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Hybrid Modeling: System Dynamics combined with Multi-criteria Analysis

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ABSTRACT

This paper proposes a methodological framework blending System Dynamics (SD) modelling with Multi-Criteria Decision Aid (MCDA). The PROMETHEE-GAIA methodology, based on outranking techniques, has been used here.

The approach will be illustrated by an application in the intermodal transportsector. Intermodal transport is the combination of at least two transportation modes in a single transport chain, without a change of container for the goods, with most of the route travelled by rail, inland waterway or ocean-going vessel, and with the shortest possible initial and final journeys by road. The aim of the model is to find ways to further stimulate this sector in order to move towards sustainable mobility.

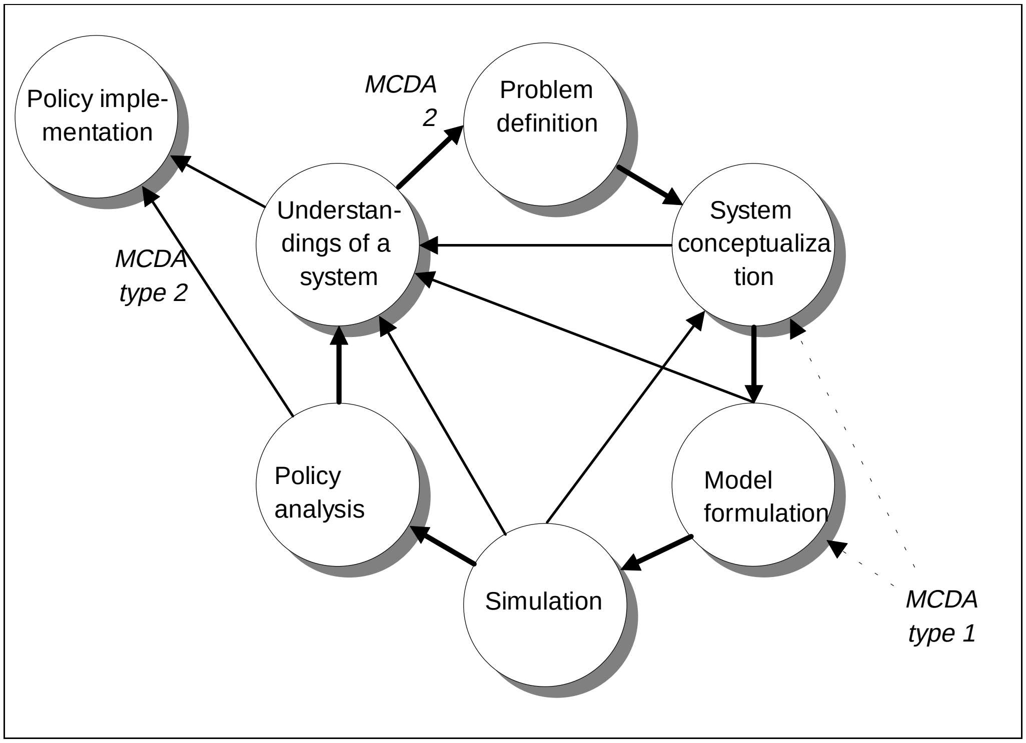
Introduction

Although system dynamics (SD) and multi-criteria decision analysis (MCDA) have the same purpose, namely to provide decision makers with a tool to better understand and control the real world by means of formal models, only a few attempts were made to merge these two methodologies.

Two types of hybrid modeling are however very interesting for both SD and MCDA. The first one is the inclusion of multi-criteria analysis in the SD-model itself. The decision rules, which are implicit in every SD-model, are all mono-criterion functions although many real world problems are taking multiple criteria into account. The second one occurs once several strategies are proposed and simulated by the model. It is obvious that decision-makers sometimes fail to know which policy to prefer. At this stage, a multi-criteria decision aid tool can provide insight into the problem and guidelines to choose the most appropriate policy to implement.

It is in these two parts, the modeling phase ("system conceptualization" and "model formulation" in Figure 1) and the phase from proposed policies to the implementation of the chosen "appropriate" one, that the SD-methodology can gain a lot from multi-criteria approaches.

Figure 1: Overview of the hybrid modeling approach



Source: on the basis of Richardson and Pugh, 1981, adapted

On the other hand, the MCDA tends to treat very localized corporate decision problems. How these decisions have an influence on the whole system is not taken into account (Forrester, 1994). It is here that MCDA-analysis can gain from the SD-approach.

A few attempts were already made to merge MCDA-methods with the SD-approach in order to decide which strategy is the most appropriate one (second type of hybrid modeling). Gardiner and Ford (1980) and Reagan-Ciricione et al. (1991) merged multi-attribute utility models (MAU) with the system dynamics approach. A weighted linear additive model calculates an overall evaluation for a policy option. Andersen and Rohrbaugh (1992) used a Social Judgment Analysis. This is a correlation-based approach for pointing out the preference structures of the decision-makers. In this method only the evaluations by the decision-makers are used on a scale from 1 to 20 and no objective data are used. A linear, additive judgement model of the preferences of a decision-maker is obtained. By Brans et al. (1998) an 11-step methodology is proposed to develop a SD-model and to select certain strategies by a multicriteria-method.

No attempts were made to incorporate the MCDA-model within the model. We suggest using the PROMETHEE (Preference Ranking Organisation METHod for Enrichment Evaluations)-

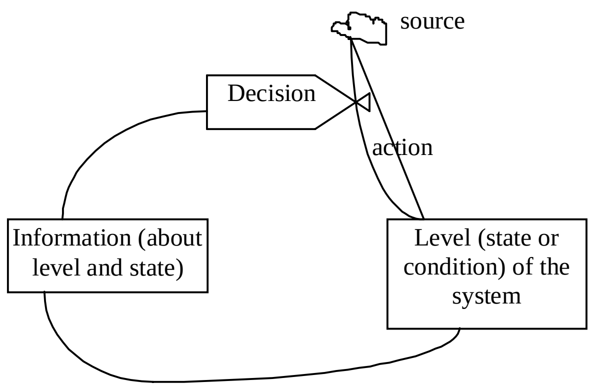
GAIA (Geometrical Analysis for Interactive Aid) methodology that belongs to the outranking methods.

The first type of hybrid modeling deals with the explicit incorporation of multi-criteria analysis in the model itself (Section 1). A model developed to understand the impact of the location of new intermodal terminals on its marketshare, illustrates the hybrid modeling.

MCDA in the SD-model

The focus of the SD approach to complex problems lies in the study of the feedback processes. These feedback loops are the result of the information obtained from the real world and the decision rules we apply to this information (Forrester, 1968,1992).

Figure 2 ***: Learning feedback loop***



Source : Forrester, 1968

The essential purpose of the SD-model is thus to uncover the loops existing in the real world. The decision rule can be a rather simple and straightforward one, e.g. looking at the inventory level in an ordering model. Other information can of course be used in composing the decision rule, for example the desired level of inventory and the adjustment time.

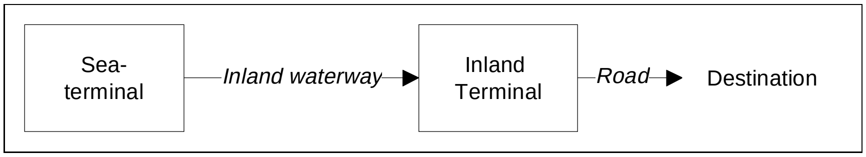
However, in many real world situations one usually encounters several desired levels that will influence the decision. In the case of inventory problems one can consider several evaluation criteria, like price, quality, delivery time, etc. for several possible products. The decision rule will then be a more complex one. In order to model these kind of decision problems MCDA has to be incorporated in the SD-model. The decision has to be made according to the level of the relevant variables. The MCDA-module in the SD-model could be calculated external by linking the associated software of the two approaches (PROMCALC or Decision Lab for MCDA and Stella II or VENSIM for SD). In this paper we will however calculate the necessary decision variables within VENSIM in order to present this hybrid modeling approach more clearly.

In the following section, we will explain the approach that was followed by means of an application in the transportation sector.

Intermodal transport

Intermodal transport is the transport of unitised loads, which combines at least two modes of transport in a single transport chain, with most of the route travelled by rail, inland waterway or ocean-going vessel, and with the shortest possible initial and final journeys by road. A common intermodal transportchain is depicted in Figure 3.

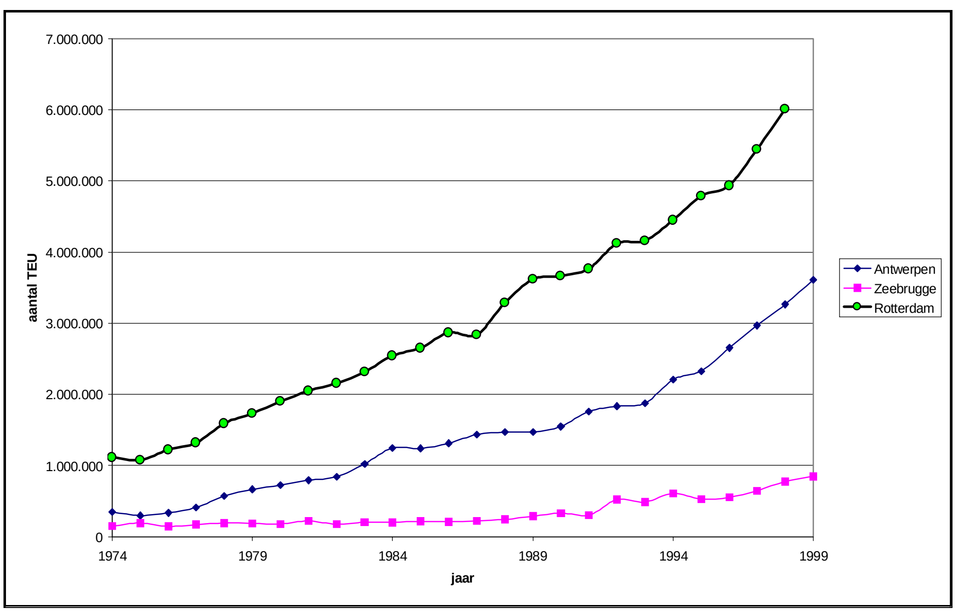
Figure 3: The intermodal transportchain



Source : Macharis, 2000

Due to the environmental and congestion pressures caused by road haulage, this type of transport has received substantial attention during the last few years. Intermodal terminals, necessary for the transhipment of the unit loads from one mode to another, are very important in this transport chain. During the last few years, several new terminal projects have been started in Belgium (see Macharis and Verbeke, 1999). Besides ecological concerns, the development of intermodal transport is also an important element for the further strengthening of the seaports. On the one hand, is the fast growth of containertraffic in the seaports (see Figure 4) putting a pressure on the distribution networks of the port. By building new intermodal inland terminals this pressure can be released (Notteboom, 2000). On the other hand, this large volume of containers passing through the ports provides the basic volume necessary to start an intermodal shuttle. A virtuous reinforcement cycle has started.

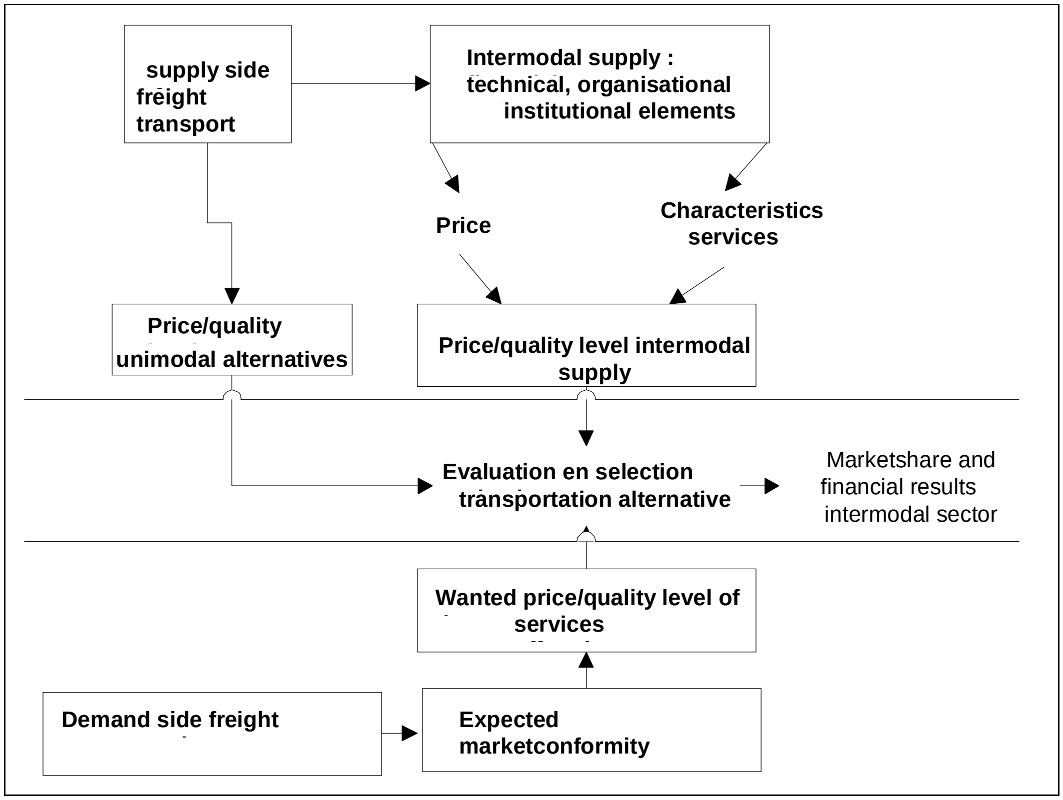
Figure 4: Containertraffic



Source: Port Authority Antwerp

The aim of the SD-model is to foresee the impact of the set up of new intermodal terminals on the modal split of the ports. A case study was made on the hinterland distribution of the port of Antwerp. In Figure 5 the basic mechanisms to determine the marketshare of the intermodal transportsector, is shown.

Figure 5: The intermodal trasportsystem



Source : Macharis and Verbeke (1999)

The selection of an optimal transportalternative is based on the comparision of the price/quality levels of the several transportoptions. As quality measures we will focus on the modal choice variables transportation-time and reliability (the way in which the transportation-time is respected). In order to take account of the three criteria (time, reliability and price) in the decision rule, support was found in the multicriteria-decision analysis tools. The way in which the decision rule was modelled, will be described in the next sections.

Model

The model was set up in VENSIM. In the next sections the several assumptions of the model will be described. Firstly, the modelspecifications are given. Secondly the growth of the container traffic in the ports and how this traffic is divided over the transportoptions, road, inland waterway and rail (modal split). The modal choice variables, being transportation-cost, transportation-time and the reliability of each of these three transportationmodi are described. The relative attractivity of the three transportationmodes are then translated in terms of a netto-flow (by means of the multicriteria-method PROMETHEE). As a last step the determination of the future marketshares are discussed. As the determination of the variables for rail and inland waterway are very similar we only discuss here the determination of the variables of inland waterway.

Modelspecification

- As base-year the year 1998 was chosen; In that year two intermodal terminals (inland waterway/road) existed in Belgium;
- The timehorizon is 2016, whereby the evolution of the systemvariables for 200 months is calculated.

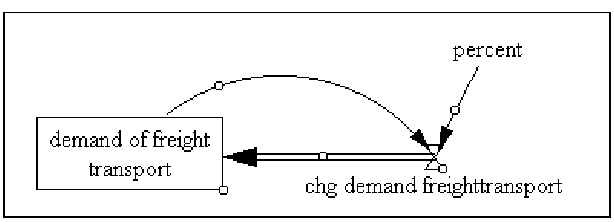
Growth of the porttraffic

- The port of Antwerp handled 1.157.000 TEU (twenty-foot-equivalent units) in 1998, of which the destination or the origin was located in Belgium (Port Authority Antwerp).
- The yearly growth of the port traffic is assumed to be 4,2% based on prognoses of Ocean Shipping Consultants (1999).

- In
- Figure 6 the *influence*-diagram is shown. The "demand for freighttransport" is a levelvariable, starting with 1.157.000 TEU and accumulating the (*chg (change) demand freighttransport*). This is described in the following equation and in :

*(1- 1) chg demand freighttransport = demand of freight transport*percent*

Figure 6: Traffic in the port of Antwerp



Source : C. Macharis

- The transport of the freight (in containers) will be transported by the following three transportation-modes: road, inland waterway/road transport (short water) and rail/roadtransport (short rail). In the base-year the modal split of the port of Antwerp was 55.000 TEU inland waterway, 47.000 TEU rail and 1.054.840 TEU over the road (Port of Antwerp).

Modal choice variables

- In order to model the evolution of the *modal split* of the port of Antwerp, the price of each transportation-mode (or combination of transportation-modes), the transportation-time and the reliability were taking into account. The determination of these *modal choice* variables is discussed in the following sections.

Marketprice

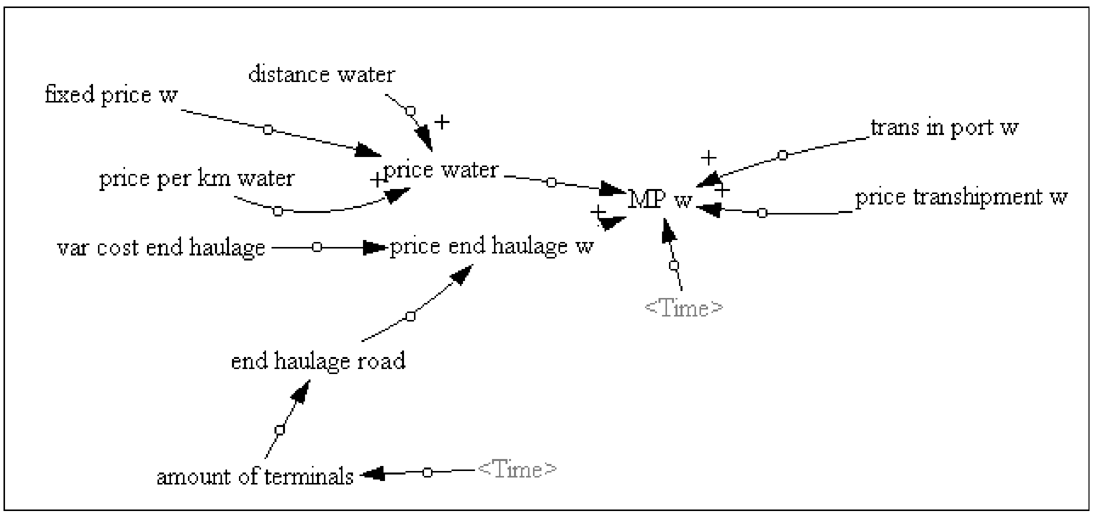
- The marketprices for the inland waterways (*MP b*) is a composition of the price of the inland waterway trajects, the transshipment at the maritime and the inland terminal and the price of the end haulage.

(1- 2) MP water= trans in port w + price transhipment w +price water + price end haulage w

Where *price water = fixed price w+distance water*price per km water*
and *price end haulage w= var.cost end haulage*end haulage road*

In Figure 7 the influence-diagram is shown for the calculation of the market-price of inland waterway. On the basis of the market-prices, received by the author from sector-experts, the several cost components were indicated.

Figure 7: Determination market price inland waterway



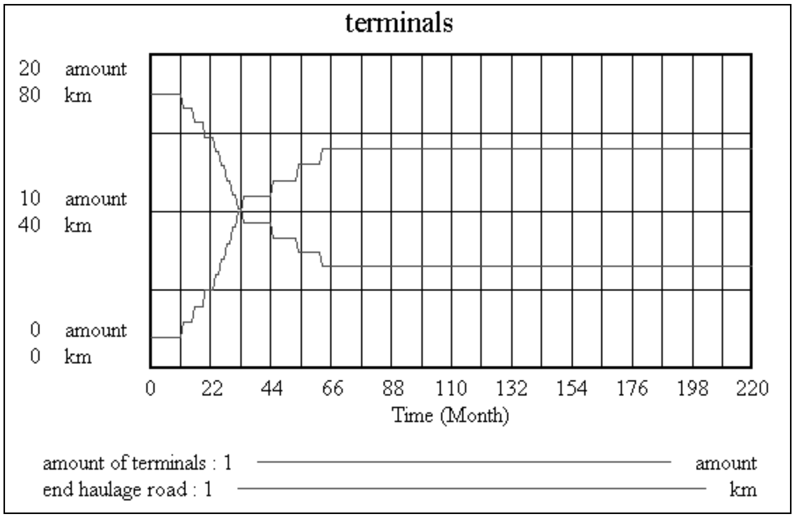
Resource: C. Macharis

The market-price of railtransport is calculated in a similar way.

- The distance of the end haulage ("end haulageroad" in Figure 7) decreases when new terminals are build. The exact timing of the insertion of these terminals is folowing the real predication of the termination of the projects. The exact decrease of the distance of the endhaulage is based on following assumptions :
  - In 1998 only two intermodal inland waterways where active in Belgium. With a total surface of Belgium of 30.528 km^2, we get a maximum end haulage of 70 km (root of 30.528 $km^2/2.\pi.$).
  - When 14 terminals will be build, the end haulage will be maximum 26 km.
  - On the basis of these two points a line can be drawn with the following equation:
    *End haulage road= 232/3-11/3*amount of terminals*

- In Figure 8 the insertion of new terminals (red line) and the effect on the distance of the end haulage (green line) is shown.

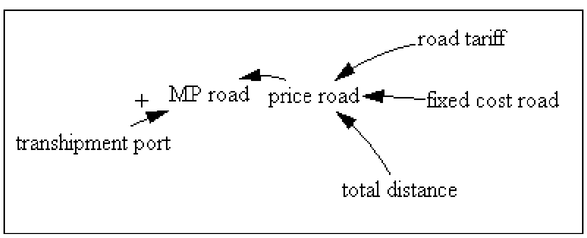
Figure 8: Impact of the insertion of new terminals on the distance of the end haulage



Resource: C. Macharis

- The price of roadtransport consists of the price of the roadtraject (road tariff**total distance+fixed cost road*) and the transshipment on the maritime terminals (*transhipment port*). The marketprices where obtained from sectorexperts. In Figure 9 the influence-diagram for the determination of the marketprice of the road (*MP road*) is shown.

Figure 9: Determination of the market price of road transport



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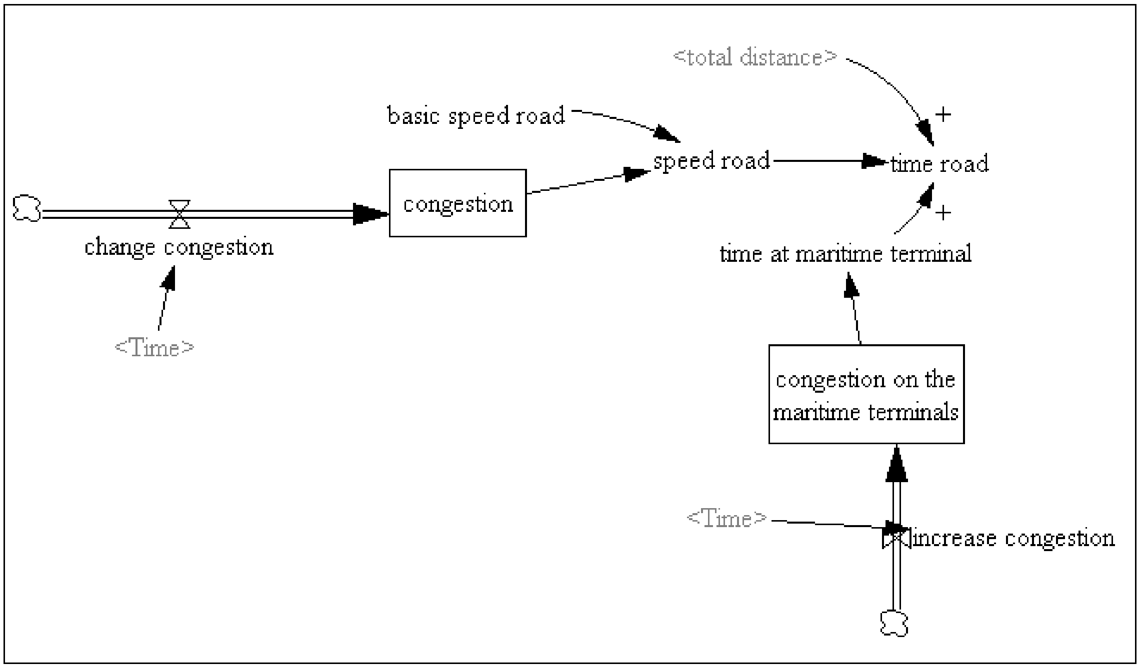
Transportation time

- For the roadtransport the average speed is multiplied with the average distance. The time of the containers for the transshipment on the maritime terminals is further added. The average speed is influenced by the congestion on the roads. On the basis of traffic countings of the Ministry of Traffic and Infrastructure (1998) the congestion can be modeled as an exponential increasing-converging variable (of the type $a+be^{-ct}$). The time of the transhipment at the maritime terminals on the trucks is also supposed to increase with the capacitityproblems. In Figure 10 these assumptions are shown. De variables congestion and congestion op the maritime terminals are described as level-variables.

Figure 10: Calculation of the transportation time for road transport

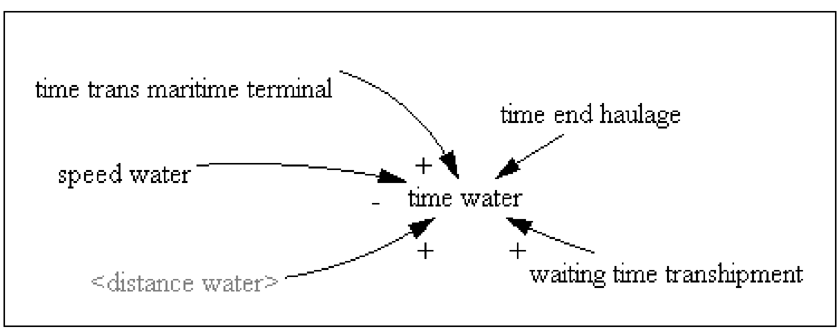


Resource: C. Macharis

- The transportation-time for the inland waterways and the rail are calculated on the basis of average speed multiplied with the average distance. The time needed for the transshipment is added. In Figure 11 the transportation-time is calculated with the following equation:

(1- 3) *Time water=time trans maritime terminal+speed water*distance water+waiting time transhipment+time end haulage*

Figure 11: Calculation time for the inland waterways



Resource: C. Macharis

The information on speed and waiting times were obtained from sectorexperts.

The capacity of the inland waterway, although not unlimited, can have a significantly increase in traffic (*Shifting Cargo*-EU, 1999). No capacity problems were thus assumed here.

Reliability

The reliability of the three transportmodes is measured on a scale from 0 to 100. In the base-year following values are assumed (on the basis of a survey, Vannieuwenhuyse, 1999):

- Road : 65
- Inland waterways : 80
- Rail : 70

The reliability of the road and the rail are depended of the congestion, for reason of more delivery problems when the infrastructure suffers from capacity problems.

Determination of the preferences

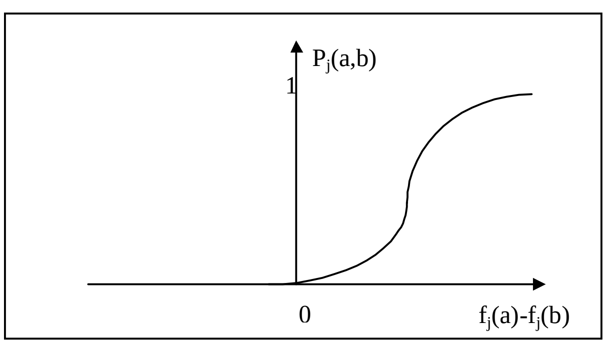
On the basis of the three *modal choice* variables the attractivity of a transportation-mode can be determined. A good indication of the relative attractivity of a transportation-mode is the netto-flow as determined in the PROMETHEE-method. More formally, let $f_1(.),f_2(.),...f_k(.)$ be the k evaluation criteria the experts wish to take into account (in this case $k=3$). The PROMETHEE-method models this decision problem and calculates a net flow that gives the relative preference of each alternative (see Brans and Mareschal, 1994; Brans et al., 1986 for an overview of this method).

A preference will be given to one alternative over the other according to the deviation between the two evaluations. So, if a and b are two transportation options, then the degree of preference (P) of a over b on criterion j (for example the price) is a function of the deviation between the values of the two alternatives on that criterion:

(1.1) $$P_j(a,b) = F_j\,[f_j(a) - f_j(b)] \qquad 0 \le P_j(a,b) \le 1$$

Figure 12 displays the shape of such a function.

Figure 12: ***Preference function***



Once a preference function has been associated to each criterion, an aggregated preference index is obtained in the following way:

(1.2) $$\pi(a,b) = \sum_{j=1}^{k} P_j(a,b).w_j$$

where w_j is the weight or the relative importance of criterion $f_j(.)$. In the intermodal transport model price has weight 5, the time has weight 2 and the reliability has weight 3. The weights are then normalized.

One can then calculate the net preference index through:

(1.3) $$\pi^*(a,b) = \pi(a,b)-\pi(b,a)$$

- The netflows are determined on the hand of following equations:

(1- 4)
$$\begin{cases} \phi^+(a) = \sum_{x\in A} \pi(a,x) \\ \phi^-(a) = \sum_{x\in A} \pi(x,a) \\ \phi(a) = \phi^+(a) - \phi^-(a) \end{cases}$$

ϕ^+ is called the dominating flow, ϕ^- the dominated flow. The higher $\phi(a)$, the better a is according to the criteria and compared with the evaluations of the other alternatives (or options).

Modal split

The netflows in the beginning have to reflect the *modal split* of that moment.

In order to make a prognosis of the *modal split* of the port of Antwerp we assumed that:

- The additional volumes of the port are divided over the three modes on the hand of the marketshares of that moment;
- A modal shift takes place between the three modes when the preference distribution changes;

This last assumptions is expressed in the following equation :

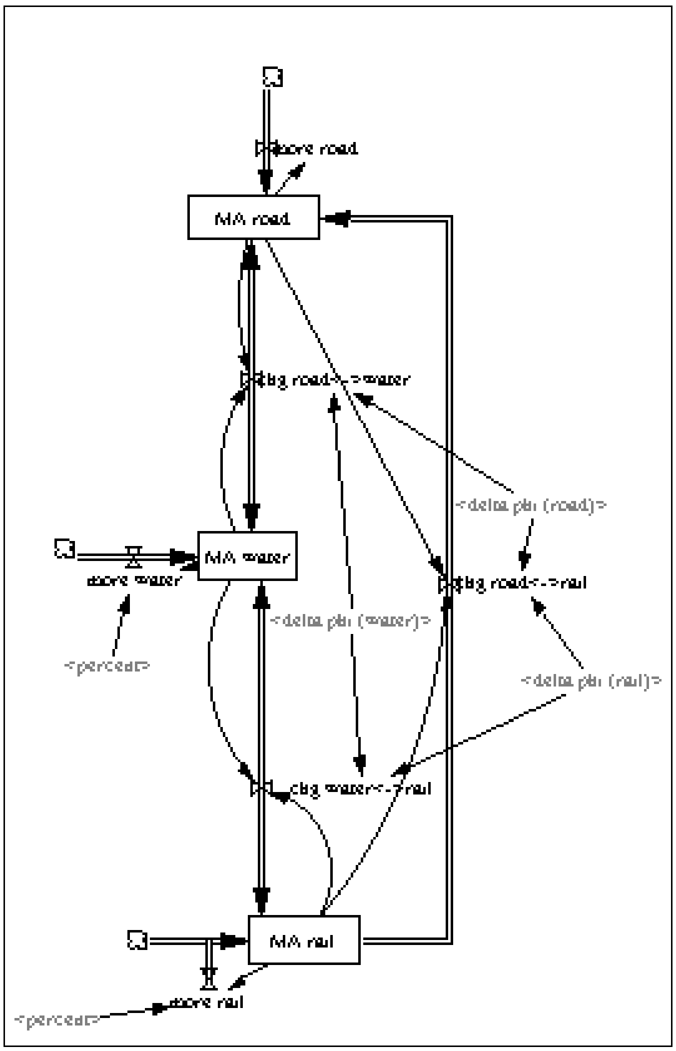
(1- 5)

*chg water<->road= IF THEN ELSE ("delta phi (road)"<0 : AND :"delta phi (water)">0 :AND: MA road 0>0, MA road *"delta phi (road)", IF THEN ELSE ("delta phi (road)">0 :AND: "delta phi (water)"<0:AND:MA water>0, -MA water *"delta phi (water)", 0));*

If the change of the netflow of the road (*delta phi (weg))* is negative or with other words if the road is becoming less attractive and the change of the netflow of the inland waterway (*delta phi (binnenvaart)*) is bigger than zero or thus the inland waterway option is becoming more attractive and the marketshare of the road is bigger than zero, than there will be a flow of the marketshare of the road to the inland waterway, from which the value will be equal to a percentage (given by the change of the netflow) of the market-share of the road. In the opposite case (the inland waterways are becoming less attractive and the road more attractive), a part of the market-share is flowing from the inland waterways to the market-share of the road.

In Figure 13 the determination of the market-shares of the road, inland waterway and rail is shown. Starting from the begin-situation (modal split-data port of Antwerp), shifts in the market-shares (*MA*) are occurring when the netflows are changing (*delta phi's*). The market-shares will further increase with the growth of the porttraffic (from which the growth is the variable *percent*).

Figure 13: Determination of the marketshares



Resource: C. Macharis

Feedbackloops

In this model no feedbackloops are created. This is due to the narrow focus, which was held on from the beginning. Several feedbackloops could however be created when the model would become more comprehensive.

The increase of the congestion was held exogenous in this model. This is due to the fact that container-traffic to and from the port is only a small port of the traffic on the roads. A possible feedback from the market-share to the roads through the prefence functions to the congestion would be in this case a misrepresentation of reality.

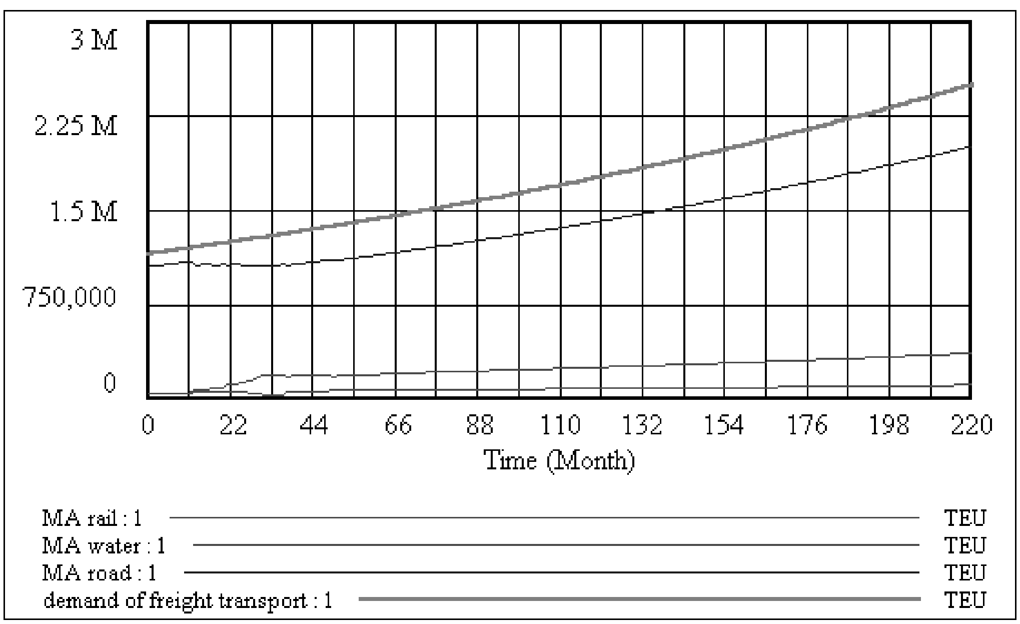
There were no capacity-problems of the inland terminals assumed. This could possibly cause a feedback because the increase of the market-share of the inland waterways would be restricted by capacity shortages. A capacity extension of the existing terminals is supposed to absorb these capacity-problems.

The results of this model are thus easy to understand and are not leading to counter-intuitive behavior. The development is however worthwhile to understand the interactions of the different elements of the system better and to create a view of a possible future. The aim was also to show the possibilities of incorporating multi-criteria analysis in a SD-model

Results of the model

In Figure 14 the results of the model are shown. On the horizontal axis the years are marked and on the vertical axis the amount of TEU that is respectively transported by road, inland waterway or rail from or to the port of Antwerp.

Figure 14: Expected evolution of the modal split



Source : C.Macharis

In the base-year (1998) 91% of the containers to the Belgian hinterland is transported over the road, 4,75% by inland waterway and 4,25% by rail. The dominance of road transport for the interior hinterland traffic in 1998 is due to the small amount of terminals in that year, so that for most part of the freight intermodal transport was not possible. Furthermore is it very difficult for intermodal transport option to be competitive on such small distances that have to be overcrossed in Belgium. Due to the large end haulage prices it is in the current situation not possible for most of the containers to make use of the inland waterways. In the model it was further supposed that thanks to the increasing congestion in road transport and the insertion of new terminals, the market share of the inland waterways and rail is increasing over time. At the end of the time horizon (in the year 2016), rail-transport increased its marketshare to 4,7%, inland waterways to 14,8% and road-transport only takes 80,5%.

Conclusions

In this paper we showed that a combination of the System Dynamics methodology with the multi-criteria-PROMETHEE-GAIA-methodology is very fruitful. By doing so, we take explicitly account of the multi-criteria nature of the decision rule. Hence, one is able to develop a dynamic multi-criteria analysis model. We illustrated this hybrid modeling in a transportation model developed to understand the impact of the insertion of new intermodal terminals on the modal split of the port of Antwerp.

The model can be the basis to develop possible strategies for sustainable mobility, like for example the internalisation of external costs.

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