Simulation of underground freight transport systems

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Abstract

Underground logistics distribution systems seem to be a sustainable solution for environmental, congestion and space problems. In Holland many underground projects spring up like mushrooms, starting a definition phase to test the feasibility of the first underground designs. At local level some cities seek for opportunities to distribute by means of underground freight transport. At regional level junctions between underground transport lines are examined to connect companies. At (inter)national level the interconnection of high-speed freight railroads with underground transport pipes between Schiphol and Aalsmeer should be in practice in 2002. In order to determine the feasibility of these transport systems, logistic simulation is a supportive method for designing questions. The layout of the underground infrastructure, the location of terminals, the use of underground floor space, the number of electric vehicles and the handling capacities are logistic issues which have to be determined integrally. In order to gain a structured insight into the logistic dependencies, we define three modelling levels of control: at vehicle level (micro), in order to control the traffic movements of the vehicles in the handling areas and tubes; at transport order level (meso), in order to control the transport orders, the assignment of shipments and vehicles, and the empty vehicle stock management; and at interconnection level (macro), in order to achieve good connectivity with the transport schedules of the external transport modalities. Based on several empirical case studies, the development of generic building blocks has already such an underground functionality that effects of layout, handling capacities and available underground floor space can be represented.
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1 Introduction

In 1993 the Dutch government initiated a programme for the development of sustainable transport systems. The overall programme comprised five sub-programmes: food, chemistry, housing, water and transport. The mission of the sub-programme transport is to develop sustainable transportation systems for both people and goods in order to achieve a factor twenty reduction in transport related emissions, noise pollution, energy consumption and use of space in the next fifty years. Within the framework of this programme underground distribution was selected as promising transport system to adapt the phenomenal growth of transport needs, and to meet in the meantime, the environmental conditions.

The interest of the market for the development of an underground freight infrastructure is derived from the following reasons:

- current overground infrastructure becomes congested more often;
- the demand for reliable transportation grows;
- for road transport the cost price rises and the radius of action for international links decreases;
- extension of the road infrastructure leads to an increase in nuisance and social resistance.

The serious interests can be reflected in a growing number of plans for implementation of underground transport. At city level many municipalities are discussing the possibilities of urban freight transport. At regional level some companies located at different industrial zones could become connected by an underground distribution system. Especially companies with a strong supplier-customer relationship in terms of volumes and pieces are potential users of these systems. Due to the flexible, continuous and reliable underground transport system just-in-time deliveries become possible, thus reducing stock positions at suppliers’ as well as at customers’ side. At (inter)national level huge economic centres will be interconnected by an underground distribution network, and by high-speed rail connections. An example of projects at this level is the OLS project which connects the flower auction Aalsmeer, Schiphol national airport and a (high-speed) rail terminal at Hoofddorp. The renewal of these underground transportation projects is based on a fully-automated system with several transhipment locations for different end-users.
At this moment many underground distribution projects have started the definition phase. The feasibility of these projects has been examined for logistical aspects, technical specifications of infrastructure and means of transport, financial aspects, and environmental conditions. In order to represent the appropriate coherence between logistic and technical specifications simulation models have been developed to gain a clear insight into the entire design of the underground distribution system. Especially sensitivity analysis of specific technical parameters or choices might indicate which parameters are critical for the functioning of the system.

For the next decade the development of underground distribution systems will be high on the agenda of local and national policy makers, we have started with the development of library with generic building blocks. This paper describes our first ideas about conceptual modelling and shows survey of our work in the current projects for underground distribution networks.

2 Conceptual Modelling

To obtain a structured insight into all the dependencies among the logistic activities, the technical aspects of vehicles and infrastructure, the transport demands and the interconnectivity with other transport modes, three conceptual modelling levels of control are defined here:

- at interconnection level \textit{(macro)}, in order to achieve good connectivity with the transport schedules of the external transport modalities;
- at transport order level \textit{(meso)} in order to control the transport orders, the assignment of shipments and vehicles and the empty vehicle stock management;
- at vehicle level \textit{(micro)}, in order to control the traffic movements of the vehicles in the handling areas and tubes.

Figure 2.1: System Hierarchy (e.g. Heijden)
The construction of the hierarchy in conceptual models is important to provide transparency in the models. Each controlling level can be considered a market, i.e. the dynamic interaction between demand and supply. From each controlling perspective the models are specified to such a level of detail being relevant for the market situation. Consequently, some processes or activities are modelled as a blackbox. The blackbox is specified more detailed in another, usually lower-level controlling perspective. The validation of this chosen hierarchy in models can be evaluated by techniques such as meta-modelling and experimental design (e.g. Kleijen\textsuperscript{2}). Each controlling level will be discussed in detail.

2.1 The micro-level: traffic management

The large-scale nature as to the high number of vehicles and transport demands, the great traffic intensity caused by short throughput times, and the high capacity loads require a high reliability of the transport system and a great flexibility in the transport services. To meet these engineering aspects, heavy demands are made upon the development of an adequate controlling system for vehicle and traffic management.

We can base ourselves on a lot of research experience on vehicle management which is available from the implementation of the automated guided vehicles at the European Combined Terminals (ECT) in Rotterdam and the implementation of a new transport technology CombiRoad (e.g. Evers\textsuperscript{3}). At present, the Automated Guided Vehicles (AGV) working at the ECT terminal are controlled by a central system. For example, two vehicles crossing each other, both slow down resulting in a loss of time. If the intelligence will be decentralised to the level of vehicles, the vehicles can respond using their own knowledge of traffic rules. In the Smagic-project (e.g. Evers\textsuperscript{4}) a new type of vehicle and traffic control has been developed recently. The system design consists of four segments being called the Process Infrastructure. The Process Infrastructure is specified in terms of primitives, such as (domain) positions and semaphores, controlling the conflicting usage of resources by several demanding actors. These primitives are categorised in the next four segments:

- **Process Co-ordination**
  The function of this segment is to control processes which try to allocate the competitive process resources of the available process infrastructure. The way in which the processes actually take place is described in so-called 'scripts'.
• **Priorities & Timing**
  The modules of the segment Priorities & Timing provide additional information regarding the intelligence of the semaphore-mechanisms in the segment Process Co-ordination. This information is supplementary in terms of additional controlling with respect to timing rules and priority rules.

• **Actor Mission**
  The segment Actor Mission registers information about the arrivals of the actors. Information about the actor's position, its timing and priority is given as pre-information to the segment Priorities & Timing. The actual arrival is finally given by the Process Co-ordination.

• **Basic Processes**
  Basic Processes contain modules for the elementary physical processes which have to be carried out by an actor. The input/output channels of these modules are somehow connected with the domain positions of the process infrastructure.

The architecture of the system design resembles the process architecture of the variable sliding block technique for trains (e.g. Duin\(^5\)). The difference and its strength between the more conventional system architectures and this system architecture is the exclusive availability of the resources. In traditional systems only one vehicle is allowed to be in a control segment. Even if the routes of the vehicles are not conflicting, the system will ask for an exclusive usage of this segment. Generally, loss of handling capacity and growth of the leadtimes will be the result. In informatics the problem with concurrent use of hardware seems to have identical characteristics. Dijkstra (e.g. Dijkstra\(^6\)) and later Ben-Ari (e.g. Ben Ari\(^7\)) introduced the semaphore mechanism. The threshold of a semaphore, say value S, is a non-negative integer which represents the capacity available. With signal(S)-wait(S)-instructions the permission of entering a resource can be controlled. So far, the first tests for different crossings seem to provide good results with respect to conflict handling. Later this year the simulation software will be decoded into programming language C++. This software will be integrated into the hardware of vehicles and semaphores and will be tested and evaluated in a 'real-life' laboratory.
2.2 The meso-level: order management

To develop the order management, the logistic functions to be performed in the logistic concept are identified. On the basis of underground urban freight distribution we demonstrate the logistic concept. Goods with the destination inner city are received just outside the city at an interchange referred to as a Logistics City Park (LCP). At this LCP a storage warehouse is installed for rolling stock articles enabling frequent deliveries to customers. The LCP also facilitates the direct distribution and the cross-docking flows. For these flows grouping/degrouipng and sorting activities are provided. The goods are transhipped on the AGV's and transported to one of the district distribution shops (DDS) in the inner-city.

![Logistics system design (meso-level)](image)

From a modelling perspective the logistic functionality of DDS can be copied from LCP. The logistics intensities are only on a small scale but the logistic functions are similar. From the DDS goods can be temporarily stocked and finally distributed to the shops, consumers, offices and businesses. The district interchanges also function as the starting point for collecting the return of goods, waste products and packaging. Several network configurations are setup and are optional in relation to the radius...
of the service area. Table 1 represents the implications of several parameter values of the service radius for an average town of 200,000 inhabitants.

<table>
<thead>
<tr>
<th>Service Area</th>
<th># Houses/Shops</th>
<th># DDS</th>
<th>Length of pipes</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 m</td>
<td>50</td>
<td>1800</td>
<td>250 km</td>
</tr>
<tr>
<td>250 m</td>
<td>500</td>
<td>180</td>
<td>100 km</td>
</tr>
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<td>500 m</td>
<td>2000</td>
<td>45</td>
<td>50 km</td>
</tr>
<tr>
<td>750 m</td>
<td>5000</td>
<td>18</td>
<td>30 km</td>
</tr>
<tr>
<td>3000 m</td>
<td>25000</td>
<td>4</td>
<td>25 km</td>
</tr>
</tbody>
</table>

Table 1: System configurations

With this conceptual model we are able to perform sensitivity analyses for shortening lead-times and changes in the network configuration in order to determine the total fleet-size of vehicles in the system. As a result of the simulated transport demands and the resulting vehicles moves we will have a closer insight into the necessity of the underground spaces.

2.3 The macro-level: Logistic Freight planning

From the meso-level the arrival and departure processes of incoming and outgoing transport loads are to be derived. In case of the underground urban transport system the transport-loads arrive at the LCP and are distributed by the underground system. The return flows are collected by the underground system and are temporarily stocked at the LCP. For the underground urban transport system the LCP is the highest echelon. From this echelon the transport loads have to be co-ordinated to the external transport processes. The LCP has an accessibility for transport modes such as rail transport, barge transport and road transport.

An important characteristic of these transport modes is the batchproduction. Usually the transport-loads of trucks, vessels, or trains contain several packages for various customers. Therefore, the planning of empty vehicles should be geared to these arrival processes. For the return flows the number and space of loading-docks have to be determined. The size and number of loading-docks are dependent on the external transport schedules. Utilisation of loading-docks, and required loading space are performance indicators which can be tested for robustness of the external transports. For example, the sensitivity to delays, as a consequence of congestion at adjoining roads, can be determined.
With the conceptual model represented in figure 3 the layout of this distribution can be easily evaluated for bottlenecks.

3 Projects and Conclusions

At this moment the described conceptual models are applied in a great deal of current underground pilots. Most of the underground projects have just passed the definition phase and have continued their projectwork with an exact specification of the elements. To support this work, similar simulation studies have been started.

At city level two towns in the Netherlands, i.e. Utrecht and Alphen a/d Rijn, are examining the possibilities of underground freight transport. A detailed plan has already been developed for Utrecht. This plan contains a description of the network structure. The network consist of two underground circles with one common central point, the LCP. The total number of DDSs in the network is 38. Given this configurations and the potential transport demands the question to be answered is ‘what size should be the DDSs?’ and ‘how many vehicles should be in the system?’ and ‘how do we control the applications for empty vehicles?’. For these questions a restricted model has been developed with 1 LCP and 3 DDSs.
By developing a more restricted model, the effects of changing the controlling system of empty vehicles could be observed in a more structural way.

The most advanced, and most sophisticated project at underground logistics is the OLS project at Aalsmeer. The network layout is already fully specified, which means that the flower auction, the cargo terminals at Schiphol airport, and the new rail terminal are connected by this underground network. In this project the guidance and management of the vehicles on the infrastructure is chosen as the first research question to be tackled. The semaphore mechanism is overall tested in simulation models. The developed internal logic in the simulation models can be decoded into the vehicles' hardware. If the final results of this traffic management system are still favourable in a 'real-life'-laboratory, this system will also be used for the other underground transport projects.

The last project which seems to be started at a regional level is the project in the Province of Limburg. DSM, an international company for chemical products, NedCar, an assemblage facility of Volvo and Mitsubishi, some sub-suppliers, a rail terminal and a barge terminal will be connected by an underground distribution network. The first ideas of underground distribution arose last year. So far, not all the actors are directly involved and many people have to be persuaded to acknowledge the possible merits of an underground distribution network. Again the simulation models can play a key role during this phase, because they make an animation of the internal processes in the system. Due to this support, one can imagine how processes 'really' work, and change of attitude can be obtained.

Finally, it is to be concluded that the development of generic simulation models will provide us a lot of insight into some technical engineering issues which are important for progress in the development of underground distribution networks.
References


