SE and ED models that best present the use of phases for the main structuring of a project include: the matrix models by Hall (Figure 3-1 and Figure 3-2), the waterfall models by Royce and Sage (Figure 3-5), the V-process model by Sage (Figure 3-6), the DoD phases model (Figure 3-8), the comparison of phases by INCOSE (Figure 3-10), the Divergence & Convergence model developed by the VDI (Figure 3-13) and the Pahl & Beitz model (Figure 3-14). Many of these phases can be recognized in the new model for structuring a project.

Criterion 2. Present phases primarily in a linear / sequential relation.
The phases should be represented as being primarily sequential. Because of the long development time and the complexity of the project it is impossible to constantly go back and repeat each phase. Phases are not part of an iterative process, but are completed one after the other. Models that best reflect the linear or sequential relation between phases are: the matrix models developed by Hall (Figure 3-1 and Figure 3-2), the waterfall model by Royce (Figure 3-5), the DoD Phases model (Figure 3-8), the Comparison of Phases by INCOSE (Figure 3-10), and the Divergence & Convergence
model developed by the VDI (Figure 3-13). The new model integrates several elements found in these models. It suggests a primarily sequential relation by using a waterfall-like representation in combination with a time line, but also allows for interaction between the phases by letting the phases overlap.

Criterion 3. Clearly distinguish between phases and other elements.
Phases should be clearly presented in the model and not be obscured by or confused with other types of elements within the models. In general, phases are better distinguished in the SE models. A clear distinction between phases and steps is presented in the matrix models by Hall (Figure 3-1 and Figure 3-2). Obviously, models that present only phases, such as the waterfall models by Royce and Sage (Figure 3-5), the DoD Phases model (Figure 3-8) and the Comparison of Phases by INCOSE (Figure 3-10), also clearly distinguish between phases and other type of elements. Of the ED models, the model by Pahl & Beitz (Figure 3-14) best distinguishes between phases and steps. The new project structure model presents only phases in order to clearly distinguish between phases and other elements.

Conceptual Design should be presented as a phase. Models that clearly present conceptual design as a phase are: the waterfall and V-process model by Sage (Figure 3-5 and Figure 3-6), the Comparison of Phases by INCOSE (Figure 3-10), the ED process model and Divergence & Convergence model developed by the VDI (Figure 3-11 and Figure 3-13) and the Pahl & Beitz model (Figure 3-14). Conceptual design is also clearly presented as a separate phase in the new model.

Criterion 5. Represent the total lifecycle of a system.
The total lifecycle of a system should be represented in the model. The models that best reflect all the phases in the total lifecycle are the matrix models developed by Hall (Figure 3-1 and Figure 3-2). Although many of the other models also present various phases in the lifecycle of a system, it is not clear, complete or explicit enough. The new model presents the total lifecycle of a system from the first initiation phase to the final retirement phase.
Criterion 6. Present milestones at the end of every phase.

Milestones must be presented at the end of each phase to mark a point in time. The DoD phases model (Figure 3-8) and the Comparison of phases by INCOSE (Figure 3-10) clearly present milestones at the end of each phase. None of the other models present milestones. Milestones are integrated in the new model at the end of every phase. Such milestones allow for a formal discussion about the results of the foregoing phase and represents the start of the next phase; and ensures that everyone involved accepts this milestone and the formulated points of departure as the starting point for the next phase.

From the discussions above it can be concluded that all six criteria, defined for evaluating the Project Structure, are presented in the new model shown in Figure 4-2.

4.3 Design Process

The main aspect Design Process focuses on the actual design process within the conceptual design phase. The criteria defined in Chapter 3 for evaluating the design process were:

1. Use of steps to present design process.
2. Present design as an iterative process.
3. Present steps in logical sequence.
4. Present fundamentally correct steps.
5. Include step(s) for analyzing the problem.
6. Include step(s) for developing possible solutions.
7. Include step(s) for analyzing possible solutions.
8. Include step(s) for evaluating and selecting a solution.
9. Show divergence & convergence in the design process.
10. Show decomposition & integration in the design process.
11. Show the relations between problem and solution.
12. Show the parallel development of concepts.

Using these criteria and the SE and ED models that best present these criteria, a new model was developed for presenting the actual design process within the conceptual design phase. In this respect, reference is made to Figure 3-18, which presents the
evaluation matrix for the Design Process in Chapter 3. Elements of the existing SE and ED models that best represent the criteria have been integrated in the new model shown in Figure 4-3.

Figure 4-3 Model of the design process
The twelve criteria mentioned above, which were instrumental for the development of the new model, are discussed in more detail below.

Criterion 1. Use of steps to present design process.
Within the conceptual design phase, as within all other phases, several logical steps can be defined. These steps help to structure the conceptual design phase in a logical way and form the basis for presenting the conceptual design process. Models that present the design process using steps include: the models developed by Hall (Figure 3-1, Figure 3-2 and Figure 3-3), the SE process models by the DoD (Figure 3-7) and INCOSE (Figure 3-9), the Pahl & Beitz model (Figure 3-14), and the model by Roozenburg & Eekels (Figure 3-16). Many of these steps can be recognized in the new model of the design process. Here the defined steps are: problem analysis, system definition, system synthesis, simulation and evaluation & selection.

Criterion 2. Present design as an iterative process.
The design process is an iterative process and should be presented as such. Models that best reflect the iterative process are: the spiral model developed by Hall (Figure 3-3), the SE process models developed by the DoD and INCOSE (Figure 3-7 and Figure 3-9), and the model developed by Roozenburg & Eekels (Figure 3-16). Iteration is introduced in the new model by adding feedback loops, similar to the models developed by e.g. Roozenburg & Eekels and the DoD.

Criterion 3. Present steps in logical sequence.
Although steps can be repeated several times during the design process, they should have a logical sequence. Most models that use steps to present the design process (see criterion 1) also present the steps in a logical sequence. However, the SE process model developed by INCOSE has some difficulty with the sequence of the elements they use, as also discussed in Chapter 3. The steps of the new model have a logical sequence, as if they could be taken in one go from top to bottom.

Criterion 4. Present fundamentally correct steps.
The steps used to present the conceptual design process should be fundamentally correct. Optimization for instance is not a step, but rather a repetitive or iterative process in itself containing two or more steps. Models that present fundamentally
correct steps are: the SE process model by the DoD (Figure 3-7), the Pahl & Beitz model (Figure 3-14) and the model developed by Roozenburg & Eekels (Figure 3-16). The new model also presents fundamentally correct steps.

Criteria 5, 6, 7 and 8. Include steps for respectively analyzing the problem, developing possible solutions, analyzing possible solutions and evaluating and selecting a solution. Models representing the design process should include all these four steps. One of the first steps of the conceptual design phase should be to analyze the problem. After analyzing the problem, a logical next step is to develop possible solutions for that problem. After developing possible solutions, these solutions should be analyzed e.g. by computer simulations or prototyping. Using these simulation results, the possible solutions or concepts can be compared, and the most suitable concept can be selected. Models that include all these steps are: the matrices developed by Hall (Figure 3-1 and Figure 3-2), the spiral model by Hall (Figure 3-3), and the basic cycle of design developed by Roozenburg & Eekels (Figure 3-16). The new model also includes these four steps, named Problem Analysis, System Synthesis, Simulation and Evaluation & Selection. It is noted that, after further analyzing the different SE and ED models and comparing them to the new model under development, an additional fifth step was added to the new model. A so-called System Definition step was placed between the Problem Analysis step and the System Synthesis step in order to better position for instance the functional structuring of a system and the development of criteria. The five steps of the design process and their logical sequence are discussed in more detail in Section 4.5.

Criterion 9. Show divergence & convergence in the design process.
Both divergence and convergence are important characteristics of the design process and should be shown in the model. This is best presented in the divergence – convergence model developed by the VDI (Figure 3-13). A similar representation has been integrated in the new model of the design process.

Criterion 10. Show decomposition & integration in the design process.
Decomposition and integration is typical for developing complex systems, such as AFTS’s, and should therefore be reflected in the model. The models that best reflect this are the Decomposition model and the Divergence & Convergence model, both
developed by the VDI (Figure 3-12 and Figure 3-13). Elements from both models can be recognized in the new model.

Criterion 11. Show the relations between problem and solution.
A design process basically starts with a problem for which a solution must be found. However, apart from this primary relation from problem to solution through the design steps, there are other important (inter)relations between problem and solution. For example, contemplating possible solutions can often help to clarify and better define the problem. The model developed by Cross (Figure 3-15) best reflects the different possible relations between problem and solution. The new model also distinguishes between the primary relation from problem to solution through the various design steps, and other possible interrelations between problem and solution, presented by the two-way dashed arrow between problem and solution.

Criterion 12. Show the parallel development of concepts.
Alternative solutions or concepts should be developed during the conceptual design phase. Although these concepts could be developed one after the other, it is preferred to develop these concepts parallel to one another. This again is best reflected by the Divergence & Convergence model developed by the VDI (Figure 3-13). As discussed for criteria 9 and 10, a similar representation has been integrated in the new model.

From the discussions above it can be concluded that all twelve criteria, defined for evaluating the Design Process, are presented in the new model shown in Figure 4-3.

4.4 Multi-X aspect
The main aspect Multi-X focuses on how the models show the multiple layers, disciplines, types of people and stakeholders involved in the conceptual design of automated freight transport systems. The criteria defined in chapter 3 for evaluating the multi-X aspect were:

1. Present different layers.
2. Present different disciplines needed for development.
3. Present different types of people needed for development.
4. Present different stakeholders, with different objectives.
A new model was developed concerning the Multi-X aspect, using the above four criteria. The SE and ED models discussed in Chapter 3 were not very useful, as most of them do not reflect any of the Multi-X criteria. In this respect, reference is made to Figure 3-19, which presents the evaluation matrix for the Multi-X aspect in Chapter 3. The newly developed model is shown in Figure 4-4.

![Figure 4-4 Model of the Multi-X aspect](image-url)
The four criteria mentioned above, which were instrumental for the development of the new model, are discussed in more detail below.

Criterion 1. Present different layers.
Characteristic for automated freight transport systems are the layers: Infrastructure, Equipment, Control System and Operational Organization. These layers should all be integrated in the conceptual design phase, as presented in the model. In the past this has often been neglected, e.g. by detailing and sometimes even constructing the infrastructure before considering the equipment and control system. Project management should stimulate integration of all four layers, e.g. by forming a systems group that keeps an overview of the total integrated system and by organizing (integration) sessions during the development of the system. This is all presented at the top of the model.

Criterion 2. Present different disciplines needed for development.
The conceptual design of AFTS’s requires many different disciplines. Civil Engineering, Mechanical Engineering, Electrical Engineering and ICT are only some of the disciplines, which have to work together to design a system. This is clearly reflected by the multi-disciplinary project organization presented in the bottom half of the new model. The new model clearly presents a multi-disciplinary team approach.

Criterion 3. Present different types of people needed for development.
Apart from distinguishing between the different disciplines, one should also distinguish between the different types of people needed. The V-Process model by Sage (Figure 3-6) shows that different perspectives or types of people are needed for different phases in a project. This is also true for the different steps within the conceptual design phase. The different types of people needed for the conceptual design of automated freight transport systems are presented on the bottom left of the new model. The model distinguishes between e.g. generalists and specialists, problem focused and solution focused people, theoretical and practical people whom should all take part in the conceptual design phase.
Criterion 4. Present different stakeholders, with different objectives.
The different parties involved in a project, such as future operators, users or clients of
the system, local governments and environmental organizations, all have their own
objectives. This Multi-X criterion was not presented as a separate item in the new
model of the Multi-X aspects, but was integrated in the new model of the Design
Process (Figure 4-3). The different objectives and parties involved are shown as part
of the Problem Analysis step on the upper right side of the Design Process model.
This is of course also incorporated in the integrated design approach.

From the discussions above it can be concluded that all four criteria, defined for
evaluating the Multi-X aspect, are presented in the new models shown in Figure 4-3
and Figure 4-4.

4.5 The integrated design approach

By integrating the models developed for the three main aspects Project Structure,
Design Process and Multi-X discussed in the previous three sections, a design
approach was developed for the conceptual design of Automated Freight Transport
Systems. This integrated design approach is presented in Figure 4-5 (pages 90 and 91)
and will be discussed in more detail below.

Starting at the top left of Figure 4-5, the main project structure is presented by using
sequential phases in time. The conceptual design phase is positioned at the beginning
of the total lifecycle of a system, between the initiation phase and the detailed design
phase of a project. Although the phases can overlap, allowing for interaction, the
phases are basically sequential. Within the conceptual design phase, detailing is
sometimes necessary in order to properly evaluate a certain concept. This is also
acknowledged by letting the conceptual design phase and the detailed design phase
overlap. Finally, milestones are introduced at the end of each phase to mark a point in
time where decisions have to be made. At the end of the conceptual design phase, the
decision has to be made whether it is justified to continue with the next phase of the
project and what concept should be selected.
Although the focus of this thesis is on the conceptual design phase, it is important to
recognize and consider all other phases in the total lifecycle of a system. As phases
are primarily sequential and not part of an iterative process, and the conceptual design phase is positioned at the beginning of the total lifecycle of a system, it is even more important to consider all phases in the lifecycle of a system while working in the conceptual design phase. The decisions made in the conceptual design phase will influence all subsequent phases. Therefore, the possible consequences for all these phases should be carefully considered during the conceptual design phase. Questions one should ask during the conceptual design phase are: can we build the system, can we operate and maintain the system, can we retire the system and what are the costs and other consequences.

Apart from considering all phases in the lifecycle of a system, it is also important to consider the different characteristic layers of a system during the conceptual design phase. The four layers (Infrastructure, Equipment, Control System and Organization) that are characteristic for AFTS’s, are presented in the top right of Figure 4-5. These layers should all be considered in an integrated manner during the conceptual design phase. Project management can stimulate integration of all four layers by forming a systems group that keeps an overall overview of the integrated system and by organizing (integration) sessions during the development of the system.

The conceptual design phase usually starts with a project description and planning, which should be products from the previous initiation phase. In essence, the conceptual design phase starts with a problem for which a solution must be found. At the end of the conceptual design phase, the most suitable solution or concept should be presented. The design process which leads to this most suitable concept is presented in Figure 4-5 on the bottom left. The design process shows a logical sequence of five steps from problem to solution, starting with Problem Analysis, followed by System Definition, System Synthesis, Simulation and Evaluation & Selection. Unlike phases, steps are not necessarily taken one after the other, but are often taken in a more iterative manner, and repeated several times during the design process. The steps are discussed below.
**Main Project Structure**

**Phases**
- Initiation
- Conceptual Design
- Detailed Design
- Construction
- Operation
- Retirement

**Milestones**
- Time

**Design Process within Conceptual Design Phase**

**Steps**
- Problem Analysis
- System Definition
- System Synthesis
- Simulation
- Evaluation & Selection

**Products per Step**
- Problem Analysis: Project Goal & Need, Parties Involved, Objectives (demands, requirements, constraints), Environment
- System Definition: System boundaries, System (sub)functions, Criteria, Basic assumptions
- System Synthesis: Collect/develop building blocks, Combine into system concepts, Expected Costs, Performance etc per concept (valuation per criterion)
- Simulation: Comparison of concepts and selection of most suitable concept

**Visualization of Design Process**
- **Goal & Need**
- **Environment**
  - Parties Involved
  - System Boundaries
  - Sub-Systems
  - Sub-Functions
  - Building blocks for Sub-Functions
  - System concepts
  - Simulation of System Concepts
  - System concepts with expected properties
  - Comparison & selection of Concept
- **Evaluation matrix**
- Comparing Concepts using criteria
- **Selected Concept with specification**

**Figure 4-5 Integrated design approach (pages 90 and 91)**
Integration of all 4 Layers for AFTS in the conceptual design phase

<table>
<thead>
<tr>
<th>Infrastructure</th>
<th>Equipment</th>
<th>Control system</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept</td>
<td>Concept</td>
<td>Concept</td>
<td>Concept</td>
</tr>
<tr>
<td>Details</td>
<td>Details</td>
<td>Details</td>
<td>Details</td>
</tr>
<tr>
<td>Construction</td>
<td>Construction</td>
<td>Construction</td>
<td>Construction</td>
</tr>
</tbody>
</table>

Project Realisation Time from Conceptual Design to Operation

Type of People During Design Process

Disciplines
- Civil Engineering (CE)
- Mechanical Engineering (ME)
- Electrical Engineering (EE)
- ICT
- Logistics
- Economics
- Administration
- Human Resources (HR)
- Others...

Each Team Manager is responsible for:
- A total system concept
- A Sub-system / Function
- A Layer
- Other type of group

Manager Design Team 1
- ME
- EE
- ICT
- Admin
- Logistics
- Economics
- HR
- Others

Manager Design Team 2
- ME
- EE
- ICT
- Admin
- Logistics
- Economics
- HR
- Others

Manager Design Team 3
- ME
- EE
- ICT
- Admin
- Logistics
- Economics
- HR
- Others

Manager Design Team 4
- ME
- EE
- ICT
- Admin
- Logistics
- Economics
- HR
- Others

Manager Design Team 1
- ME
- EE
- ICT
- Admin
- Logistics
- Economics
- HR
- Others
The first step is the Problem Analysis step. The main aim of the problem analysis step is for everybody involved to understand the full problem. The problem analysis step produces the general goal of the project together with the need for the project. It distinguishes between the different parties involved (e.g. future operators, users or clients of the system, local government and environmental organizations) and collects all (possibly conflicting) objectives. The problem analysis step focuses on the outside world, collecting relevant data in order to clearly define the problem within the environment in a solution neutral way.

The System Definition step focuses the project and defines the solution space, within which alternative solutions can be developed. It guides the search for alternatives by defining the system borders, formulation of the basic assumptions and defining the criteria for selecting the most appropriate system concept. The system is defined within its environment and the system functions and sub-functions are determined. As such, the system is defined in a solution neutral way. There is however a strong iterative relation between this step and the next solution focused step in order to develop the most suitable functional structure of the system. For instance, considering existing possible solutions, with their sub-systems, often helps to define and structure the system functions and sub-functions.

The System Synthesis step focuses on developing possible solutions. The System Synthesis step contains the collection of, or searching for, alternative sub-solutions and combining these into different total solutions or system concepts. For each sub-function or sub-system defined in the previous step, different possible sub-solutions or building blocks are developed. Different total solutions or system concepts are then developed by combining different building blocks.

The Simulation step produces the expected performance, cost and other properties of the system concepts developed in the previous step. In essence, the simulation step should help to determine how the system concepts score per criterion, so that the concepts can be evaluated and compared. Although computer simulation, also referred to as virtual prototyping, is often used to determine the performance of a certain system in the conceptual design phase, this is not the only type of simulation possible. Simulation in more general terms is the imitation of a system not yet in existence. This can be done not only by building computer models or prototypes and performing experiments, but also by brainstorming with experts which are knowledgeable and experienced in the field of e.g. automation, equipments, logistics, infrastructure.
The last step is the Evaluation and Selection step. In this step the system concepts are compared to one another using the criteria defined in the system definition step. This is done, by using a so-called evaluation matrix. Different Multi Criteria Analysis techniques are available for selecting the most suitable concept. The selected most suitable concept with its specifications forms the basis for further development of the system in the detailed design phase.

Finishing with the bottom right hand side of Figure 4-5, the multi-disciplinary organization of the conceptual design of automated freight transport system is presented. Different design teams can be formed with different disciplines per team. The design teams can be organized by e.g.: system concept where each team is responsible for a certain concept, sub-system or function where each team is responsible for a certain sub-system or function for which they develop several alternatives, or layers where each team is responsible for a certain layer of the system such as infrastructure or equipment. If required, one could even form groups by using the steps of the design process (e.g. simulation group or evaluation group). Although there are many different ways to classify the design teams, it is important to recognize the multi-disciplinary team approach and to structure the project in such a way that the responsibilities per group are logical and clear. It is for instance better to make a team manager responsible for a certain concept or sub-system than to make him responsible for a certain discipline. Furthermore, it is important to maintain flexibility in the organization, as the number of design teams and the composition of the design teams most likely will need to change during the design process.

Finally, the conceptual design of automated freight transport systems does not only involve different disciplines, but also different types of people. This is reflected at the bottom centre of Figure 4-5. Although there are no fixed links between “a certain type of person” and “a certain step in the design process”, several relations can be observed. Generalists are for instance required to keep an overall broad overview and are likely to be more involved with the formulation of the general goals and needs of the project in the problem analysis step, while specialists are likely to be more involved with for example computer simulations in the simulation step. Analytical people are required for instance to analyze and structure the problem, while creative people are required to develop new ideas and possible solutions. It is important to
realize that many different types of people are required for the conceptual design of automated freight transport systems.

4.6 Summary & Conclusions

The development of a new design approach for the conceptual design of automated freight transport systems has been presented in this chapter. By integrating the specific models developed for the main aspects Project Structure, Design Process and Multi-X, a so-called integrated design approach has been developed. The criteria defined in chapter 3 for evaluating these three main aspects were instrumental for the development of the new models, and are all presented in the three new models described in Sections 4.2, 4.3 and 4.4. The integrated design approach, shown in Figure 4-5, therefore satisfies all criteria. As such the developed design approach distinguishes itself from all other models found in literature and is regarded as new and unique.

The criteria used to evaluate the three main aspects have all been discussed separately, often making reference to the SE and ED models that best present the criteria. As such, it has been explained how the design approach was developed, and which elements of the SE and ED models have been integrated in the new design approach.

The new design approach was developed after an extensive literature survey on design methodology and further analysis of the most important well-established existing SE and ED models. Apart from being new and unique, the design approach is therefore also considered to be well-founded.

Although the focus of this thesis is on the conceptual design of automated freight transport systems, the design approach can also be used for other complex systems with similar characteristics as AFTS’s.

The design approach is validated in the next chapter by demonstrating the application and practical value of the design approach.
5 The OLS Case, designing terminal concepts

OLS is an acronym for “Ondergronds Logistiek Systeem” or “Underground Logistics System”. This chapter presents the conceptual designing of OLS terminals as a case study. For this case study, the developments as they took place within the OLS project have been mirrored to the integrated design approach presented in the previous chapter. This case does not only show how the design approach can work in practice, but also presents some lessons learnt from the OLS project.

The structure of this chapter largely follows the structure of the integrated design approach discussed in Chapter 4 (Figure 4-5). Section 5.1 presents a general introduction of the OLS project and discusses the main structuring of the project. Sections 5.2 through 5.6 present the conceptual design process using the same five steps defined in the integrated design approach. The Multi-X elements are addressed throughout this chapter, wherever these are most relevant. Section 5.7 presents the basic terminal design that resulted from the design process and Section 5.8 discusses some of the changes that took place after the basic terminal design was developed, showing some of the benefits of using a structured design approach. Section 5.9 presents the summary and conclusions.

5.1 General Introduction & Structure of the project

During the 1990’s, several OLS projects were initiated within The Netherlands, concerning the underground transportation of freight. One of the first and largest projects was the so-called OLS-ASH project, focusing on transporting time-critical freight underground between Aalsmeer, Amsterdam Airport Schiphol and Hoofddorp. This chapter focuses on this project, which will be referred to as the OLS project throughout this thesis. For a broad overview of developments in Underground Freight Transport Systems (UFTS) in the Netherlands and abroad, reference is made to [Pielage et al., 2005].

The first ideas for developing the OLS were formed in the early 1990’s, involving an underground connection between one of the worlds largest flower auctions in
Aalsmeer (VBA) and Amsterdam Airport Schiphol (AAS). The deteriorating accessibility of the area, due to congestion of traffic, increasingly threatened the position of the airport and the flower auction. An underground transport system was considered a possible way to ensure sufficient transport capacity, with a minimal impact on the environment. Although the initial idea only considered a connection between the auction in Aalsmeer and Schiphol Airport, it soon became clear that a third connection, with an international railway terminal near Hoofddorp (RTH), could be very beneficial. Connecting the airport, the auction and the international railways by means of an automated underground freight transport system, would create a reliable link not only between the auction and the airport, but also with the rest of Europe by means of the international railways. An overview of the area with the initial general routing and terminal locations is presented in Figure 5-1.

![Figure 5-1 Overview of the area of OLS-ASH](image)

**Figure 5-1 Overview of the area of OLS-ASH [Pielage, 2000]**

**Main structuring of the Project**

For this subject, reference is made to the main project structure of the integrated design approach (Figure 4-5), highlighted in red in Figure 5-2. The main structuring
or phasing of the OLS project can be translated and presented according to the integrated design approach, as shown in Figure 5-3.

Figure 5-2 "Main Project Structure" highlighted (red) in the integrated design approach (Figure 4-5)

Several studies were performed in the beginning of the project, which could be seen as part of the initiation phase. These studies were undertaken to determine the feasibility and possible direction of the project. A feasibility scan, completed in January 1996, concluded that the OLS could make an important contribution to the improvement of the accessibility of the Schiphol area and could reduce the pressure on the environment [Geijn et al., 1996]. A second study, completed in January 1997, focused more on defining the direction of the project. This study produced some further financial and technical transparency and confirmed the findings of the initial feasibility scan [CTT, 1997]. The first half of 1997 was needed to round off this initiation phase and prepare for the next phase of the project, being the conceptual design phase. On July 30th 1997 the OLS steering committee decided to continue the project. This date could be seen as the milestone that marked the end of the initiation phase and the official start or go-ahead of the conceptual design phase. Although earlier studies had already addressed some of the design issues that were important in
the assessment of the feasibility of such a system, the actual conceptual design of the total integrated system started mid 1997 and continued through 1998 and 1999 [Rijsenbrij et al., 2000]. The initial planning was to start with the detailed design phase in 1999, followed by the construction in 2001 and have the system in operation by 2004 [SPC, 1999]. At the end of 1999, the conceptual design phase was largely completed. Although certain elements of the system were detailed and tested at the end of the conceptual design phase to determine for instance the feasibility of the design, the actual detailed design phase was never performed. After some final tests and last reports in 2000 and 2001, and after several discussions concerning the financial problems, the project was finally put on hold in 2002 to wait for better economic times.

Although not all phases were actually carried out, the main project structure as presented in the integrated design approach in the previous chapter (Figure 4-5) can be recognized in Figure 5-3. The phases are presented as primarily sequential, but do overlap allowing for interaction. The long development time is also clearly reflected. Furthermore, the conceptual design phase is clearly presented as an important phase in the development of the OLS system. Although not all phases are fully represented, e.g. the operational phase is not fully presented and the retirement phase was left out,
Figure 5-3 does largely reflect the structuring of the project in line with the integrated design approach discussed in the previous chapter.

**Multiple Layers**

For this subject, reference is made to the multiple layers presented as a multi-X aspect in the integrated design approach (Figure 4-5), highlighted in red in Figure 5-4. The four layers: infrastructure, equipment, control system and organization as well as the required integration of these four layers in the conceptual design phase, can also be considered within the OLS project.

Looking at the total OLS system, several different concepts were developed for e.g. the layout of the system, the type of infrastructure, the type of vehicles and material handling equipment, the type of control system and the operational organization. Although the focus will be on OLS terminals and not on the total OLS system, the four layers and their interdependence can still be clearly recognized. The integration of all four layers for the conceptual design of OLS terminals is discussed in more
Focus on OLS Terminals
As already indicated, the focus in this chapter is on the conceptual design of OLS terminals. This focus on OLS terminals was chosen because terminals formed one of the main areas of expertise of the author of this thesis, during the OLS project. Furthermore, terminals can be clearly defined as sub-systems within the total OLS system, while still incorporating all the characteristics of automated freight transport systems as discussed in Chapter 2. For this case, terminals are considered as the system to be developed.

Project Organization and Multi-X elements
For this subject, reference is made to the project organization with multiple disciplines and different types of people, presented as Multi-X aspects in the integrated design approach (Figure 4-5), highlighted in red in Figure 5-5. Such a project organization can also be considered for the OLS project.

Figure 5-5 Project organization, multiple disciplines and different types of people highlighted (red) in the integrated design approach (Figure 4-5)
OLS Project Management considered terminals as one of the main focus areas. Answers would have to be produced on e.g. the required area, the terminal performance and service levels to be offered and the desired interaction with the different clients. Many different disciplines took part in the design team responsible for the terminals. Civil engineers, mechanical engineers, electrical engineers, ICT specialists, administration and organization specialists were most frequently involved, although the composition of the design team often changed. Apart from the different disciplines, the development of the terminal concepts required frequent interaction with other design teams, responsible for e.g. the tunnel infrastructure, the vehicles and the overall control system. Figure 5-6 presents the main project organization including the OLS steering committee, the management team, the support office and three main project groups: SPC (Schiphol Project Consult), CTT (Centre for Transport Technology) and COB (Centre for Underground Construction). The terminal design team was officially positioned within the CTT project group, although members from both other project groups also participated in the conceptual design of terminals for the OLS. This demonstrates the multi-disciplinary elements of the Multi-X aspect.

Figure 5-6 Main project organization, after [SPC, 1999]
During the conceptual design phase of the OLS project this main organizational structure was maintained. However, the design teams positioned within this main structure, did often change. Not only the composition of the design teams changed, but entire design teams were formed and again dismantled during the conceptual design phase, depending on their specific tasks. These experiences within the OLS project formed the main reasons for integrating the multi-disciplinary organization aspects and the use of design teams in the integrated design approach as is now presented in the previous chapter, but at that time this was still under development. It could be argued that the main organizational structure of the OLS project has been too rigid as it separated the organizational or management aspects (SPC group), the transport technological aspects (CTT group) and the infrastructure aspects (COB group). However, by organizing several sessions with all parties involved, the project management tried to keep the project together as an integrated project. In the end, this proved to be a very challenging task. One lesson learnt is not to organize a project too strictly according to a certain discipline or area of expertise, such as transport technology or infrastructure, but to allow for a more flexible organization with working groups which can be modified during the project if and when required. Furthermore it could prove useful to organize working groups or design teams in such a way that their responsibility can be defined more clearly. Instead of thinking in disciplines or layers for structuring the groups, one could for instance think in sub-systems (such as terminals) which integrate multiple disciplines and layers, as discussed in Chapter 4.

The different types of people involved in the conceptual design of OLS terminals, is the last Multi-X element of the design approach discussed in this section. Being such a large and complex project, the OLS project involved many different types of people. The generalists, often taking a broader perspective, were mostly found in the management and coordinating functions within the project. The more analytical people often excelled in analyzing a certain existing situation or system, while the more creative people excelled more in developing innovations. Likewise, problem focused people tried to fully understand the problem, while solution focused people emphasized more on developing a feasible solution. Furthermore, it was observed that the more practical types of people focus more on the practicality of the concepts being developed, while the more theoretical types of people were more concerned with the
methodology and scientific developments. Finally, integrators and communicators were needed to bring it all together and present the final concept. All these different types of people were needed within the conceptual design phase of the OLS project. Clearly, the conceptual design phase forms a very challenging phase in the development of automated freight transport systems. It requires many different types of people to work together and listen to one another, with enough drive and focus to actually develop a new and complex system.

As discussed in Chapter 4, one can link certain types of people to certain steps in the design process. Although this is not always true for all types of people, it can help to select the right type of person for the right job. For example, the analytical and problem focused type of people can be linked to the problem analysis step and the system definition step, while the creative solution focused type of people can be linked to the system synthesis step.

In retrospect it can be stated that at the beginning of the conceptual design phase, no real attention was paid to the types of people required. The integrated design approach presented in the Chapter 4 should help avoid this in the future.

5.2 Problem Analysis

For this subject, reference is made to the problem analysis step of the integrated design approach (Figure 4-5), highlighted in red in Figure 5-7. The problem analysis step has been defined as the first step in the conceptual design process. Although the problem could (or should) have been formulated in the initiation phase, it is necessary to (re)formulate the problem in the conceptual design phase in more detail. This stimulates the communication between all parties involved and helps the conceptual design team to understand the full problem. Furthermore, the problem formulation often changes during the initial phases of a project.

Following the integrated design approach presented in the previous chapter (Figure 4-5), the problem analysis step should:

- Produce the general goal and need of the project.
- Distinguish between the different parties involved and collect all (possibly conflicting) objectives.
Clearly present the problem within its environment.

This section discusses these aspects in more detail.

5.2.1 The Goal & Need of the project

The goal of a project should be formulated as a broad statement of intent, that all parties involved want to achieve. The goal for the OLS was to develop an automated underground freight transport system to transport flowers and other time-critical cargo between the flower auction in Aalsmeer, Schiphol Airport and an international Railterminal near Hoofddorp. Although alternative methods or modes of transport were also considered, such as conventional road or rail transport above ground, these were not the focus of the OLS project.

The need of a project should indicate why a project is necessary. The need highlights the actual problem, formulating undesired situations now or in the future. The reason why the OLS project was initiated was foremost the deteriorating mobility in the area due to the growing congestion of road traffic, which increasingly threatened the
The position of Schiphol airport and the flower auction at Aalsmeer. Furthermore, as the expansion of existing road infrastructure was not always possible or desired in this densely populated area, underground freight transportation was considered an interesting alternative worth researching (also for the future).

A technique that can be used to help define the general goal and need of the project is generalization or abstraction. Generalization of the more specific objectives of the different parties involved would facilitate the formulations of a general goal of the project as something all parties involved want to achieve. However, as will be discussed in the next section, it is not always easy to formulate what all parties involved really want. Some simple questions that can help to define the goal and need are:

- What do we want? (goal)
  - What do we want to achieve?
  - What is the transport systems supposed to do?
  - What service must be offered by the system?
- Why do we want it? (need)
  - Why do we want to achieve it?
  - Why is it important to develop this transport system?
  - What is wrong with the present situation?
  - What will happen in the future if nothing is done?
  - Is it important for the future business position?

### 5.2.2 Parties involved and their objectives

Recognizing all the different parties involved and formulating their objectives is another important part of the problem analysis step. In this case, the parties involved are the parties that have (or should have) some say in the outcome of the project. Parties involved could therefore be future operators of the system, future clients of the system, local/national governments, financial institutes, but also for instance environmental organizations. Here, parties involved are not the members of the design teams but rather parties who together formulate the objectives that the design teams should meet. For the OLS project the parties involved were e.g. the flower auction in Aalsmeer (VBA), Amsterdam Airport Schiphol (AAS), the Dutch Railways (NS), the
Dutch Distribution Council (NDL) and the Air Transport Association Netherlands (ATAN), the Ministry of Transport, the Ministry of Economical Affairs and the local municipalities. These were all part of the OLS steering committee. Furthermore, the objectives of for instance the local environmental organizations and the fire department also had to be taken into account. Although many of the parties often participated in the project, for instance as members of steering committees, they were not part of the design teams. This meant that it was necessary to formulate their objectives as clearly as possible. This would prove very difficult, as is discussed below.

Objectives can be demands or requirements (items that the parties involved want to achieve) but also constraints or restrictions (items that the parties involved want to avoid). In theory, one would like to formulate the general goal of the project by generalizing the more specific objectives of the different parties involved, as mentioned in the previous section.

So called "objectives trees" can be used to structure and analyze the objectives. Objectives trees are formed by placing lower level objectives under higher level objectives, as means to an end, or as a more specific formulated objective under a more generic formulated objective, thus forming treelike structures. This structuring of objectives helps to clarify one's aims and to identify missing objectives [Roozenburg & Eekels, 1998]. The objectives can be explored "top down" in order to find lower level objectives which are usually more operational and easier to measure, and "bottom up" to identify any missing yet essential higher-level objectives. Objectives trees can therefore help, not only to formulate the general goal of a project, but also to formulate the lower level objectives. More on objectives-trees can be found in e.g. [Roozenburg & Eekels, 1998].

It is noted that it is not always possible to fulfil all objectives in the same manner. These so-called conflicting objectives will in turn result in conflicting criteria, for example low costs versus high performance. The criteria developed for the OLS will be discussed in Section 5.3.3.

Within the OLS project an attempt was made to clearly formulate and structure the objectives. In fact, an “OLS Users” group was formed to investigate what future users of the system would want. However, it proved very difficult firstly to identify all the
parties involved (e.g. who will be the users in 2010?) and secondly to formulate their objectives (what would a future user want?). As a result, the objectives that were formulated were often incomplete and not very specific or quantified. The following main objectives were formulated for the OLS [Haverman et al., 1999]:

1. The OLS must be cost effective.
2. The OLS must be socially acceptable.
3. The OLS must be able to handle the flows of goods between the airport, flower auction market and rail terminal.
4. The OLS must be rapid enough.
5. The OLS must be sufficiently reliable.
6. The OLS must be sufficiently available.
7. The OLS must be sufficiently accessible.
8. The OLS must make a positive contribution to the spatial structure.
9. The OLS must be sustainable.
10. The OLS must be safe.
11. The OLS must have a good management structure.
12. The OLS must link up to the national and international rail transport systems (Feeder activity).
13. The OLS, in combination with the rail transport system, must compete with road and air transport.

Although many more objectives were formulated, which could all be positioned under one of the main objectives as suggested by the objective-tree methodology, the objectives formulated remained incomplete and not specific enough. For example, formulating a requirement that the OLS must be rapid enough, which was later further specified as “at least as fast as road traffic”, is not specific enough. Not only because this statement has no quantitative value, making it difficult to measure, but also because the point of reference will change over time, as the time it will take by road will change. As most of the objectives were not specific enough it would prove very difficult to formulate the criteria for developing and evaluating the terminal concepts. This will be discussed in more detail in the next section. For a complete overview of the objectives formulated for the OLS project reference is made to [Haverman et al., 1999].
One of the lessons learnt in the OLS project was that, although it was clearly considered important to involve all the different parties and formulate their objectives, it proved very difficult to formulate all the objectives in such a way that they could be useful for the design process. This was partly because not all “future users” were involved in the project, but most likely also because the parties that were involved, were asked to formulate requirements for a system they could not yet envisage. In future, more effort should be made to involve all the parties in the iterative conceptual design process, so they can specify and quantify their objectives as clearly as possible.

5.2.3 General project environment

The environment in which a project has to be realized is also of importance. For instance: the local political situation, the local social situation, the local geographical situation, but also the time and budget available for the project are important issues.

Specifically for automated freight transport systems, the costs of labour and local working conditions can have a major influence on the choices made during the design process or even the general direction of the project. An assessment of the environment in which the project has to be realized is of importance for a successful development of a system.

At the start of the conceptual design phase of the OLS project in 1997, the political and financial situation in the Netherlands was quite favourable for developing new innovative transport systems that could help to solve the increasing transport problems within a small densely populated country like the Netherlands. Furthermore, the unemployment was quite low and the standard of living quite high, making automation an interesting option. All this created a favourable situation for starting a large-scale project such as the OLS with sufficient funding and time available.

Although the environment of a project is very important for its success, or even its existence, this thesis will focus on the actual design process.

As a final remark on the problem analysis step it is noted that, although the problem analysis step is the first step of the conceptual design process, it does not have to be
completed before starting with the next step. It is possible and in practice quite likely that one understands the problem better after contemplating possible solutions. This is true for the design teams, but also for the other parties involved. As a result, many objectives are formulated only after the parties involved get a better idea of what could be possible with the system under development. This further illustrates the iterative nature of the design process, not only for the design teams but also for the other parties involved. Furthermore the development of AFTS’s takes a long period of time, during which things will change. Even the parties involved and the general goal and need of the project may change during the conceptual design phase. Therefore, the objectives and other products of the problem analysis step are in practice also developed in an iterative manner during the conceptual design phase, and not necessarily clearly defined at the beginning of the conceptual design process. However, the objectives and goal of the project should become clearer during the conceptual design phase.

For the OLS project it can be said that, although the need remained the same during the conceptual design phase, the goal changed somewhat from developing an underground freight transport system to developing an undisturbed freight transport system. The objectives indeed were developed during the course of the project, but were never made very specific. The project environment also changed, from a very healthy financial and economical situation to a much more troublesome economical situation, with less willingness to accept risks or to invest in innovations.

5.3 System Definition

For this subject, reference is made to the system definition step of the integrated design approach (Figure 4-5), highlighted in red in Figure 5-8. The system definition step has been defined as the second step of the conceptual design process. This step should define the solution space, in which alternative system concepts can be developed. In this case, the OLS terminals are considered the system to be developed.

Following the integrated design approach presented in the previous chapter (Figure 4-5), the system definition step should produce:

- The system boundaries and interfaces.
- The system functions.
- The criteria for selecting the most appropriate concept.
- The basic assumptions.

This section discusses these aspects in more detail.

Figure 5-8 "System Definition" step highlighted (red) in the integrate design approach (Figure 4-5)

5.3.1 The system boundaries and interfaces

The OLS system can be presented as shown in Figure 5-9. The centre presents the OLS system itself as a link between the flower auction, the airport and the railway station. At the interfaces (red lines in Figure 5-9), cargo and information are moved from one system to the other.

The OLS system as a whole can be divided into two sub-systems: the OLS Terminals and the OLS Transport system. OLS terminals are positioned between the OLS transport system and the various clients and as such take care of the interfaces between the various clients and the OLS transport system. The transport system takes
care of the actual physical transport of cargo between the terminals. The focus here will be on the terminals.

![Diagram of OLS system boundaries](image)

**Figure 5-9 OLS system boundaries, after [Haverman et al., 1999]**

The initial system layout with the different terminal locations is presented in Figure 5-10. The figure shows one OLS terminal near Hoofddorp (left), three terminals at Schiphol Airport (centre) to serve the different cargo areas and one terminal at the flower auction in Aalsmeer (bottom right). Figure 5-10 also shows the proposed routing of the transport system (with alternatives presented as dashed lines) and the different building techniques possible for the infrastructure. Circular bored tunnels are considered as the main infrastructure to connect both, the rail terminal to the airport and the airport to the auction. Close to the rail terminal and within the Schiphol area, the tunnels will be built largely by using the so-called cut and cover method, producing rectangular shaped tunnels. Near the flower auction a section of the route can be built above ground, as there is only limited interference with other infrastructure on that section. Although the focus here is on developing terminal concepts, it is important to understand how the connecting infrastructure could be built, for example to consider how the terminals can be connected to the tunnel infrastructure and which constraints should be taken into account and/or discussed.
Defining system boundaries is necessary to focus the design activities. It defines the area in which to search for alternative solutions. However, the system boundaries should not be interpreted too strictly. As with all other aspects in the design process, systems boundaries may change over time. Shifting boundaries is also a technique that can be used to help to define the system boundaries and possible sub-systems. By moving the boundaries one can analyze what the most suitable or likely boundaries are.

**Terminal Interfaces**

After defining the system boundaries, one should define the interfaces between the systems. Considering a terminal as a system, two main interfaces can be distinguished: the interface with the OLS transport system and the interface with the various clients of the OLS. Both are discussed below.

**Interfaces with clients**

The interfaces with the various clients are represented by the red intersections in Figure 5-9. These intersections mark the locations where the cargo is transferred
between the systems. The interfaces with the various clients located at the flower auction, airport and rail terminal, are of course not all the same as different clients have different types of cargo that must be transported by the OLS system. Figure 5-11 shows some of the different types of cargo. The development of alternative concepts to handle all these different types of cargo, is discussed in the system synthesis step (Section 5.4).

<table>
<thead>
<tr>
<th>Auction cart</th>
<th>Danish cart</th>
<th>euro pallet</th>
<th>Airmodule</th>
<th>10 ft. aircraft pallet</th>
</tr>
</thead>
<tbody>
<tr>
<td>lxwxh = 130x104x260 [cm]</td>
<td>lxwxh = 135x57x240 [cm]</td>
<td>lxwxh = 120x80/100x240 [cm]</td>
<td>lxwxh =122x102x150 [cm]</td>
<td>lxwxh = 318 x 244 x244 [cm]</td>
</tr>
</tbody>
</table>

**Figure 5-11 Different types of Cargo to be transported by OLS [Pielage et al., 1999-a]**

The physical appearance of the cargo to be transported by the system is not the only aspect of importance. The volumes to be transported and the distribution of these volumes over time are also important aspects for the conceptual design of a transport system, for instance to determine the number of required transport vehicles needed, or to check the required service levels (performance) of the terminals. Transport volumes can be expressed in Tons per year or m$^3$ per year, which are preferred units for bulk transport systems. However, using “units to be transported” (like containers or pallets) is a preferred method here. By using transport units per year, one can more easily convert to the number of transport jobs a system has to handle. For the OLS such a standard transport unit was defined as a TRE (TRansport Eenheid). The TRE was chosen as the equivalent of a 10-feet main deck aircraft pallet with base dimensions 318 x 244 centimetres, a maximum height of 3 metres and a maximum load of 3500 kg. A TRE can comprise of one 10 foot aircraft pallet, six euro pallets, eight Danish (flower) carts or 4 auction carts, as shown in Figure 5-12.
After defining the standard transport unit, all the separate flows could be translated from for instance tons per year or carts per year to TRE per year. Figure 5-13 shows the prognosis for the transport volumes in TRE/year for the year 2020 [Dunselman et al., 1999-a]. At this point, no choice was made with respect to the physical appearance or realization of the TRE.

Figure 5-12 Definition of a standard transport unit (TRE) [Dunselman et al., 1999-a]

Figure 5-13 Prognosis of transport volumes in 2020 in TRE/year [Dunselman et al., 1999-a]
The transport volumes are however not evenly spread over the year, month, week or day. Although one could dimension a system on the peak capacity, required perhaps only once a year, this would result in a very expensive system with an enormous overcapacity during normal/average operations. Therefore, a peak day within an average week in an average month was chosen for dimensioning the OLS system. The number of TRE per month amounted to 1/12 of the total number in a year, and the weekly demand was again a proportional part of the monthly demand and amounts to 12/52 of the average monthly total. This weekly total was then spread over the days using the distribution shown in Table 5-1. The simulations that have been carried out are based on the peak day (Tuesday) in an average week in an average month, using the distribution over the day as shown in Figure 5-14 [Harten et al., 1998].

Table 5-1 Distribution of the weekly flow in percentages over the week [Harten et al., 1998]

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AAS</td>
<td>VBA</td>
<td>30</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>VBA</td>
<td>AAS</td>
<td>14</td>
<td>28</td>
<td>14</td>
<td>10</td>
<td>21</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>VBA</td>
<td>RTH</td>
<td>14</td>
<td>28</td>
<td>14</td>
<td>10</td>
<td>24</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>RTH</td>
<td>VBA</td>
<td>30</td>
<td>15</td>
<td>10</td>
<td>25</td>
<td>5</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>AAS</td>
<td>RTH</td>
<td>28</td>
<td>21</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>RTH</td>
<td>AAS</td>
<td>10</td>
<td>10</td>
<td>14</td>
<td>24</td>
<td>25</td>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>

AAS: Amsterdam Airport Schiphol
VBA: Verenigde Bloemenveiling Aalsmeer (Flower auction Aalsmeer)
RTH: Rail Terminal Hoofddorp
Figure 5-14 Distribution in percentages over a day [Harten et al., 1998]

Interfaces with OLS transport system.

The other main interface is between the OLS terminals and the OLS transport system. As already indicated when discussing the layout of the system, it is important to consider how the terminals can be connected to the tunnel infrastructure. Apart from the infrastructure, one should also consider possible interfaces associated with the other layers: equipment, control system and operational organization. For the conceptual designing of the OLS terminals, most emphasis was placed on the interfacing of the infrastructure and equipment, which will be discussed in more detail below. The operational organization and control system were, at the time of designing...
terminal concepts, still under development and clear interfaces had yet to be defined. Nevertheless, all four layers were considered during the designing of terminal concepts and will be discussed in the system synthesis step and the simulation step (Sections 5.4 and 5.5).

The way the terminals can be connected to the tunnels depends on the orientation or position of the terminals in relation to the tunnels. Using the initial system layout and terminal locations (Figure 5-10) as point of departure, two basic terminal connections were defined: the Through Terminal and the End Terminal as shown in Figure 5-15. The terminals were thought to be on ground level connected to the underground tunnel infrastructure by means of slopes. Although variations were still considered possible, these were some of the points of departure used for developing terminal concepts, which will be discussed in more detail in Section 5.3.4. The green areas shown in Figure 5-15, graphically present the areas in which terminal concepts can be generated.

![Figure 5-15 Two basic terminal connections [Pielage et al., 1999-a]](image)

Apart from the infrastructure connections, the different vehicle concepts were also a main concern for the conceptual design of terminals. For the OLS project, three different vehicle concepts were developed, each by a separate design team. Figure
5-16 presents the three vehicle concepts, each with their own specific characteristics. These three vehicle concepts were taken as points of departure for the development of terminal concepts.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Specific Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spykstaal vehicle</td>
<td>• Rubber tyred AGV with full electronic guidance</td>
</tr>
<tr>
<td></td>
<td>• Front-wheel steering</td>
</tr>
<tr>
<td></td>
<td>• Front and side loading</td>
</tr>
<tr>
<td></td>
<td>• DC electric drive</td>
</tr>
<tr>
<td></td>
<td>• Battery powered</td>
</tr>
<tr>
<td>Lödige vehicle</td>
<td>• Rail mounted AGV in tunnel and rubber tyred electronic guided on terminal</td>
</tr>
<tr>
<td></td>
<td>• Four-wheel steering</td>
</tr>
<tr>
<td></td>
<td>• Two Side loading</td>
</tr>
<tr>
<td></td>
<td>• AC electric drive</td>
</tr>
<tr>
<td></td>
<td>• Battery powered on terminal and power rail in the tunnel</td>
</tr>
<tr>
<td>DTM vehicle</td>
<td>• Rubber tyred AGV, self guidance in tube (wheels on tube surface) electronic guidance on terminal</td>
</tr>
<tr>
<td></td>
<td>• Front-wheel steering</td>
</tr>
<tr>
<td></td>
<td>• One side loading</td>
</tr>
<tr>
<td></td>
<td>• AC electric drive</td>
</tr>
<tr>
<td></td>
<td>• Battery powered</td>
</tr>
</tbody>
</table>

Figure 5-16 Three OLS Vehicle concepts [Rijsenbrij et al., 2000] & [Pielage, 2001]

Although each vehicle had its own specific characteristics, there were also some general vehicle specifications defined for all vehicles, to allow for a better interfacing between vehicles and terminals:

- All vehicles must transport all types of cargo (see Figure 5-11).
• All vehicles must be fully automated and be free ranging on terminals (Vehicle routings are defined by software rather than by fixed infrastructure elements such as rails).
• All vehicles must be electrically powered on the terminal (without external power supply).
• A vehicle must be able to travel at 6 m/s in the tunnels and 2 m/s on the terminals, manage slopes up to 12% and accelerate with 1 m/s².

The development of different concepts for handling equipment and their interrelation with the different vehicle concepts will be discussed in the system synthesis step (Section 5.4).

5.3.2 System functions

For the OLS terminals, the following main functions can be distinguished:

• Vehicle handling on the terminal.
• Loading and Unloading the vehicles.
• Material handling on the terminal.

The different concepts or building blocks that were developed for these main functions are discussed in the system synthesis step (Section 5.4).

Although this suggests a top down approach, first define the functions and then develop possible solutions or building blocks that could fulfil these functions, this was of course not the case. As discussed before, designing is an iterative process, which is also true for defining functions and the development of possible concepts or building blocks. The functions defined above were formulated mainly in retrospect for this case. However, the building blocks used in the OLS project to develop terminals concepts were seen as sub-systems of the terminal and do allow for such a functional structuring. As such, the systematic approach for developing systems concepts (defining system and sub-systems, defining functions, creating building blocks for these functions and developing system concepts by combining building blocks) is demonstrated in this case.
5.3.3 Criteria

In theory, one should be able to formulate the criteria by using the objectives formulated in the problem analysis step. The criteria, to be used for evaluating and selecting the concepts, should reflect what the different parties involved want to achieve or expect from the system. However, as discussed in the previous section, the objectives formulated for the OLS project were incomplete and not very specific. As a result, the criteria were also not very clear. This of course influenced the entire conceptual design process, including also the system synthesis step and the simulation step as is shown in the integrated design approach (Figure 4-5), and will be discussed in more detail in the following sections.

In retrospect, the only two criteria considered important for the terminals were the area utilization and the service or performance. Both criteria were taken into account during the development of the various concepts (Section 5.4), the simulation activities (Section 5.5) and the evaluation and selection of terminal concepts (Section 5.6).

Although other criteria were mentioned during the conceptual design process, such as investment costs and operational costs, these were never actually used as criteria for the conceptual design of OLS terminals. However, at the end of the conceptual design phase, terminal costs were estimated as part of the total estimated cost of the OLS system as a whole.

As mentioned above, costs as such, were not used as a criterion for evaluating and selecting terminal concepts. However, by considering the required area for the terminals, the infrastructure costs were considered, be it indirectly. Furthermore, by separately evaluating the vehicles and material handling equipment, as will be discussed in Sections 5.5 and 5.6, the feasibility and possible costs for the equipment were considered, be it more hidden within the development of the terminal concept and not at the end during the system evaluation and selection.

This case showed again that it is important to define the criteria more clearly. The criteria should be used throughout the conceptual design process and guide the development of concepts. If the criteria are not clear or explicit enough, they will not be used throughout the conceptual design process and cannot be used for guidance to
develop alternative concepts. Furthermore, the selection of the most appropriate concept will not be very transparent and therefore more difficult to explain or defend. This will be discussed in more detail in the evaluation and selection step (Section 5.6).

For future reference, the following items are suggested as a minimum set of criteria to be considered for the conceptual design of automated freight transport systems:

- Costs (Investment cost, operational cost etc.).
- Performance (Average, peak, availability/reliability etc.).
- Flexibility (Scalability, expandability, adaptability etc).
- Environmental impact (Use of Land, energy consumption, pollution etc.).
- Risk (for investors, users etc.).
- Working conditions (safety, ergonomics for operators, maintenance engineers etc.).
- Maintenance impact (up time etc.).

In the ideal situation, criteria can be calculated or quantified. This can be done e.g. for the costs or performance of a concept. Some criteria however, are more difficult to quantify. It is for instance difficult to calculate the flexibility of a certain concept. These and other evaluation and selection issues are discussed in more detail in Section 5.6.

As a final remark on defining criteria for the conceptual design of automated freight transport systems, it is noted that it is not always possible to clearly define all the criteria and integrate these in the conceptual design process. Not only because the objectives are unclear, or because designing is an iterative process and not all criteria are defined at the beginning of the conceptual design process, but also because it is not always possible to consider all these criteria during the conceptual design phase within the given budget and time frame. Quantifying some criteria may take too much detailing, time and/or money, which is not always available during the conceptual design phase. However, it is recommended to pay a lot of attention to defining all the criteria as clearly as possible.
5.3.4 Basic assumptions / points of departure

The basic assumptions or points of departure are formulated by the design team and are not necessarily a product of the objectives formulated by the other parties involved. They are formulated to focus and guide the design process. Points of departure can simply be a bullet summary of the most important aspects already discussed in this section, but can also contain other additional statements which help the design team going. This is sometimes needed if there are still too many possibilities and/or unknowns, which would hinder the development of possible solutions. Although formulating such points of departure can be seen as limiting the conceptual design process, it can also be seen as a method to systematically search for other possible directions. Formulating points of departure, in order to keep the direction of design as clear as possible, helps to consider and distinguish other design directions, by systematically changing points of departure. Thus, the formulation of basic assumptions or points of departure can stimulate the search for alternative solutions.

For developing OLS terminal concepts, the following points of departure were formulated [Pielage, 1999-b] & [Rijsenbrij et al., 2000]:

- Terminals are located on ground level, where interaction can take place with the various clients in the area.
- Terminals are connected to the tunnel infrastructure by slopes.
- OLS vehicles will not leave the OLS system boundaries, although in future it must still be possible to extend these boundaries into e.g. the warehouses of the clients.
- OLS vehicles destined for a certain terminal must not hinder the main ongoing traffic.
- Only OLS vehicles destined for a terminal may enter this terminal.
- On the terminal, the OLS vehicles must be free ranging.
- The OLS vehicles are loaded and unloaded on the terminals at so called docks.
- The loading and unloading at the docks is done horizontally.
- The terminals must be able to handle all types of cargo mentioned in section 5.3.1 (e.g. pallets, carts, ULD’s).
• Long-term storage of cargo or vehicles is not a primary function of the terminals and will therefore not take place at the terminals. Operational buffering of cargo and vehicles however should be possible.

These points of departure were used for developing the terminal concepts discussed in the next section.

5.4 System Synthesis

For this subject, reference is made to the system synthesis step of the integrated design approach (Figure 4-5), highlighted in red in Figure 5-17.

Figure 5-17 "System Synthesis" step highlighted (red) in the integrated design approach (Figure 4-5)

The system synthesis step has been defined as the third step of the conceptual design process and focuses on developing the actual system concepts. Following the integrated design approach presented in the previous chapter (Figure 4-5), the system synthesis step should produce alternative system concepts by combining different (sub-)solutions or building blocks for the different (sub-)functions defined in the
previous step. This section first discusses the building blocks developed for the OLS terminals, followed by the terminal concepts themselves.

### 5.4.1 Building blocks

In order to develop terminal concepts, building blocks were created for:
- Vehicles.
- Loading Docks.
- Material handling.

These building blocks correspond with the functions defined in the previous step. As discussed in Section 5.3.2, these functions were defined mainly in retrospect for this case, to demonstrate how the design approach presented in the previous chapter could work in practice. The building blocks created for developing terminal concepts are discussed below.

#### Vehicles

For developing terminal concepts, the three vehicle concepts discussed in the previous step were simplified and reduced to the two main vehicle concepts: the low loader concept and the flat bed concept, as presented in Figure 5-18.

![Figure 5-18](image_url)  
*Figure 5-18 Two main vehicle concepts for terminals [Pielage, 1999-a]*

The low loader concept has its loading deck between the front and rear wheels, thus allowing for a lower vehicle and thus smaller tunnel dimensions. The vehicle however
does have a longer wheel base, and the cargo can only be handled over the left and right side of the vehicle.

The flat bed concept has the wheels under the loading deck, making the vehicle higher. The wheelbase can be shorter, allowing for tighter manoeuvres on the terminal. Theoretically cargo can be handled on all four sides of the vehicle.

Although there are still some variations possible for both vehicle concepts, e.g. the number of steering axles which will influence the manoeuvring capabilities, these were the two basic vehicle concepts considered as building blocks for designing terminal concepts. The different vehicles concepts will be discussed in more detail in Section 5.5.

**Loading docks**

After entering the terminal, the free ranging vehicles will drive to a certain dock to unload and/or load cargo. Three different possible docking concepts are presented in Figure 5-19: side docking, double-side docking and front-side docking.

![Three docking concepts](image)

**Figure 5-19 Three docking concepts [Pielage, 1999-a]**

For the side docking concept, the vehicle will exit the normal driving lane on the terminal and dock parallel to this lane, thus not hindering the other ongoing traffic on the terminal. The cargo can then be handled over the side of the vehicle. After loading and/or unloading the vehicle continues and re-enters the driving lane, driving in the same direction.
For double-side docking, the vehicle will exit the normal driving lane by turning into the dock positioned at a 90-degree angle. The double-side docking concept can handle the cargo over both sides of the vehicle, making it possible to unload over one side of the vehicle and immediately load over the other side. This allows for a fast combined loading and unloading operation. After loading and unloading, the vehicle leaves the dock in opposite direction. The vehicle must be able to drive normally in both directions.

For the front-side docking concept, the vehicle will exit the normal driving lane on the terminal and docks at an angle of e.g. 45 degrees. The cargo can then be handled over the front and over one side of the vehicle. After unloading and/or loading, the vehicle will reverse and can wait parallel to the normal driving lane before re-entering the driving lane on the terminal. The vehicle has one main driving direction, but can also reverse.

There is a clear interaction between the type of vehicle concept and the type of docking concept. For example, the low loader vehicle concept fits better with the first two docking concepts, while the third docking concept fits best with the flat bed vehicle concept. Furthermore, the type of docking also influences the vehicle concepts e.g. with respect to the driving direction (does a vehicle have to reverse) and number of doors required for loading and/or unloading (1 or 2 sides, front or rear etc.). How the vehicle building blocks are combined with the docking building blocks is discussed in Section 5.4.2.

**Material handling**

After docking, the cargo can be handled in different ways. The cargo can for instance be handled by lifting or rolling in and out the vehicle. Also, so called “slave pallets” can be used instead of separate handling of all different types of cargo in and out of the vehicles. Four different concepts developed for the material handling are presented in Figure 5-20 [Dunselman et al., 1999-b]. The basic idea was to choose between rolling and lifting, combined with the use of slave pallets or separate handling of the different types of cargo.
The first concept, rolling cargo and using slave pallets, can be seen as the state of the art for handling air cargo. All the different types of cargo are placed on a slave pallet, which is then handled by roller conveyors. Both, the dock and the vehicles will be equipped with rollers for loading and unloading the slave pallets. Roller conveyors on the terminal will take care of the transport between the docks and the different clients. Clients are presumed to deliver and receive the cargo using slave pallets.

The second concept, lifting cargo in and out the vehicle combined with the use of slave pallets, can have some advantages as lifting can overcome the differences in height between vehicle and dock. Furthermore, the vehicle does not have to be equipped with rollers, saving vehicle mass and therefore energy consumption. Similar to the first concept, roller conveyors can transport the cargo between docks and clients. Also for this concept, clients are presumed to deliver and receive the cargo using slave pallets.

The third concept, rolling all different types of cargo separately in and out the vehicle, has the advantage that no slave pallets will be needed thus avoiding the extra costs for

<table>
<thead>
<tr>
<th>1. Rolling cargo &amp; use of slave pallets</th>
<th>2. Lifting cargo &amp; use of slave pallet</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image 1" /></td>
<td><img src="image2.png" alt="Image 2" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Rolling cargo &amp; separate cargo handling</th>
<th>4. Lifting cargo &amp; separate cargo handling</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3.png" alt="Image 3" /></td>
<td><img src="image4.png" alt="Image 4" /></td>
</tr>
</tbody>
</table>

Figure 5-20 Four material handling concepts [Dunselman et al., 1999-b]
purchase, maintenance and empty handling of these pallets. The handling itself however is more complex, as all different types of cargo will have to be handled. Figure 5-20 shows how the aircraft pallets could be rolled in and out the vehicle over the side, and how the different types of carts could be rolled in and out over the front of the vehicle using their own wheels. Not only the loading and unloading is more complex but also the transport on the terminal between docks and clients is more complicated.

The fourth concept, lifting all the different types of cargo separately in and out the vehicle, could be performed by a single piece of equipment able to lift both, aircraft pallets and carts in and out the vehicles. However, the subsequent handling on the terminal between docks and clients, would require different types of equipment.

These were the four material handling concepts developed as building blocks for creating terminal concepts.

5.4.2 Developing terminal concepts

This section presents three different terminal concepts, which were developed using the building blocks presented in the previous section. This is graphically presented in the morphological chart in Figure 5-21.

In theory, the number of concepts that can be developed can be very high, depending on the number of functions defined and the number of alternatives or building blocks developed for a certain function. In practice however many combinations are often not possible or practical. This often reduces the number of system concepts to consider. For instance for the OLS case, it was not practical to combine a deep loader vehicle with a front-loading dock.

Although one must not reject possible concepts too early, one must also not develop too many different concepts, as this would require excessive simulation and evaluation efforts.
When developing concepts, one can often start by trying to combine the most logical building blocks, often resulting in known or obvious concepts. If there are then still building blocks left, one should try and develop more concepts using these building blocks. In this phase of the project, one must try to develop concepts that are very different from one another. Considering minor variations for a certain basic concept is more an optimization aspect, which belongs in the next more detailed design phase of the project.

Apart from combining the actual building blocks, other aspects such as vehicle routing and possible parking spaces were also considered during the conceptual design of the OLS terminals and are discussed below for each concept. Furthermore, each terminal concept was developed focusing on a certain aspect or criterion, e.g. compactness or performance. As such the criteria defined in the system definition step for evaluating and selecting concepts, were also considered and used for the development of concepts in the system synthesis step. This is also reflected in the integrated design approach presented the previous chapter (Figure 4-5).
The three terminal concepts are discussed below.

**Terminal Concept 1**

For terminal concept 1, the deep loader vehicle was combined with the side loading dock, the handling of cargo by rolling and the use of slave pallets or aircraft pallets. Terminal Concept 1 is presented in Figure 5-22. Vehicles can drive on the terminal using the No-Stop lane. For loading or unloading vehicles exit the no-stop lane and position themselves at a dock. The slave pallets or aircraft pallets are then rolled in or out the vehicles. Vehicles can park in the centre of the terminal.

![Figure 5-22 Terminal Concept 1](Image)

Concept 1 was developed as one of the most obvious concepts. The low loader vehicles, preferred because of the smaller tunnel dimensions, would only have to load or unload cargo over one side of the vehicle, and would only require one main driving direction. Rolling the cargo and making use of slave pallets, means using the state of the art technology in the air cargo industry which has proven itself. As such it was seen as a basic, simple, robust concept. This concept would perhaps not be the most
compact concept, because of the required manoeuvring area in the centre of the terminal and at the loading docks, but could have a decent performance because of the easy manoeuvring of the vehicles on the terminal (flow friendly design). Furthermore, the complexity and control of the equipment were thought to be relatively simple. Simulations however would have to be performed in order to better assess these aspects. The different types of simulation performed for the terminal concepts are presented in Section 5.5.

**Terminal Concept 2**

Terminal Concept 2 also uses the low loader vehicle, but this time in combination with the double-side docking concept. Again rolling of the cargo in combination with the use of slave pallets was chosen as most practical, although lifting the cargo in and out the vehicles was still considered an option. Terminal Concept 2 is presented in Figure 5-23. Vehicles can drive on the terminal by using the no-parking lane. For loading and unloading the vehicles exit this lane and position themselves at a dock. The dock consists of two roller conveyors, one for transporting the cargo to the vehicle and one for transporting the cargo from the vehicle. The vehicle positions itself between these conveyors and can unload its cargo on one side of the vehicle and load on the other side of the vehicle. Vehicles can be parked behind the docking area.

Concept 2 was developed focusing on combined fast loading and unloading. To reduce the width of the terminal the no-parking lane or driving lane is positioned in the centre of the terminal, with vehicles now having to cross the NO-parking lane to enter and exit a dock. As there was no parking space left in the centre of the terminal, parking spaces had to move outwards. This concept proposed parking spaces just behind the loading and unloading areas. A possible negative result of reducing the width of the terminal could be the increase in its length, if the vehicles would have to turn around at one or both ends of the terminal. Terminal simulations would have to be performed in order to better predict the required space and performance of such a terminal. The simulations are discussed in Section 5.5.
Terminal Concept 3

Terminal Concept 3 combines the flat bed vehicle with the front-side docking concept and the separate handling of the different types of cargo. Pallets are loaded and unloaded over the side of the vehicle, while carts can be loaded and unloaded over the front of the vehicle. No choice was yet made on the rolling or lifting of the different types of cargo. Terminal Concept 3 is presented in Figure 5-24. Vehicles can drive on the terminal using the NO-stop lane and enter a dock by making a 45-degree turn and then stop at the dock. Flower carts can be loaded and/or unloaded over the front of the vehicle and pallets can be loaded and/or unloaded over the side, as described above. After unloading and/or loading, the vehicle reverses into a position parallel to the NO-stop lane and waits until it can re-enter this lane. This vehicle position could also be used as a buffer area (very short term parking). There are no separate parking areas for the vehicles in this terminal concept.
Concept 3 was developed as a potential compact terminal. The driving lanes are again positioned in the centre of the terminal with only a slight turn (e.g. 45 degrees) needed for docking (similar to compact parking spaces for cars). The flat bed vehicles allow for a shorter wheelbase compared to the low loader vehicles as the wheels are positioned under the loading deck, which in turn allows for tighter manoeuvring and therefore requires less manoeuvring space. By not using slave pallets, the operational organization would become easier (slave pallets also need to be bought, maintained and distributed), but the physical control of the different load units would become more difficult. The simulations required to better assess the technical feasibility of this concept, to estimate the actual space needed for manoeuvring and of course to predict the overall performance of the terminal, are presented in Section 5.5.

Figure 5-24 Terminal Concept 3 [Pielage, 1999-a]
5.5 Simulation

For this subject, reference is made to the simulation step of the integrated design approach (Figure 4-5), highlighted in red in Figure 5-25.

The simulation step has been defined as the fourth step of the conceptual design process. Following the design approach presented in the previous chapter (Figure 4-5), the simulation step should produce the expected cost, performance and other properties of the concepts developed in the previous step. In essence, the simulation step should help to determine how the system concepts score per criterion, so that these concepts can be compared and evaluated in the next (evaluation and selection) step. As discussed in Section 5.3.3, the two main criteria considered for the conceptual designing of OLS terminals, were the area-utilization and the performance. Many of the simulation activities focused on these two aspects. For the conceptual designing of OLS terminals three different types of simulation were carried out: computer simulation or virtual prototyping, physical prototyping, and expert evaluation. All three types of simulation are discussed in this section.
5.5.1 Computer simulation / Virtual prototyping

Computer simulation, or virtual prototyping, is a powerful tool to analyze complex systems. Different types of simulation software are available to analyze for instance the logistic performance of a terminal (performance) or the physical appearance and dynamic behaviour of equipment (required area). Both types of computer simulations were performed for the OLS project and are discussed below.

Logistic Terminal performance

To assess the logistic performance of the three terminal concepts presented in the previous Section 5.4.2, simulation models were developed. Figure 5-26 shows the simulation models of these three terminal concepts with their main characteristics. Building blocks were developed for the different types of vehicle manoeuvres, making it easy to change e.g. the routes and/or number of docks or parking spaces. Furthermore, the simulation team added so-called line-up spaces behind every side dock in Terminal Concept 1, and so-called chain-parking loops in Terminal Concept 3, both to improve the performance of the terminals. This again shows the iterative nature of the conceptual design process.

<table>
<thead>
<tr>
<th>Terminal Concept 1</th>
<th>Terminal Concept 2</th>
<th>Terminal Concept 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 – side-docks</td>
<td>10 double side-docks</td>
<td>10 side / front docks</td>
</tr>
<tr>
<td>1 line-up space per dock</td>
<td>No line-up space</td>
<td>1 back-up space per dock</td>
</tr>
<tr>
<td>parallel parking in centre</td>
<td>crossing the main track</td>
<td>chain (serial) parking in outer &quot;loop&quot;</td>
</tr>
</tbody>
</table>

Figure 5-26 Simulation models of three terminal concepts [Verbraeck et al., 1998]
It was here, during the initial simulation studies, that more attention had to be paid to the development of the control system. In fact, one cannot perform terminal simulation without a control strategy. Terminal simulation is in fact a way to test the control system. As such, it could be stated that the development of the OLS control system started here, with these initial terminal simulations. The development of the control system is discussed in more detail in Section 5.5.2.

Several different experiments were performed with the simulation models shown in Figure 5-26. The models themselves could be adapted by varying e.g. the number of docks, line-up spaces and parking places. Other parameters that could be changed were for instance the vehicle speed, loading and/or unloading time at a dock and whether a dock could either load or unload cargo or do both (combi-dock). Furthermore different patterns of supply and demand could be fed into the models. The different variables interact with one another in a complex manner. In order to compare the three different terminal concepts, similar experiments had to be carried out. For comparing the three terminal concepts, so-called impulse experiments were carried out, which produced the maximum processing capacity of the terminal concepts. These experiments were carried out with similar values for parameters such as, vehicle speed and loading/unloading time. The key performance indicators monitored during the experiments were: the number of Automatic Guided Vehicles (AGVs) able to dock per dock per hour; the number of operations per dock per hour; the average time a vehicle is in the terminal; the average distance driven on the terminal; the number of times a vehicle accelerates; and the average speed of the vehicles on the terminal. Table 5-2 presents the results of the impulse experiments performed for the most important terminal concept variants, with a loading or unloading time of 60 seconds and a maximum vehicle speed of 2 m/s. Many more experiments were performed with a wide variance in parameters. More information on the logistic simulations can be found in [Verbraeck et al., 1998].
Table 5-2 Results of impulse experiments on terminal concepts [Verbraeck et al., 1998]

<table>
<thead>
<tr>
<th>Terminal-concept</th>
<th>AGVs per dock per hour</th>
<th>Dock operations per dock per hour</th>
<th>Terminal time [min.]</th>
<th>Driven distance [km]</th>
<th>Number of times accelerated</th>
<th>Average speed [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC1/8</td>
<td>28</td>
<td>44</td>
<td>6.8</td>
<td>0.34</td>
<td>15</td>
<td>1.1</td>
</tr>
<tr>
<td>TC1/8combi</td>
<td>35</td>
<td>53</td>
<td>5.5</td>
<td>0.28</td>
<td>10</td>
<td>1.2</td>
</tr>
<tr>
<td>TC1/12</td>
<td>27</td>
<td>42</td>
<td>5.7</td>
<td>0.34</td>
<td>13</td>
<td>1.4</td>
</tr>
<tr>
<td>TC2/8</td>
<td>14</td>
<td>22.5</td>
<td>13.6</td>
<td>1.22</td>
<td>26</td>
<td>1.7</td>
</tr>
<tr>
<td>TC3/10</td>
<td>13</td>
<td>20</td>
<td>6.8</td>
<td>0.55</td>
<td>8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

The general conclusion from the logistic terminal simulations was that Terminal Concept 1 has the best terminal performance of the three concepts. It could handle the highest number of vehicles per dock per hour (highest dock occupation) and the flow friendly design on the terminal allowed vehicles to enter and exit the terminal without too many disturbances (short terminal times / dwell times).

Furthermore it was found that the lining-up of vehicles at the dock increases the performance of a terminal. The crossing of lanes as presented in Terminal Concept 2 should be avoided because of the interference between vehicles. Furthermore, front-side docking as proposed in Terminal Concept 3 has a low performance due to the time consumed by reversing out of the dock combined with the absence of a line-up space. These simulation results are further discussed in the evaluation and selection step (Section 5.6).

Vehicle manoeuvring / required area

Computer simulation or virtual prototyping can also be done for separate pieces of equipment such as vehicles. In order to better predict the required space needed for the vehicle manoeuvres, simulation models were developed for the different vehicle concepts. Using the basic vehicle dimensions and characteristics, such as number of steering axles and mass, different manoeuvres were simulated. Figure 5-27 shows an impression of the space needed for a typical docking manoeuvre and a U-turn for the three different OLS vehicle concepts. The Spijkstaal vehicle was the shortest vehicle with the shortest wheelbase due to the wheels positioned under the loading deck. It has only one steering axle and uses the front-side docking concept. The Lödige
vehicle is a low loader, with a longer wheelbase, but has two steering axles so it can move sideways and make symmetric turns. The DTM vehicle is also a low loader, but with only one steering axle. As such it needs more manoeuvring space for a side docking manoeuvre. The manoeuvres were all plotted on a grid of 1 by 1 meter.

![Diagram of vehicle manoeuvres](image)

**Figure 5-27 Typical vehicle manoeuvres on the terminal [Boezeman et al., 1999]**

These experiments were performed with a driving speed of 2 m/s on the no-stop lanes, a maximum acceleration and deceleration in longitudinal direction of 1 m/s², a maximum allowed transverse acceleration of 1 m/s² and a required positioning accuracy between vehicle and dock of between 5 and 10 centimetres. More information on vehicle simulations can be found in [Boezeman et al., 1999].

The simulated vehicle manoeuvres provided a good impression of the space needed for the various docking manoeuvres and U-turns [Pielage, 1999-b]. Some general conclusions were that side docking with front wheel steering needed the longest path
and side docking with four wheels steering needed the shortest. An alternative to reduce the space needed for docking a front wheel steered vehicle could be realized by docking at a 45 degree angle, as shown by the front-side docking concept for the Spykstaal vehicle concept. However, this front-side type docking requires the vehicle to reverse out of the dock, making it difficult to line-up a waiting vehicle, which does not improve the dock performance as observed at the logistic terminal simulations. The side docking manoeuvre with the four wheel steering Lödige vehicle also does not allow for a line-up space behind the docked vehicle, which again reduced the terminal performance.

Although it was possible to determine the required space for manoeuvring quite accurately, the dimensioning of terminals did require a more integrated approach, taking into account not only the required physical space for certain manoeuvres and equipment, but also the interaction between the different elements on a terminal and the overall terminal performance. For example, it was acknowledged that a terminal with very compact vehicle manoeuvres may reduce the overall performance of a terminal because of the limited manoeuvring space available and as a result would require more loading docks or bypass lanes to deliver the same performance, which in turn would increase the total terminal space needed. This again shows the required interaction and cooperation between different groups. In this case for example between logistic control simulation specialists and equipment/vehicle simulation specialists.

The two types of computer simulations presented in this section are different from one another and require different types of software and different simulation specialists. The one focuses more on logistic processes and control, using event based simulation software (e.g. Simple++ and Arena), while the other focuses more on the physical simulation of the equipment itself, using more analytical or mechanical simulation software to describe the continuous physical motion (kinematics/dynamics) of physical objects (e.g. ADAMS). The type of simulation required depends greatly on the type of problem under consideration. The two types of simulation presented here are often used for the design of automated freight transport systems.
5.5.2 Physical prototyping

Although virtual prototyping has become more important, actual or physical prototyping is still used for instance to assess the technical feasibility of a concept (can it be built, does it work properly, is it reliable) or to determine or verify the characteristics of models used for computer simulations. To facilitate the physical prototyping for the OLS project, a TestSite was built in Delft. Most of the pictures presented in this section were taken at this TestSite.

This section briefly discusses the physical prototyping and testing of the different vehicle and material handling concepts, and shows how physical prototyping has contributed to the development and testing of the control system for the OLS project.

Vehicles

All three vehicle concepts, discussed earlier, were developed into a 1:1 scale prototype and are shown in Figure 5-28.

![Spykstaal vehicle](image1.png) ![Lödige vehicle](image2.png) ![DTM vehicle](image3.png)

Figure 5-28 Three vehicle concepts and their prototypes [Rijsenbrij et al., 2000] & [Pielage, 2001]

The different vehicle concepts were developed each with their own specific characteristics, which could now be tested and compared. Figure 5-29 shows the testing of the maneouvring capabilities of the Spijkstaal vehicle at the TestSite in
The OLS Case, designing terminal concepts

Delft. More information on the development and testing of the OLS vehicles can be found in e.g. [Putten, 1998], [Ravestein, 1998], [Wiersma, 1998], [Kusters, 2000] and [Angevaren et al., 2000].

![TestSite 12-10-2000 Test positioneren Spijkstaal](image)

**Figure 5-29 Testing the Spijkstaal vehicle at the TestSite [Angevaren et al., 2000]**

Although several tests were performed at the TestSite with the three 1:1 scale vehicle prototypes, they were never fully tested in an integrated environment (with all the elements working together). None of the vehicles were tested over longer periods of time (endurance tests) while having to perform all its functions and interactions with the other automated equipment and overall control system. This was mainly due to the many disturbances encountered during testing. These disturbances were mostly experienced in the electronics and control system, both within the vehicles themselves and between the vehicles and the other components of the system. The lessons learnt are discussed at the end of this section on physical prototyping.

**Material handling**

Not all material handling concepts presented earlier were developed into physical prototypes. After consultation with experts in the field of material handling, it was concluded that only two of the four material handling concepts would be developed into physical prototypes. This expert evaluation is discussed in the next section (5.5.3). The two material handling concepts that were developed on a 1:1 scale prototypes are presented in Figure 5-30.
Several experiments and tests were performed with the 1:1 scale material handling prototypes. However, as with the vehicles, no fully integrated tests took place. The reasons why and lessons learnt are again discussed at the end of this section on physical prototyping. Most of the testing and evaluation that did take place was based on isolated experiments. Figure 5-31 shows some of the experiments performed at the TestSite with the two material handling prototypes. These experiments were done mainly by manual control to test the physical aspects of the material handling prototypes and their interactions with the vehicles.

The rolling of the cargo in and out the vehicles was done by roller conveyor technology commonly used in the air cargo industry. Roller extractors were installed on the material handling equipment to load or unload the Lödige vehicle (see Figure 5-31 bottom left).

For lifting the cargo in and out the DTM vehicle, forks were used which could lift the cargo slightly before loading or unloading. The forks were equipped with in height adjustable wheels to support the cargo. The forks would fit in the cut-away areas in the floor of the vehicle (see Figure 5-31 bottom right).
Rolling Cargo in/out Lödige vehicle using extractors

Lifting cargos in/out DTM vehicle using forks

Figure 5-31 Material handling experiments at the TestSite [Angevaren et al., 2000], [Pielage, 2000] & Other pictures taken at the TestSite

Although only a limited number of tests were performed, some general conclusions were formulated [Angevaren et al., 2000]. First of all, it was concluded that the vehicles and handling equipment were not yet performing according to expectations, making it very difficult to test and evaluate the different concepts.

With respect to the material handling experiments, it was concluded that the fork lifting concept was a very promising concept. This concept allowed for larger gaps between vehicle and handling equipment, although it did require accurate positioning in the driving direction. Furthermore, it did not require any moving part for handling cargo in the vehicles and separate provisions for securing the cargo were not needed.

As it was expected that there would be more vehicles present than loading or unloading docks in the OLS system, reducing the complexity of the vehicles was considered important.

This was also one of the motivations for using extractors on the roller conveyor. The vehicles would not require any drive for rolling the cargo in and out the vehicles, as the extractors would drive the rollers on the vehicle. This did however require accurate positioning of the vehicle at the dock. Furthermore, the cargo was not sufficiently secured within the vehicle (cargo moved while driving) and would require
additional securing measures. Driving the rollers by an electric motor installed inside the vehicles was therefore still considered a possible option, preferably in combination with retractable rollers, making it possible to support the cargo on the vehicle floor instead of on the rollers while driving.

Finally it was concluded that many more experiments would be required in order to better evaluate and assess the performance of the different vehicle and material handling concepts. Fully integrated tests were proposed with: automated vehicle manoeuvring, accurate positioning, loading and unloading full loads (up to 3500 kg.) and driving at higher speeds [Angevaren et al., 2000]. Such experiments were eventually performed at TNO in Delft, but only much later (after the TestSite had been closed down) and only for the DTM vehicle and the forklift concept [Gietelink, 2003-a] & [Gietelink., 2003-b]. Figure 5-32 shows some of the loading and unloading tests performed at TNO in Delft. Even at that time, due to disturbances with the electronics and control system of the vehicle, it proved difficult to perform fully integrated automated test cycles. Before discussing the lessons learnt from the physical prototyping and testing at the TestSite, the development of the control system is discussed first in the next paragraph.

![Figure 5-32 Loading and unloading experiments at TNO [Gietelink, 2003-a]](image)

**Control system**

Apart from testing the 1:1 scale vehicle and material handling prototypes, the TestSite was also used to develop and test the control system. The proposed architecture for the OLS control system is presented in Figure 5-33 [De Vos Burchart et al., 1998].
Three levels can be distinguished. LOCES, at the top of the hierarchy is the logistic control module that communicates with the clients of the OLS systems and generates transport orders. TRACES is the traffic control module that coordinates the movement of the vehicles, thus preventing conflicting use of infrastructure. The control of physical equipment itself is shown at the bottom of the figure. This layer controls for instance the steering angle or speed of a vehicle, or the actuator on the material handling equipment for rolling cargo in or out the vehicle. By using these different layers of control with clearly defined interfaces, it was possible to structure and simplify the total control system and to change certain elements of the control system without having to change the whole system.

Different types of control strategies were considered for the OLS, ranging from strict hierarchical (centralized) control to heterarchical (de-centralized) control. Hierarchical control systems are easy to control and predictable, but are also rigid, making it
difficult to cope with changes or disturbances. Heterarchical systems are often also referred to as agent based systems composed of independent agents without a centralized or explicit direct control. These type of systems can naturally cope with disturbances and are easy to change by replacing or adding agents. A disadvantage is however, that the behaviour of the system is difficult to predict or control and all system elements must have sufficient intelligence (information + strategies + algorithms) to react efficiently on changes and events. For the controlling of large scale automated freight transport systems, like the OLS, a combination of the two was eventually proposed [Versteegt, 2004].

For the development and testing of the control systems at the TestSite, a larger number of smaller so-called 1:3 scaled vehicles and docks were used. Although these differed from the 1:1 scale prototypes with respect to the physical/equipment control layer, the other control layers remained the same. In total there were 10 of these 1:3 scale vehicles, which were in fact almost standard AGV’s able to transport standard euro pallets. In combination with the 1:3 roller conveyors (also largely standard conveyors for euro pallets) different terminal layouts and traffic situations could be simulated and tested. Figure 5-34 (left) shows a computer model/virtual representation of the TestSite, with a layout for testing the control system using the 1:3 scale vehicles and docks. The layout of terminal concept 1 can be recognized clearly on the right side of the screen. A photograph of that same area of the TestSite is presented in Figure 5-34 (right), showing the actual 1:3 scale vehicles and 1:3 scale roller conveyors.

This setup allowed the developers to test the control system, not only by computer simulation but also by using physical prototypes. In the end, it did not matter whether the control system was controlling real or simulated vehicles, as they were interchangeable. Figure 5-35 shows how the control system was developed, starting with computer simulation models of the control system as well as the system being controlled (simulated resources), then continuing with emulated models for the logistic resources (e.g. AGV’s) and finally ending with physical prototypes. Different simulation software packages were used to show that the developed control system was software independent. Using the event and command based communication
structure and a CORBA interface, the control system could not see any difference between simulated, emulated and prototype logistic resources [Versteegt et al., 2003].

Figure 5-34 Experiments with 1:3 scale vehicles and docks at the TestSite [Verbraeck et al., 2001]

Figure 5-35 Control of simulated resources, emulated resources and prototype resources [Versteegt et al., 2003]
Lessons learnt

Summarizing, this section shows how physical prototyping can help to test and assess not only physical equipment, such as vehicles and material handling equipment, but also how it can help to develop and test the control system. Tests are also required to check the assumptions with regard to e.g. cycle times, area utilization and reliability (mean time between failures and mean time to repair).

However, a number of the physical tests were not performed in accordance with the initial testing program. This was mainly due to the many disturbances encountered during testing, especially with the electronics and control system (both, within the vehicles themselves and between the vehicles and other components of the system). Fully integrated automated test cycles were never performed at the TestSite. This again illustrates the difficulties and complexity involved in developing fully automated freight transport systems and shows the need to do simulations and physical prototyping, not only for separate components but also for the integrated system with all the interfaces. It could also be argued that there was insufficient pressure to produce quality products and results within the limited financial resources and time available.

Lessons again learnt are: not to underestimate the complexity of developing fully automated freight transport systems; to spend sufficient time and effort on the development and testing of the system (especially the control system); and to always use physical prototyping as this will reveal many (often unexpected) problems which could influence the concept selection.

Furthermore, the physical prototyping at the TestSite showed the importance of clearly defining the main functions of a system and the development of alternative sub-systems to fulfil these main functions. For example, when considering the vehicle as a system, the positioning function or sub-system should be clearly separated from e.g. the communication sub-system or the sub-system that controls the actuators on the vehicle. This makes it easier, not only to choose between different sub-systems and suppliers, but also to locate the malfunctioning sub-system in case of a problem. This clear functional structuring and separation of sub-systems and responsibilities was not always sufficiently done, often making it more difficult to first isolate the problem and then to identify the responsible parties and efficiently solve the problem.
5.5.3 Expert evaluation

Apart from virtual and physical prototyping, expert evaluation can also be used to assess a certain aspect of a system. By asking a specialist in a specific field of expertise to determine the values of different concepts in relation to a certain criterion, he or she can help in the process of evaluating and selecting the most appropriate concept. Expert evaluation is often used for the less quantifiable criteria or in situations where there is only limited time and/or budget available for virtual or physical prototyping. In such situations, experts can be used to assess for instance the technical feasibility of certain design concepts, without having to build prototypes. Experts can also help to determine or assess the value of the different parameters used in computer simulations. For the conceptual designing of OLS terminals, expert evaluation has been used in several different situations. This section discusses the following three typical situations:

- Determining input values for computer simulations.
- Evaluating material handling concepts with little or no quantified criteria.
- Assessing the feasibility of material handling concepts.

**Determining input values for computer simulations**

Producing realistic input values for the simulation models, is often used at the beginning of the project. Experts from different fields of expertise can for instance help to determine realistic vehicle speeds, or loading and unloading times for terminal simulations, and produce acceptable acceleration rates and required accuracy for the vehicle manoeuvres. For the terminal computer simulations, the vehicles speeds, acceleration and deceleration values and the expected loading and unloading time were estimated by different vehicle and material handling experts. For the vehicle manoeuvre simulations, the required accuracy for positioning at the dock and the maximum allowable accelerations and friction coefficients, were also discussed with experts in the field of material handling and vehicle dynamics.

Although simulation specialists often have experience with certain types of processes or systems, and can make many assumptions themselves, it is wise to also involve specialists with experience and knowledge of the systems being simulated. It was found during the OLS project, that many simulation experts focused more on the
development of a simulation model and performing the experiments, but less on the accuracy, probability and reliability of the input values.

**Evaluating the four material handling concepts**

The four material handling concepts that were developed in the system synthesis step, were evaluated separately by material handling experts to get a better understanding of the potential advantages and drawbacks of each concept. The results of this expert evaluation are presented in Figure 5-36, showing the main characteristics for each of the material handling concepts.

This is a good example of how experts can value a certain concept without quantifying each criterion. Although some of the aspects are quantifiable, such as the estimated loading times, most of the characteristics describe a property of the concept without adding a number.

**Assessing the feasibility**

Assessing the feasibility of a specific type of element or sub-system can also be done by specialists in that specific field of expertise. For instance, for the OLS project a group of material handling specialists advised not to develop two of the four material handling concepts into full-scale prototypes. They were of the opinion that the separate handling of all the different types of cargo would become too complex and would greatly influence the reliability of the system. As a result, the two material handling concepts with separate cargo handling were abandoned and the two concepts using slave pallets, or cargo with a similar handling characteristic such as aircraft pallets, were advised. These two material handling concepts were developed into prototypes as discussed in Section 5.5.2.
<table>
<thead>
<tr>
<th>Concept</th>
<th>Estimated loading or unloading time</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| Rolling cargo & use of slave pallets | 49 seconds                         | • Estimated loading or unloading time 49 seconds  
• Proven technology  
• Compatible with existing systems  
• Slave pallet simplifies loading but introduces empty handling  
• Accurate horizontal positioning required                                           |
| Lifting cargo & use of slave pallet | 82 seconds                         | • Estimated loading or unloading time 82 seconds  
• Horizontal positioning realised by lifting  
• Lifting device eliminated rollers on vehicle  
• New concept / less compatible with existing systems  
• Slave pallet simplifies loading but introduces empty handling                                                                 |
| Rolling cargo & separate cargo handling | 68 seconds                         | • Estimated loading or unloading time 68 seconds  
• Proven technology & compatibility for aircraft pallets  
• New concept / less compatible with existing systems for carts  
• Separate cargo handling without slave pallet empty handling but with complex loading of different types of cargo  
• Accurate horizontal positioning required                                                                 |
| Lifting cargo & separate cargo handling | 86 seconds                         | • Estimated loading or unloading time 86 seconds  
• Lifting device eliminated rollers on vehicle  
• Horizontal positioning realised by lifting  
• New concept / less compatible with existing systems  
• Separate cargo handling without slave pallet empty handling but with complex loading of different types of cargo |

**Figure 5-36 Characteristics of material handling concepts [Dunselman et al., 1999-b]**
Closing remarks on Simulation
This section discussing the simulation step presents computer simulation or virtual prototyping, physical prototyping and expert evaluation as three different types of simulation one can use to help to determine how the system concepts score per criterion. For the conceptual design of OLS terminals only two criteria were distinguished: area-utilization and performance. Many of the simulation activities were involved in determining the performance of the different terminal concepts and/or the required areas, either directly (e.g. computer simulations to assess the logistic terminal performance) or indirectly (expert evaluation to determine input parameters for computer simulations). However, certain simulations were also used to assess and evaluate certain sub-system concepts “on the spot”. This was the case for the expert evaluation of the material handling concepts, for which problems were expected with the feasibility. Furthermore, several simulation activities focused on the detailing of certain elements of the system, for example by physical prototyping, to better assess the technical feasibility, robustness and reliability. One could state that the development of the control system started only after the initial terminal concepts were developed and terminal simulations were performed in order to determine the overall performance of a terminal concept. However, the development of the control system did influence the initial terminal concepts presented in the previous section, by integrating line-up and parking spaces where possible. This again illustrates the iterative nature of the conceptual design process. The basic terminal concept that was developed for the flower auction in Aalsmeer (presented in Section 5.7) shows how these line-up spaces were integrated. The next section (5.6) will first discuss the evaluation and selection step for the conceptual design of OLS terminals.

5.6 Evaluation and Selection
For this subject, reference is made to the evaluation and selection step of the integrated design approach (Figure 4-5), highlighted in red in Figure 5-37.
The OLS Case, designing terminal concepts

Figure 5-37 "Evaluation & Selection" step highlighted (red) in the integrated design approach (Figure 4-5)

The evaluation and selection step has been defined as the last step of the conceptual design process. Following the design approach presented in the previous chapter (Figure 4-5), the different system concepts should be compared with one another using the criteria defined in the system definition step. An evaluation matrix can be drawn up with on one axis the system concepts and on the other axis the criteria. Such a matrix facilitates a clear evaluation and comparison of the different concepts and should lead to a well-founded and transparent selection of the most suitable system concept. The selected system concept can then be detailed further in the next phase of the project, the detailed design phase.

For the OLS terminals, an evaluation matrix could be developed similar to the matrix shown in Figure 5-38. The three terminal concepts are presented horizontally, and the criteria suggested for future reference in Section 5.3.3 are presented vertically. The concepts can then be compared using different techniques, from purely qualitative with plusses and minuses, to fully quantitative with numerical values for all the criteria including numerical ranking or weighing of the criteria, resulting in a total numerical score per concept.
However, such an integral evaluation and selection was not carried out within the OLS project. Although evaluations and selections were made for certain elements of the terminals (e.g. material handling concept) or for certain specific criteria (e.g. terminal performance), both discussed in the previous section, an integrated evaluation and selection whereby all the terminal concepts were evaluated in relation to all the different criteria as shown in Figure 5-38, was not performed. This was not only due to for instance the lack of clearly defined criteria as discussed in Section 5.3.3, but also because there were some major changes being considered for the system layout, which would also have a major impact on the terminals. These changes, which will be described in Section 5.8, would require the development of other new terminal concepts and took away the need to actually select one of the three terminal concepts discussed so far.

**The evaluation and selection process that led to a basic terminal concept**

Although the evaluation and selection step was not performed according to the integrated design approach as discussed in Chapter 4, a basic terminal design was developed for the flower auction in Aalsmeer, not as a final design, but rather as a benchmark for future terminal designs [Pielage, 1999-b]. The evaluations and considerations that led to this basic terminal design, are discussed in this paragraph. The discussion starts with the findings of the terminal simulations (logistic terminal performance), followed by the findings of the vehicle manoeuvring simulations.
(required area) and finally the findings of the material handling concepts. The interdependence between these three subjects is also addressed.

The general conclusion from the logistic terminal simulations was that Terminal Concept 1 had the best terminal performance of the three terminal concepts. Furthermore it was found that the lining-up of vehicles at the dock increased the performance of a terminal. The crossing of lanes as presented in Terminal Concept 2 should be avoided because of the interference between vehicles. Furthermore, front-side docking, as proposed in Terminal Concept 3, resulted in a lower performance due to the time consumed by reversing out of the dock combined with the absence of a line-up space. Parking spaces were also of great influence on the performance of a terminal. By spreading the parking places as evenly as possible over the terminal, the distances driven by the vehicles were greatly reduced. For parking empty vehicles, serial parking at both ends of the terminal, as shown in the simulation model of Terminal Concept 3 in Figure 5-26, was suggested as an alternative to the parallel parking in the centre of the terminal as proposed for Terminal Concept 1. For parking empty vehicles, serial parking proved satisfactory. For parking loaded vehicles however, parallel parking was preferred as the vehicles could then be addressed randomly.

A general conclusion drawn from the simulated vehicle manoeuvres was, that side docking with front wheel steering needed the longest path (required area) and side docking with four wheels steering needed the shortest. A good alternative to reduce the space needed for docking a front wheel steered vehicle, was realized by docking at a 45 degree angle as shown by the front-side docking concept for the Spykstaal vehicle concept. However, this front-side type docking required the vehicle to reverse out of the dock, which did not improve the dock performance as also was observed at the logistic terminal simulations. Furthermore, the side docking manoeuvre with the four wheel steering Lödige vehicle did not allow for a line-up space behind the docked vehicle, which also reduced the terminal performance. Based on these considerations, the side docking manoeuvre with front wheel steering was selected as the most promising combination. This combination would require relatively simple vehicles, while the extra space needed for manoeuvring could be used as a line-up space, improving the overall performance of the terminal. The space needed for performing a U-turn was about the same for all three vehicles and therefore less of an
issue. However, the final selection for the type of vehicle and type of docking would also depend on the preferred type of material handling. For instance, if the loading of cargo over the front of the vehicle would prove to be desired from a material handling point of view, the side docking concept would have to be reconsidered.

The expert evaluation of the four material handling concepts eventually led to the development of only two 1:1 scale prototypes. The separate handling of the different types of cargo would become too complex and would affect the reliability of the system. Therefore the use of slave pallets or aircraft pallets was advised, with the options of lifting or rolling the cargo in and out the vehicles. These two material handling concepts were developed into 1:1 scale prototypes. Both concepts could be implemented for similar side docking configurations and did not require loading over the front of the vehicle.

These were the considerations resulting in the basic terminal design for the flower auction in Aalsmeer, presented in the next section (5.7).

**Remarks on the use of evaluation matrices**

As discussed in the introduction of this section, an evaluation matrix can help to evaluate, compare and select the most suitable concept. However, there are many different ways to utilize the evaluation matrix. One of the simplest ways is using plus and minus qualifications to assess the value of the concepts for the different criteria. For each criterion the concepts should be compared, the plusses and minuses reflecting the comparative relation or proportion. The most suitable concept can then be identified as the concept with the most plusses in total, or the concept with plusses for the most important criteria or any other way of selection. This technique is often used for very simple evaluation matrices, with only a few alternative concepts and only a few mainly “non quantitative” criteria. Determining the relative value of a certain criterion for the different concepts is often done by expert evaluations. Although selecting a concept using this method is perhaps not very exact, it is probably the method mostly used for relatively simple and straightforward choices.

For more complex matrices, with many different concepts and many different criteria, it is more difficult to maintain a clear overview of the evaluation and selection process. To cope with this increase in complexity, numerical values are often used for evaluation and selection. Numerical values are first calculated or determined for all criteria and for each concept, after which a total score can be calculated for each
concept. The concept with the highest score would then be the most suitable concept. More information on multi criteria analysis methods can be found in e.g. [Keeney et al., 1976] and [Lootsma, 1999].

A final remark is made on the suggested accuracy sometimes found when using the more quantitative evaluation methods. Although it may be needed in complex situations to use numerical values and calculate the highest scores, these scores should not be interpreted as exact science. Calculating a total score for a concept of for instance 5.89 suggests an accuracy, which is often not valid due to large variations or margins of error of the underlying values. For the same reason, a concept that scores for instance 6.1 is not necessarily better than a concept that scores 6.0 although sensitivity analysis can help to determine the stability of a numerical score.

**Lessons learnt**

In retrospect, the evaluation and selection of the OLS terminal concepts should have been done in a more integrated and structured manner, using an evaluation matrix as shown in Figure 5-38. This would have required and stimulated a better definition of the criteria, which in turn would have better guided the development of concepts and focused the simulation activities, eventually resulting in a better founded and transparent selection of the most suitable concept. Not only the criteria and evaluation and selection would be different, but most probably also the concepts themselves.

On the other hand, one should also take care not to define too many criteria and then determine their value for the different terminal concepts in too great a detail, while there are still many uncertainties or major changes possible. For instance, calculating the exact investment costs for the different terminal concepts discussed up to now (estimated in the order of tens of millions of euros), while there are still major changes being considered for the entire system layout and tunnel infrastructure (in the order of hundreds of millions of euros), would seem a waste of time and money.

Finally it is noted that the evaluation and selection step, as all other steps of the design process, should be seen as part of the iterative design process, and not as something that has to be done only at the end of the conceptual design phase. In fact, evaluating and comparing different concepts will often lead to new insights, combinations of building blocks and/or system concepts.
5.7 A basic terminal design for the VBA

This section presents a basic terminal design as it was developed for the flower auction in Aalsmeer (VBA). This terminal design was the result of the design process described in the previous sections. It was not presented as the final terminal design for the OLS, but rather as a concept to be used as a basis for further developments. This basic terminal design, shown in Figure 5-39, could be used as a benchmark for future terminal designs [Pielage, 1999-b].

![Figure 5-39 Basic terminal design for the VBA](image)

The terminal, located on ground level, is connected to the tunnel infrastructure via a slope, where the automated vehicles enter and exit the terminal. The free ranging fully automated vehicles can park parallel in the centre of the terminal and drive on the revolving one-way track, similar to Terminal Concept 1 (Figure 5-22). To load or unload cargo the vehicle leaves the track to a designated dock, where the aircraft...
A pallet or slave pallet is handled over the right side of the vehicle. The actual handling method (rolling or lifting) was not yet determined. While a vehicle is loading or unloading, a second vehicle can line-up behind the docked vehicle (line-up spaces were introduced by control specialists for better terminal performance). After loading or unloading, the vehicle re-enters the one-way track. The vehicles never have to travel backwards in this terminal design. The vehicle can now leave the terminal, or park in one of the parallel parking places in the centre of the terminal.

The interface with the flower auction was also considered in more detail. In order to connect with the existing internal transport systems at the flower auction, the slave pallets were built-up or broken down at the terminal, each slave pallet consisting of, e.g. 6 euro pallets, 8 danish carts or 4 auction carts. In total 8 such stations were foreseen for the VBA terminal. The terminal also contained two import/export stations for the aircraft pallets. Transportation of the aircraft pallets and slave pallets to and from the loading docks was done by roller conveyors. Internal transport systems at the flower auction would transport the euro pallets, flower carts and aircraft pallets to and from the OLS terminal.

The dimensioning of the terminal was done by combining different types of simulation results. Specific terminal simulations were performed for different load patterns in 2020, which gave insight into the number of docks needed. For the basic terminal layout, simulation experiments were performed with both the VBA and RTH patterns. Figure 5-40 shows the delivery pattern for the RTH, which was used as input for the terminal simulations. These load patterns were derived from simulations performed for the whole system layout [Harten et al., 1998] & [Verbraeck et al., 1998], which in turn used the volumes and distributions discussed in Section 5.3 as input.

The general conclusion from the terminal simulations was that the basic terminal design with 8 docks and a loading or unloading time of 60 seconds, could handle the load without major delays [Verbraeck et al., 1998].

For the RTH pattern (Figure 5-40), the number of loaded vehicles entering the terminal is clearly the major load on the terminal. A first indication for the proper functioning of a terminal is the difference between the arrival pattern and the departure pattern, which is presented in Figure 5-41. The figure clearly shows the two
peaks around midday and in the early evening, with only a slight difference between
arrival and departure, which indicates the terminal is capable of handling the load
expected in the year 2020 [Verbraeck et al., 1998]. Table 5-3 presents some of the
main simulation results for both the VBA and RTH load pattern. For more
information on the terminal simulations, reference is made to [Verbraeck et al., 1998].
Apart from the terminal simulations, the vehicle simulations were used to further dimension the tracks on the terminal. This resulted in e.g. U-turns with a required radius of 7 meters and a distance of 20 meters between docks. The main dimensions of the terminal are presented in Figure 5-42 [Angevaren et al., 1999]. The area needed for the OLS terminal building itself was estimated at 4800 m$^2$ (40 x 120 meters). The total area needed for the terminal, including stations for building-up and braking down slave pallets, and buffering e.g. euro pallets and flower carts was estimated at 9000 m$^2$ (75 x 120 meters).

As there were major changes being considered for the system layout, which would also influence the terminals, this basic terminal was not considered a final design, but rather a basic concept to be used as a reference or benchmark for further developments. The developments that took place after the development and presentation of this basic terminal concept are discussed in the next section.
5.8 Developments after the basic terminal design

As already indicated in the previous two sections, there were some major changes being considered for the system layout. This section will briefly discuss these changes, which largely took place after the basic terminal design was developed, and will then focus on the consequences for the terminals.

Changes in system layout

The original system layout, presented in Figure 5-43, projected one OLS terminal near Hoofddorp (black rectangle left), three terminals at Schiphol (black rectangles centre-right) and one terminal at the flower auction in Aalsmeer (black rectangle bottom right). The three main areas would be connected to one another with single bored tunnels, indicated by the red lines. The remaining tunnel infrastructure would be built by using a more traditional cut and cover technology. Near the flower auction, a section of the track would be built above ground, as there was only a limited
interference with other infrastructure on that section. This original system layout was used as point of departure for developing the terminal concepts as discussed in the previous sections.

Figure 5-43 Original system layout [COLS, 1998-b]

The new proposed system layout is presented in Figure 5-44. The first major change was the relocation of the rail terminal from the area near Hoofddorp, to a location much closer to the Airport. The new railway terminal, called Rail Terminal Zwanenburg, would be built underground near the so called Zwanenburg runway and alongside the existing underground rail infrastructure, already in place. The new rail terminal is indicated in red at the top left hand corner. Furthermore, the layout at Schiphol Airport would change significantly. Instead of having three larger terminals at Schiphol, many more smaller terminals were now projected along the different loops at Schiphol, connecting all the main freight buildings on the airport.
Due to the reduced distances, significant savings were expected on tunnel infrastructure and number of vehicles needed. Furthermore, the increase in number of terminals at Schiphol would increase the services to the customers. It was therefore clear that the new proposed system layout had some major benefits. Yet, it also had some major consequences for the terminals.

For the rail terminal, instead of being developed on ground level in relatively open field conditions at Hoofddorp, the terminal would now have to be built underground,
next to existing rail tracks near Schiphol. The terminal concept developed for the new rail terminal is presented in Figure 5-45. The figure shows the terminal positioned on both sides of the existing track. The trains can exit the main track and be loaded and/or unloaded next to the existing tunnels. The OLS cargo is rolled using roller bed technology and can be buffered temporarily on the platforms. The OLS vehicles drive on the outer track and can dock at 8 locations on either side of the terminal. Although the overall layout of the terminal is very different, many of the building blocks and experiences from the initial conceptual design process could be used again for the development of this terminal concept.

Figure 5-45 Terminal concept for the new rail terminal [COLS, 1999-b] & [COLS, 1999-c]
The new layout at Schiphol would include several underground loops with terminals located at all main cargo buildings. While the former three larger terminals at Schiphol were positioned on ground level, these smaller terminals would be situated underground, but slightly higher and on the right side of the tunnels. The terminal concept developed for the smaller terminals at Schiphol is shown in Figure 5-46. These smaller terminals were positioned underground because the many long slopes would otherwise create too much of a barrier/interference on ground level. The new terminals at Schiphol were positioned on basement level and could connect directly to the basement of the OLS clients. To enter a terminal, a vehicle travelling through the one-way tunnel would exit the ongoing flow of traffic (which would bypass the terminal) and proceed up a slope reducing speed. The vehicle enters the terminal and travels to its designated dock for unloading and/or loading. The docking and material handling on the terminal is again similar to that of the basic terminal design. After unloading and/or loading, the vehicle leaves the dock and exits the terminal on the opposite side, travels down the slope and re-enters the ongoing traffic. More on this and other terminal concepts developed for Schiphol can be found in [Pielage, 2000] and [Rijsenbrij et al., 2000].

![Figure 5-46 Terminal concept for the smaller terminals at Schiphol](image)

**Figure 5-46 Terminal concept for the smaller terminals at Schiphol [Pielage, 2000]**
As the system layout did not change for the flower auction, no major changes were needed here. The basic terminal design discussed in the previous section (5.7) could still be used as terminal concept for the flower auction.

Although the concepts for the rail terminal and Schiphol terminals presented in this section differ from the terminal concepts presented earlier, many of the building blocks and findings from the earlier conceptual design process could be re-used here. It was found that the concepts could be developed much faster, using the building blocks and experience gained from the initial conceptual design process. This again shows the value of developing concepts in a more structured manner, as suggested in the integrated design approach discussed in Chapter 4.

5.9 Summary and Conclusions

The conceptual designing of OLS terminals has been presented as a case study. For this case study, the design activities as they took place within the OLS project, have been mirrored to the integrated design approach presented in Chapter 4. All the elements of the integrated design approach have been discussed in this chapter. The main project structure and most of the Multi-X aspects have been introduced and discussed in Section 5.1. The five steps of the conceptual design process have been discussed in Sections 5.2 through 5.6, again elaborating on the various elements of the design approach. The basic terminal design that resulted from this design process has been presented in Section 5.7. Some of the developments that took place after this initial terminal design was developed have been discussed in Section 5.8, illustrating some of the benefits of using a structured design approach as presented in Chapter 4.

In general it is concluded that, although not all elements of the integrated design approach have been considered in the same extensive or desired manner within the OLS project, this case does demonstrate how the integrated design approach can work in practice.

This case has shown how a large complex project can be structured by using phases. The organization of the project, with different groups, different disciplines and different types of people has also been discussed. A lesson learnt was not to organize
a project too strictly according certain disciplines or area’s of expertise, but to allow for a more flexible organization with working groups which allow for a better definition of responsibilities and integration of layers within a group. Furthermore, apart from considering the disciplines required within a group, more attention should be paid to the different types of people required. The four layers, typical for automated freight transport systems, have also been distinguished within the OLS project and elaborated on throughout the different steps of the design process.

The five steps of the conceptual design process have been used to present the conceptual designing of OLS terminals.

The problem analysis step discussed the goal and need of the OLS project, and positioned the project within its environment. However, it proved difficult to involve all parties in the project and formulate their objectives in such a way that they could be useful for the design process. It was found that the objectives formulated for the OLS were incomplete, not specific and not quantified. This would affect all other steps of the design process.

In the system definition step, the system boundaries and interface could be clearly defined. The terminals were defined as sub-systems within the total OLS system, and interfaces were defined between the terminals, the OLS transport system and the various clients of the OLS system. Three main terminal functions could be distinguished, for which building blocks were developed in the next (system synthesis) step of the design process. Nevertheless, also as a consequence of the poorly defined objectives, problems were encountered with establishing the criteria. The only two criteria that could be distinguished were terminal performance and area utilization. Although these criteria did focus the design process and were used for the various steps, many more criteria could and should have been defined. Finally the basic assumptions or points of departure, used for developing the terminal concepts, were defined as part of the system definition step.

For the system synthesis step, a clear distinction could be made between the development of building blocks for the main terminal functions and the development of terminal concepts by combining different building blocks. Each terminal concept, with its own specific characteristics, was designed with a certain line of reasoning, taking into account the criteria and available building blocks. As such, this case clearly shows the systematic development of alternative system concepts as presented
in the design approach, whilst still recognizing and emphasizing the creativity and resourcefulness required within this step.

The simulation step produced insight in the performance and area utilization of the terminal concepts. Although many of the simulation activities were focused on determining the value of the two criteria for the different terminal concepts, several simulation activities also focused on more isolated issues in order to determine e.g. the technical feasibility of certain sub-system concepts. This case shows different type of simulations that can be used for the conceptual design of automated freight transport systems. Distinction was made between computer simulations or virtual prototyping, physical prototyping and expert evaluation. Lessons again learnt were: not to underestimate the complexity of developing fully automated freight transport systems; to spend sufficient time and effort on the development and testing of the system (especially the control system); and to use always physical prototyping. This case demonstrates that it can be necessary to detail and construct certain elements of a new system in the conceptual design phase, in order to assess the technological and economical feasibility of a system. Furthermore, it should be emphasized that in the simulation step, the characteristics of the different logistic control systems can be demonstrated and evaluated. In this step, the various control systems can be tried out, in order to test e.g. the added value of (too) complex control systems.

The evaluation and selection step discussed how a basic terminal design was developed, using the simulation results presented in the previous step. Although the evaluation and selection process was not carried out as suggested by the integrated design approach, e.g. using evaluation matrices, the discussion did give insight in the evaluation and selection process as it took place within the OLS project. In retrospect it has been concluded that the evaluation and selection should have been done in a more integrated and structured manner, using an evaluation matrix with more clearly defined criteria. This would have required and stimulated a better definition of the criteria in the system definition step, which in turn would have better guided the development of concepts and focused the simulation activities, eventually resulting in a better founded and transparent selection of the most suitable concept. It has been stated that not only the criteria and evaluation and selection would have been different, but most probably also the concepts themselves. This shows the importance of clearly defining objectives and criteria as well as the importance of iteration. All steps should be seen as part of an iterative design process, and not as something that
has to be done only once e.g. at the beginning or the end of the conceptual design phase. For example, evaluating and comparing different concepts will often lead to new insights, combinations of building blocks and/or system concepts.

This chapter then presented the basic terminal design as a result of the earlier discussed design process and finalizes with changes that took place after this basic terminal design was completed. It was found that, although these changes had some major consequences for the terminals, new terminal concepts could be developed much faster using the building blocks and experience gained from the initial conceptual design process. Using the integrated design approach not only makes the design process more transparent and the results reproducible and justifiable, but also makes it easier to cope with changes and develop new concepts within a relatively short period of time. This again, demonstrated the value of using the integrated design approach.
6 Conclusions

This chapter presents the conclusions of this research on the conceptual design of automated freight transport systems. First, the main goal of this thesis is reviewed and conclusions are drawn as to whether this main goal has been achieved. These main conclusions are then further substantiated with the more specific conclusions from the different chapters of this thesis.

6.1 Main goal and conclusions

The goal of this research was to develop an approach for the conceptual design of automated freight transport systems and to use this approach in the OLS project (Section 1.5).

The design approach itself has been fully developed and extensively discussed in this thesis. However, the development and foundation of the integrated design approach proved more complex and time-consuming than initially expected. Therefore the integrated design approach could not be fully applied within the OLS project. As such, the initial goal of this thesis has been achieved only partly. Nevertheless, this thesis does present the development of a new well-founded integrated design approach for the conceptual design of automated freight transport systems, and demonstrates its practical value through the OLS case study.

6.2 Characteristics of automated freight transport systems

Discussing the characteristics of automated freight transport systems in Chapter 2, produced several aspects that should be considered for the conceptual design of automated freight transport systems (AFTS’s). It was found that AFTS’s are often complex and new systems. The development of such systems is a challenging matter and should receive full attention right from the start of a project. This again stresses the importance of the conceptual design phase as one of the first phases in the development of a system. Furthermore it was found that the conceptual design of AFTS’s involves many different disciplines and that the development of such systems takes a long time, during which period many changes will take place. There are many different parties involved or interested in such projects all with their own, sometimes
conflicting objectives. The conceptual design of AFTS’s requires an integrated approach, taking into account the infrastructure, equipment, control system as well as the operational organization. All these layers should be considered during the conceptual design phase in order to develop total (integrated) concepts that allow for a proper evaluation and selection.

It was concluded that a design approach for the conceptual design of automated freight transport systems should reflect all these aspects. Therefore, these aspects have been used to formulate criteria to evaluate both, the existing models of the design process as well as the new integrated design approach.

6.3 Existing design models

The extensive research into existing models of the design process useful for the conceptual design of automated freight transport systems, as discussed in Chapter 3, revealed two interesting fields of study: Systems Engineering (SE) and Engineering Design (ED). SE considers the system as a whole rather than focus on the individual components and often takes a broader perspective, contemplating the whole lifecycle of a system. ED focuses more on the actual design of technical products or systems. Models from both fields were presented, discussing the useful and less useful elements of the different models. This research also produced criteria for evaluating the different models.

Evaluation matrices were developed to evaluate how the different existing models score in relation to the different criteria. Three main aspects were defined: Project Structure, Design Process, and Multi-X, which were used to classify the criteria. For each main aspect an evaluation matrix was developed. This was not an exercise to select the best model, but rather to graphically show which criteria were represented in which models. It was concluded that, although all models present a number of interesting and/or useful items for the conceptual design of AFTS’s, not one satisfied all criteria.

6.4 New integrated design approach for the conceptual design of automated freight transport systems

The new integrated design approach for the conceptual design of automated freight transport systems, presented in Chapter 4, was developed by integrating the three
models developed for the main aspects Project Structure, Design Process and Multi-X. As the criteria defined in Chapter 3 for evaluating these three main aspects were instrumental for the development of these three models, the integrated design approach satisfied all these criteria. As such it was concluded that the integrated design approach distinguished itself from all other models found in literature, and is to be regarded as new and unique. Furthermore, the new integrated design approach was considered to be well-founded, as it was based on an extensive literature survey on design methodology and further analysis of the most important well-established existing SE and ED models.

6.5 The OLS case

The conceptual designing of OLS terminals was discussed in Chapter 5 as a case study. The design activities as they took place during the OLS project were mirrored to the integrated design approach presented in Chapter 4. It was concluded that, although not all elements of the integrated design approach were considered in the same extensive or desired manner within the OLS project, this case study did demonstrate how the integrated design approach could work in practice. All elements of the integrated design approach were discussed. Furthermore, it was found that using the integrated design approach would not only make the design process more transparent, and the product reproducible and justifiable, but would also make it easier to cope with changes and develop new concepts within a relatively short period of time.

Apart from being an example on how the integrated design approach could work in practice, the OLS case also produced some lessons learnt. One of the lessons learnt was not to organize a project too strictly according to certain disciplines or areas of expertise, but to allow for a more flexible organization with multi-disciplinary working groups. Apart from considering which disciplines are required within a group, it was also found that more attention should be paid to the different types of people required for the design process. Furthermore, the case showed the importance of each step and the importance of iteration. A lesson learnt here was to better involve all parties in the iterative design process, as one cannot expect potential future clients/users to formulate clear and specific objectives for a system they cannot envisage. Not only the designers of a system get inspired and improve their insights by contemplating different possible solutions, but also all other parties involved.
Communication is an important part of the conceptual design process. Other lessons again learnt from the OLS project were: not to underestimate the complexity of developing fully automated freight transport systems; to spend sufficient time and effort on the development and testing of the system (especially the control system); and to use always physical prototyping as this will reveal many often unexpected problems. The case demonstrates, that it is often necessary to detail and construct certain element of a new system in the conceptual design phase, in order to assess the technological en economical feasibility of a concept.

6.6 Outlook on the future application of the design approach

The integrated design approach has been developed to help future designers, and not to restrict them in any way. The design approach must not be seen as a stringent design code that dictates what should or should not be done. The design approach should be seen as a design guideline, which can help to structure the design process and presents several aspects for consideration when developing automated freight transport systems.

Using the integrated design approach may require some additional time and effort at the start of a project but will ultimately benefit the project in terms of time, money and results. This holds especially for large complex projects with long development times during which things are bound to change.

Although this thesis focuses on the conceptual design of automated freight transport systems, the new developed integrated design approach could also be used for the conceptual design of other types of complex systems with similar characteristics as AFTS’s. One could think of automated public transport systems, automated terminals at sea- and airports and/or new city-distribution systems. Large scale, multi-disciplinary projects such as “Maasvlakte 2”, focussing on the expansion of the port of Rotterdam, could also benefit from this thesis and could be one of the future fields of application.
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### Abbreviations

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<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>AAS</td>
<td>Amsterdam Airport Schiphol</td>
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<td>AFTS</td>
<td>Automated Freight Transport Systems</td>
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<td>AGV</td>
<td>Automated Guided Vehicle</td>
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<td>ASC</td>
<td>Automated Stacking Crane</td>
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<tr>
<td>AS/RS</td>
<td>Automated Storage and Retrieval System</td>
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<td>ATAN</td>
<td>Air Transport Association Netherlands</td>
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<tr>
<td>CE</td>
<td>Civil Engineering</td>
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<tr>
<td>COB</td>
<td>Centrum Ondergronds Bouwen (Centre for Underground Construction)</td>
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<tr>
<td>COLS</td>
<td>Consultants Ondergronds Logistiek Systeem (Consortium of consultants within COB project group)</td>
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<tr>
<td>CORBA</td>
<td>Common Object Request Broker Architecture</td>
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<tr>
<td>CTT</td>
<td>Centre for Transport Technology</td>
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<tr>
<td>DCV</td>
<td>Destination Coded Vehicle</td>
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<tr>
<td>DDE</td>
<td>Delta Dedicated East (terminal of ECT in Rotterdam)</td>
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<tr>
<td>DIA</td>
<td>Denver International Airport</td>
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<tr>
<td>DTM</td>
<td>Delft (or Dutch) Tunnel Mover</td>
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<tr>
<td>DoD</td>
<td>Department of Defense (in the USA)</td>
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<tr>
<td>EBS</td>
<td>Early Baggage Storage</td>
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<tr>
<td>ECT</td>
<td>Europe Container Terminals</td>
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<td>ED</td>
<td>Engineering Design</td>
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<tr>
<td>EE</td>
<td>Electrical Engineering</td>
</tr>
<tr>
<td>EIA</td>
<td>Electronic Industries Associated</td>
</tr>
<tr>
<td>HBS</td>
<td>Hold Baggage Screening</td>
</tr>
<tr>
<td>HIDC</td>
<td>Holland International Distribution Council</td>
</tr>
<tr>
<td>HR</td>
<td>Human Resource</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>INCOSE</td>
<td>International Council on Systems Engineering</td>
</tr>
<tr>
<td>IT</td>
<td>Information Technology</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
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</tr>
<tr>
<td>KLM</td>
<td>Koninklijke Luchtvaart Maatschappij (Royal Dutch Airlines)</td>
</tr>
<tr>
<td>LOCES</td>
<td>Logistic Control Engineering System</td>
</tr>
<tr>
<td>ME</td>
<td>Mechanical Engineering</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration (in the USA)</td>
</tr>
<tr>
<td>NDL</td>
<td>Nederland Distributie Land (see HIDC)</td>
</tr>
<tr>
<td>NS</td>
<td>Nederlands Spoorwegen (Dutch Railways)</td>
</tr>
<tr>
<td>OLS</td>
<td>Ondergronds Logistiek Systeem (see ULS)</td>
</tr>
<tr>
<td>QC</td>
<td>Quay Crane</td>
</tr>
<tr>
<td>RTH</td>
<td>Rail Terminal Hoofddorp</td>
</tr>
<tr>
<td>SAT</td>
<td>Site Acceptance Test</td>
</tr>
<tr>
<td>SBT</td>
<td>Standard Baggage Tray</td>
</tr>
<tr>
<td>SE</td>
<td>Systems Engineering</td>
</tr>
<tr>
<td>SPC</td>
<td>Schiphol Project Consult</td>
</tr>
<tr>
<td>TRACES</td>
<td>Transport Control Engineering System</td>
</tr>
<tr>
<td>TRE</td>
<td>Transport Eenheid (Transport unit defined for OLS)</td>
</tr>
<tr>
<td>UFTS</td>
<td>Underground Freight Transport System</td>
</tr>
<tr>
<td>ULD</td>
<td>Unit Load Device</td>
</tr>
<tr>
<td>ULS</td>
<td>Underground Logistic System</td>
</tr>
<tr>
<td>USA</td>
<td>United States of America</td>
</tr>
<tr>
<td>VBA</td>
<td>Verenigde Bloemenveiling Aalsmeer (Flower auction in Aalsmeer)</td>
</tr>
<tr>
<td>VDI</td>
<td>Verein Deutscher Ingenieure (society of German Engineers)</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>2D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
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Samenvatting (summary in Dutch)

Conceptueel Ontwerpen van Automatische Vrachttransportsystemen

Het conceptueel ontwerpen van automatische vrachttransportsystemen is een uitdagende zaak. Er zijn vele verschillende partijen, type mensen en disciplines bij betrokken, die allemaal moeten samenwerken om een vaak nieuw en complex systeem te ontwikkelen. Automatische vrachttransportsystemen hebben over het algemeen een lange levenscyclus, vergen grote investeringen en kunnen een grote invloed hebben op hun omgeving. De conceptuele ontwerpfase is een van de eerste en een van de belangrijkste fasen bij het ontwikkelen van een dergelijk systeem, daar de beslissingen die hier worden gemaakt alle volgende fasen in de levenscyclus van dat systeem zullen beïnvloeden.

Hoewel men zich al vele jaren bezighoudt met ontwerpen, en er vele ontwerp methodes en technieken zijn ontwikkeld, was er geen ontwerp aanpak voor het conceptueel ontwerpen van automatische vrachttransportsystemen. Het ontbreken van een dergelijke aanpak werd duidelijk tijdens het ontwerpen van een nieuw automatisch ondergronds transportsysteem in Nederland (het zogenaamde OLS). Deze observatie vormde de hoofdmotivatie voor het schrijven van dit proefschrift.

Het doel was een ontwerp aanpak te ontwikkelen voor het conceptueel ontwerpen van automatische vrachttransportsystemen, en deze te gebruiken in het OLS project.

De ontwerp aanpak zelf is volledig ontwikkeld en wordt uitgebreid beschreven in dit proefschrift. De karakteristieke aspecten van automatische vrachttransportsystemen, besproken in Hoofdstuk 2, hebben richting gegeven aan het literatuur onderzoek naar ontwerp methodologie, gepresenteerd in Hoofdstuk 3. Er zijn criteria geformuleerd om zowel de bestaande modellen uit de literatuur, als de nieuw ontwikkelde ontwerp aanpak voor het conceptueel ontwerpen van automatische vrachttransportsystemen te evalueren. Geconcludeerd werd dat, hoewel de bestaande modellen een aantal interessante en bruikbare elementen bevatten voor het conceptueel ontwerpen van automatische vrachttransportsystemen, geen van de modellen aan alle criteria voldeed. De nieuw ontwikkelde ontwerp aanpak, weergegeven in Hoofdstuk 4, voldeed wel aan alle criteria. Zodoende kon geconcludeerd worden dat deze ontwerp aanpak zich
onderscheid van alle andere modellen gevonden in de literatuur en derhalve nieuw en uniek is. Voorts wordt de nieuwe ontwerp aanpak goed gefundeerd geacht, daar deze gebaseerd is op een uitgebreid literatuur onderzoek en nadere analyse van de belangrijkste gevestigde modellen.


Naast een voorbeeld te zijn hoe de ontwerp aanpak kan werken in de praktijk, heeft de OLS casus ook een aantal lessen opgeleverd. Deze en andere bevindingen uit dit proefschrift worden tevens besproken in de samenvattingen en conclusies aan het eind van de Hoofdstukken 2, 3, 4 en 5, en in Hoofdstuk 6 (conclusies). Hoewel dit proefschrift zich richt op het conceptueel ontwerpen van automatische vrachttransportsystemen, zou de nieuw ontwikkelde ontwerp aanpak ook toegepast moeten kunnen worden voor andere complexe systemen.
Summary

Conceptual Design of Automated Freight Transport Systems

The conceptual design of automated freight transport systems is a challenging matter. It involves many different parties, types of people and disciplines which all have to work together to develop a system which is often new and complex. Automated freight transport systems typically have a long lifecycle, require large investments and can have a great impact on their environment. The conceptual design phase is one of the first and one of the most important phases in the development of such a system, as the decisions made here will influence all subsequent phases of the system’s lifecycle.

Although people have been designing for many years, and many design methods and techniques have been developed, there was no design approach for the conceptual design of automated freight transport systems. The lack of such a design approach became apparent during the design of a new automated underground freight transport system in the Netherlands (the so called OLS). This observation formed the main motivation for writing this thesis.

The goal was to develop an approach for the conceptual design of automated freight transport systems and to use this approach in the OLS project.

The design approach itself has been fully developed and is extensively discussed in this thesis. The characteristics of automated freight transport systems, discussed in Chapter 2, helped to guide the literature survey on design methodology, presented in Chapter 3. Criteria were formulated to evaluate both, the existing models found in literature as well as the new developed design approach for the conceptual design of automated freight transport systems. It was concluded that, although the existing models present a number of interesting and useful items for the conceptual design of automated freight transport systems, not one satisfied all criteria. The new developed design approach, presented in Chapter 4, did satisfy all criteria. As such it was concluded that the design approach distinguished itself from all other models found in literature, and could be regarded as new and unique. Furthermore the new design approach was considered to be well-founded, as it was based on an extensive
literature survey on design methodology and further analysis of the most important well-established models.

The development and foundation of the design approach proved more complex and time-consuming than initially expected. Therefore, the design approach could not be fully applied within the OLS project. As such, the initial goal of this thesis has been achieved only partly.

Nevertheless, the conceptual designing of OLS terminals has been presented in Chapter 5 as a case study. For this case study, the design activities as they took place during the OLS project were mirrored to the new developed design approach. All the elements of the new design approach have been discussed. The case shows how a large complex project can be structured using the phases defined in the design approach. Furthermore, the design activities as they were performed within the OLS project could be clearly positioned under one of the five design steps of the conceptual design process defined in the new design approach. Several of the Multi-X aspects, such as multiple layers, multiple disciplines and multiple stakeholders could also be clearly recognized within the OLS project. It was concluded that, although not all elements of the new design approach were considered in the same extensive or desired manner within the OLS project, the case study does demonstrate how the new design approach could work in practice. Furthermore, it was found that using the design approach would not only make the design process more transparent, and the product reproducible and justifiable, but would also make it easier to cope with changes and develop new concepts within a relatively short period of time.

Apart from being an example on how the new design approach can work in practice, the OLS case also presents some lessons learnt. These and other findings discussed throughout this thesis are also presented in the summary and conclusions at the end of Chapters 2, 3, 4 and 5, and in Chapter 6 (Conclusions).

Although this thesis focuses on the conceptual design of automated freight transport systems, it is felt that the newly developed design approach could also be used for several other types of complex systems.
Curriculum Vitae

Ben-Jaap Pielage was born on September 26th, 1970 in Rotterdam, the Netherlands. At a young age, travelling with his parents, he attended different schools in Brunei, Australia and Venezuela. After receiving his high school diploma (VWO) in 1989 from Scholengemeenschap Caland in Rotterdam, he studied Mechanical Engineering at Delft University of Technology. He graduated (MSc) in 1996 on the design of a new cargo loading system for the next generation Fokker Aircraft. In September 1996 he started working as a researcher at the department for Transport Technology and Logistics, where he became assistant professor in 1999. He has been involved in several transport related Research and Development projects and has written several papers on the design and development of transport systems. He has been a member of TRAIL Research School for many years and was a member of the Board for Transportation Engineering within the Royal Institution of Engineers in the Netherlands from 1996 to 2004.
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