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Dynamics in spatial logistic chains

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Introduction

The motivation of production, distribution and transport of commodities can be said to be purely economic. As such it might be said that the demand for freight transportation lends itself better to formal analyses using economic demand theory, but the dynamic processes involved make it necessary to incorporate feedback mechanisms. The choices available to the firm include location of production and distribution, level of output and inventory and a series of choices that are related to transportation of the product like: modes, shipment size and routing. These choices can be classified into long, intermediate and short-term decisions [Kanafani, 1983]. In 1958 a paper was published in Harvard Business Review; *Industrial Dynamics: A Major Breakthrough for Decision Makers,* which started with:

> *Management is on the verge of a major breakthrough in understanding how industrial company success depends on the interaction between flows of information, materials, money, manpower and capital equipment* [Forrester, 1958].

Since 1958 a lot of progress has been made in understanding the dynamics in production and distribution chains but still we do not fully understand the complex interactions and dynamics. Depending on the market that is being observed (production, trade, logistics, transport or infrastructure) frequencies with which logistics decisions are subject to review or renewal are between once every 5 to 10 years for production and once every day for routing decisions. Over a long period all these decisions will interact with each other and therefor a large number of models have been developed by economists and transport-planners over the century to gain insight. Each model is concerned with a specific part of the economy or transport and makes different assumptions on the processes that influence this specific part. Only recently increasing attention has been given to the relationships between the economy, environment and transport. Complex dynamic models are required to allow a description of these interacting markets over a longer period. Clearly most freight transportation models are capable of dealing with short-run decisions, but most existing integrative modeling approaches today treat economic factors as exogenous instead of endogenous. Dynamics in production locations, production networks and regional characteristics are usually not within the scope of the model.

The paper focuses on the development of an aggregate spatial system dynamics model that is being developed at the Delft University of Technology and TNO Inro in the Netherlands. The paper describes the different approaches in aggregate freight transportation modeling, system dynamics modeling and the combination of these two approaches. Finally some intermediate results of the system dynamics model that describes a spatial logistic chain will be presented.

Modeling Logistics

There are numerous approaches available to gain insight in the different processes in logistics and as there are a lot of models, there are a lot of classifications of freight transportation models. See for more information about the different types of models and classifications [Harker (1987), Ortúzar & Willumsen, (1994); Tavasszy, et al., (2000)]. In this paper we use a classification given by Ruth & Hannon, (1997), based on the dynamics of the model system. Most models fit into one of the three classes given by the authors.

The first type of models are that represent a particular phenomenon at a point in time, a static model. For example the location and size of distribution center in a certain region in Europe in a given year. The second type is a comparative static model that compares some phenomena at different points in time. This is like using a series of snapshots to make inferences about the system's path from one point in time to another without modeling that process itself. Also in this category are models that describe and analyze the very processes underlying a particular phenomenon, like a mathematical formula that describes the demand, for and supply of a commodity as a function of its price. These equilibrium analysis are widespread in economics and transport modeling. The third category consists of dynamic models. A model could be developed to show the changes in demand and supply over time. Dynamic models are those that try to reflect changes in real or simulated time and take into account that the model components are constantly evolving as a result of previous actions.

Despite the importance of freight flows for policy-makers and spatial planning, the modeling of aggregate freight flows has received relatively little attention in literature. In this paragraph we give a short review of modeling freight transport and decisions made in different markets that determine the logistic behavior . In figure 1 and 2 the different markets and their demand and supply relations are illustrated. The main criterion for this classification are the choice-problems that logistic decision-makers face. At an aggregate level, we can say that these represent the markets that are at work in the freight system and this acts as a framework for modeling behavior of (groups) decision-makers [Ortúzar&Willumsen, 1994; Kanafani, 1983; Tavasszy, 1997]. For a review of existing modeling approaches see Tavasszy, et al., (2000).

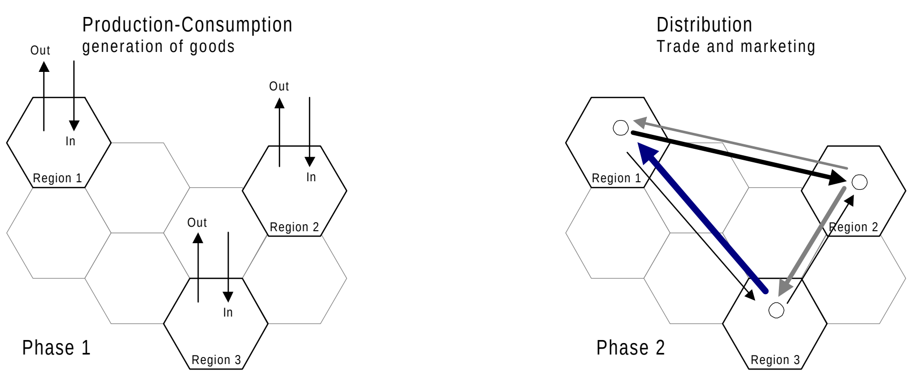

Figure 1:Production - Consumption and Distribution Phase

The first market (phase 1) is the production and consumption market. Models of freight generation find their application in public policy relating land-use and regional development. Although a large number of models exist for the different logistics decisions that constitute this stage we limit our view in this paper to models that describe flows from production and consumption at given locations. For the decision of location choice in production see Eiselt, et al. (1993). Two different approaches can be distinguished, namely: Regional Demand Models, based on either micro economic theory of decision making of producing firms or empirical functions [Harker, 1987; Bayliss, 1988; Ortúzar & Willumsen, 1994]. The second approach consists of inter-sectoral exchanges that are considered explicitly, i.e. the input/output analysis or Make&Use tables.

The second market: the distribution function of firms results in spatial interaction (figure 1, phase 2). At an aggregate level this class of models is used to calculate the magnitude of flows between regions. Depending on the underlying assumptions of spatial choice at the individual level we can distinguish two main types of distribution models: Linear-Programming models and models of the gravity type [Fotheringham&O'Kelly, 1989; Erlander, 1991; Anas, 1988; Linneman, 1966; Balck, 1972; Chisholm&O'Sullivan, 1973].

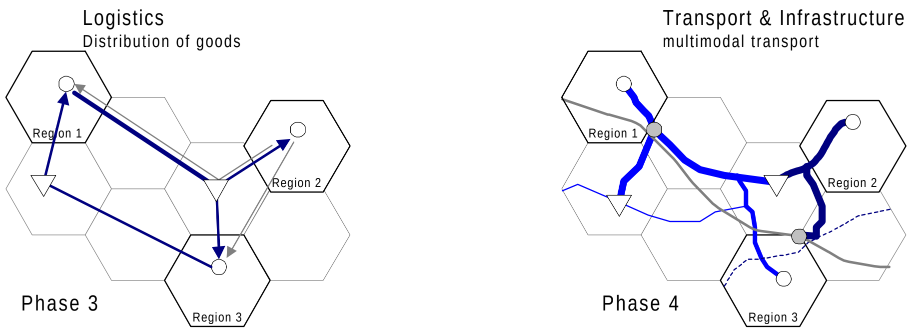

Figure 2: Logistics and Transport

Phase 3: Logistics: in order to control the availability of goods through time and space, a temporary storage of goods will be necessary. The typical output by the conventional invetory model is an optimal inventory policy, which can be generated at different levels of aggregation. In order to determine the costs involved in storing goods the characteristics of indivual shipments (size, frequency, value) have to be known. Inventory models in principle rely on the *Logistical* characteristics of indivual items (product value, packaging density, shipment size, lead-time). More and more the importance of logistics and inventory costs is recognized and taken into account in freight transportation modeling.

Phase 4: Transportation: a large part of literature in freight transportation modeling is dedicated to decisions related to the usage of transportation infrastructure and services. Given the origins and destinations, between which goods have to be moved, the intensity of the vehicle flows on the network is determined in this stage. The calculation of traffic from goods involves the following types of models: mode&route choice models, for the assignment of freight flows to modes of transport and sections of the infrastructure network and traffic conversion models, for the conversion of aggregate freight flows into load units, shipments or vehicles. See Baumol&Vinod, 1970;Winston, 1978;Chiang et al., 1980; Dial, 1994.

These four markets interact with each other. Depending on the market that is being observed (production, trade, logistics or transport) frequencies with which logistic decisions are subject to review or renewal are between once every five years to once every day for routing decisions, making the system even more complex are the interactions between the different markets. Winston (1983), noticed a considerable progress in the development of freight transportation models, but also indicated a new area that had to be explored: the relation between economy and transport. Since then substantial progress in integrative modeling approaches has been made [Tavasszy, et al., 2000]. Most of the integrative models in freight transport modeling are based on the equilibrium approach (first phase in figure 1). The models used are based on the basic classical theory, where the view is hold that price determines both supply and demand [Whelan&Msefer, 1996]. Many econometric and transport models assume that markets are in equilibrium at all times. When adjustment dynamics are modeled, variables are usually assumed to adjust in a smooth and stable manner towards the optimal, equilibrium value and lags (delays) are nearly always fixed in length [Stermann, 1986; Stermann, 1988].

Use of System Dynamics in Logistics

The use of system dynamics in logistics models is widespread. A lot of models have been developed that focus on the production chain and inventory, started in 1958 with *Industral Dynamics* [Forrester, 1958]. In the following years the application of system dynamics in logistics increased. In many of these system dynamics models a standard production sector is used to represent different sectors.

This standard sector is used for a variety of goods and services with appropriate parameter values to simulate the specific behavior for the sector [Forrester, 1958;Cakravastia&Diawati, 1997]. In this paper we have made an addition to the standard production sector. We introduce the use of a production function based on the Make&Use[1] table for the Netherlands. The standard production sector used in this paper is illustrated in 3.

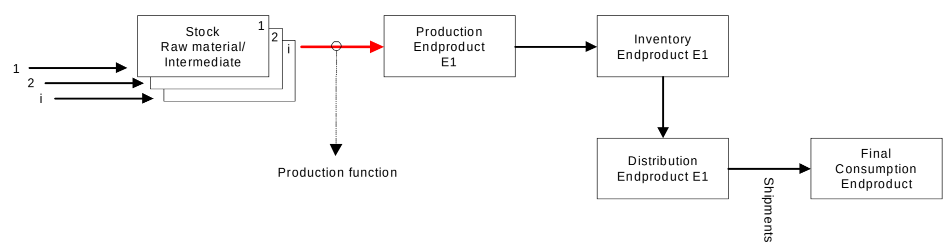

Figure 3: Production chain End product

In the figure above the standard production sector is illustrated for the production of a typical Endproduct[2], this product is produced out of Intermediate products (1..i) and/or raw materials (1..i). In the figure below the standard production sector of an Intermediate is illustrated and is identical except for the consumption side. The Intermediate goods are consumed by other industrial sectors: the endproducts are used by consumers.

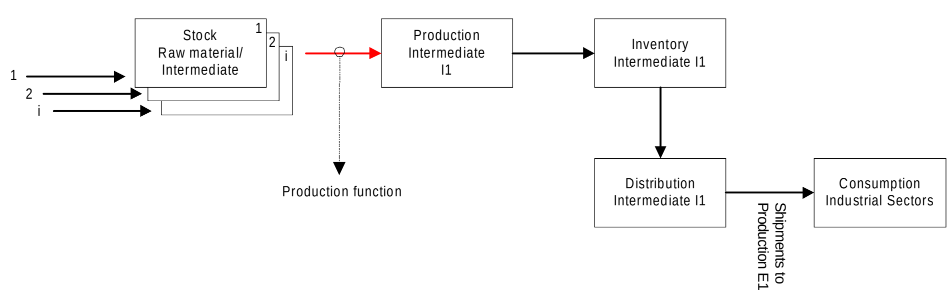

Figure 4: Production chain Intermediate product

Intermediate 1 (figure 4) is produced by the sector which uses Intermediate/Raw material (1..i). In this manner the entire production chain can be modeled; using three types of production sectors (End-Products, Intermediate and Rawmaterials). The major advantage of using the interactions between sectors in terms of product is that the specific logistic behavior (that varies greatly) can be incorporated in the model. This logistic behavior depends on the product characteristics (e.g. value density, volume, value of time, etc).

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1 The make and Use table states the production and consumption interaction between sectors for the Dutch economy. With this table it is possible to generate a production network for all sectors and products.

2 In this paper we distinguish Endproducts, Intermediate Goods and Raw Materials. For each type of product we defined a standard production sector.

Figure 5 shows a much-simplified diagram of the production sector with some important interactions with other system components. This structure is almost similar to the production sector used in a lot of models [Stermann, 1986; Forrester, 1989; Cakravastia&Diawati, 1997; Meadows, et al., 1974; IWW, 1998], (except for the additional stocks of products from other sectors for the production of product E1). Second addition is the logistic service; logistic characteristics are incorporated for each product because of the differences in logistic behavior. In the output section of figure 5, orders enter a backlog and the relationship between backlog and inventory determines ability of the sector to ship product (delivery delay and logistic service). Inventory is increased by production and decreased by shipments. Generated information includes the conditions of inventory, backlog, shipments and production. In the two ordering functions for capital and labor in the figure, ordering of either factor of production is based on multiple inputs.

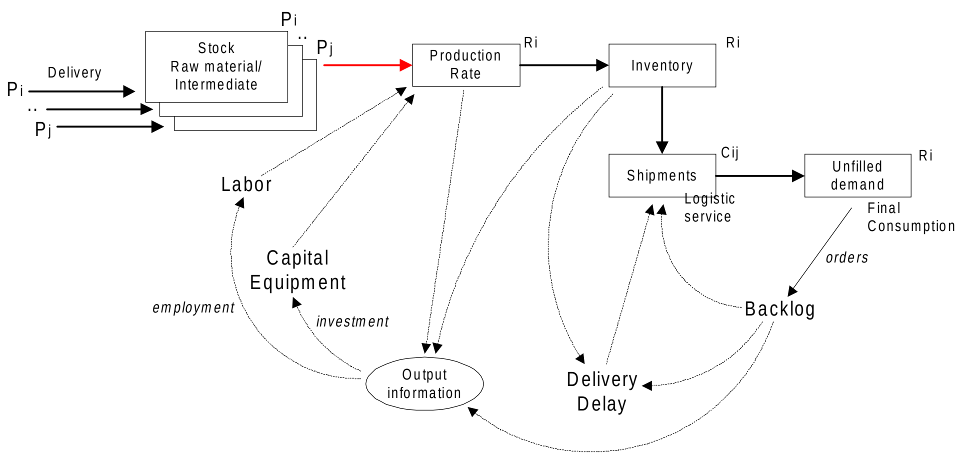

Figure 5 :Feedback production sector

The structure of a production sector and the interconnection supply sectors are complex enough to cause many different modes of dynamic behavior. Especially if we take into account the different intervals with which the decisions are reviewed (production, trade, logistics, transport) and the major economic behavior debated in literature; Business-cycles (3-7 years), Kuznets-cycles (15-25 years) and the Kondratieff-cycles (45-60 years) [Burns&Mitchell, 1951; Gordon, 1951; Hickman, 1963; Stermann, 1986; Forrester, 1989].

Spatial Component

In the previous paragraphs conventional models and the applications of system dynamics in production chain modeling are discussed. In this paragraph a short review is given of different approaches to incorporate the spatial component in system dynamic models. The dynamic phenomena that can arise in spatially extended systems as a result of interactions among similar subsystems are well known. These phenomena are observed in different fields like biology, physics, medicine, economy and logistics.

Much work has been done, for instance, on modeling the dynamics of migratory systems [Kanaroglou, et al., 1986; Sturis&Mosekilde, 1988; Forrester, 1969]. Migration in a subdivided population is a standard example of a migratory system [Levine, 1986], where the elementary dynamic system describes a set of sub-populations inhabiting a particular area. The relations of this set with other sub-populations from other areas depend on the possibility and intensity of migration as well as the geometry of the entire habitat. A further very general description of the migratory behavior of interacting subpopulatons was developed by Haag&Weidlich, (1984) and applied to real interregional migration systems in a series of papers by the same authors [Haag&Weidlich, 1986; Weidlich&Haas, 1988; Reiner, et al., 1988]. At the level of biological organism, interrelated structures are represented by spatially separated tissue elements such as cell, tumors, etc. [Alekseeva, et al., 1991; Alekseeva&Kirzhner, 1994] and in this field there is also research being done to include the spatial component into system dynamics models. In the economic and transport realm, one might consider individual companies and countries as pointwise systems, interacting through their exchanges of raw materials, goods, services and capital. A strong resemblance can be observed in the basic problems in these totally different fields.

Dynamic models provide insight into the feedback processes inherent in the evolution of a system. In contrast, Geographic Information Systems (GIS) are inherently static but provide spatial databases as well as statistical and visual data interpretation methods. Combining these two will make it possible to develop a model that is both dynamic and spatially explicit. The advantages of combining GIS and dynamic modeling is widely discussed [Nyerges, 1991;Despotakis, et al., 1991; Grossman&Eberhardt 1992]. In the attempts to combine the two approaches Grossman&Eberhardt, (1992) identify three categories: the first category is characterized by complex aggregated dynamic feedback models. This category is well represented in system dynamics. Most models developed in system dynamics are of this type.

The second category of models consists of the classical transport models of physics. These models typically partition the system under investigation into a grid whose cells are initialized with a few bits of data. Examples are pollution transport and propagation of noise. These transport problems can also be solved with cellular automata [Toffoli&Margolus, 1987]. In a brief article entitled cellular geography Tobler (1979) discussed the potential interest of cellular spaces for geographic modeling. Since then cellular automata are used in numerous applications and the methodology was developed further [Couclesis, 1985; Phipps, 1989; Constanza, 1990].

The third category comprises simple generic models that describe, in a prototypical way, the dynamics of a system or a system component. These generic models are also referred to as Active Area Dynamics [Ruth&Pieper, 1994]. Because the development of each area is calculated individually and depicted by its own model object the development of each area is calculated individually based on the attributes unique to that area. An example of this type of model is the Everglades Landscape Model (ELM), [Fitz, et al., 1993; Maxwell&Constanza, 1993]

In transportation modeling usually static models are used. But there are some examples of models from the third category. The first example we mention here is the SMILE model (Strategic Model on Integral Logistics and Evaluation. This model is not developed within the system dynamics framework, but incorporates both dynamics and the spatial data [Tavasszy, et al., 1998; Groothedde&Haselen, 1999].
This model was constructed in a joint effort of the Transport Research Centre of the Ministry of Transport and the research organisation NEI (Netherlands Economic Institute) and TNO Inro. The general aim of SMILE is to get a better view on future developments in freight flows that use the infrastructure networks in the Netherlands. The second example of a dynamic model in transportation is the model developed by IWW; Astra [IWW, 1998]. This model focuses on interregional transport in Europe. The third example is the scenario explorer, a dynamic transportation model [TNO Inro, 1995].
These last two models in fact fall between the aggregated models (first category) and generic models that describe in a prototypical way the dynamics of a system (third category). Both models use functional regions in the system dynamics model that are desegregated in a later phase, so strictly speaking these last two models are not spatially separated.

Model Structure

With the development of a System Dynamic freight transportation model we distinguish two key issues: we try to gain insight in how economical developments affect the spatial production network and the performance of the logistics and transport system. Secondly *what-if* questions are important. Scenario's related to measures to improve the system's performance and the impact of these measures. The general aim of the model is to get a better spatially extended view on future developments in changes in the production-consumption networks and the accompanying freight flows.

As described in the previous paragraphs there are different approaches available to deal with spatial data and dynamic modeling. In this paper we focus on simple generic models that describe the

dynamics of system components (third category), where the development of each region is calculated individually based on the attributes unique to the region. Each region is physically connected through infrastructure networks (road, rail, inland shipping). This makes it possible to transport the goods from one region to another. The first model element consists of the calculation of the production and consumption, in analogy with the classical transport model (see figure 6).
Each region has its own model that simulates the different production sector located in the region. In fact the model simulates the production for more than one production sector, but in this example just one is illustrated.

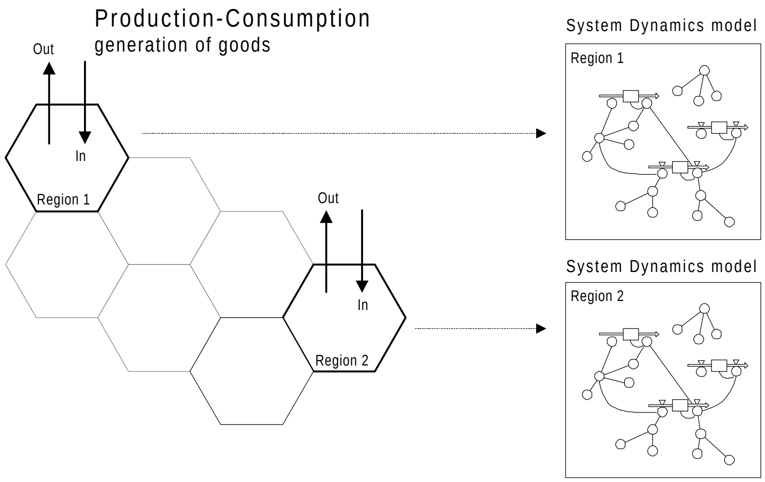

Figure 6:Production Consumption Phase

The final consumption (by consumers) is input and the production depends on different factors like labor, capital and inventory. The structure of the models located in each region are similar to the structure used by Forrester, (1989), Cakravastia&Diawati, (1997), Mass, (1975). Also see figure 5 for the general outline of the model. Given the initial final consumption (endproduct consumption) and the production capacity, the production output is calculated. To calculate the price of product E1 the inventory carrying costs, labor costs and prices of the intermediate and raw materials are calculated. After the initial production output is calculated the trade between the production region and the consumption region has to be derived. Here a distribution function is used. There are many methods to distribute the production; Growth Factor methods [Furness, 1965], Gravity Models [Casey, 1955; Fotheringham&O'Kelly, 1989] and Entropy Maximising approaches [Wilson, 1974]. In this study we use an Entropy-Maximising method [Evans, 1979]. In this method the resistance perceived on relation ij determines the trade on ij, where resistance is formulated as the logistic costs made on ij (transport, inventory, time-based costs, handling costs, etc.). After this phase is completed the spatial production network is known, as illustrated in the figure below.

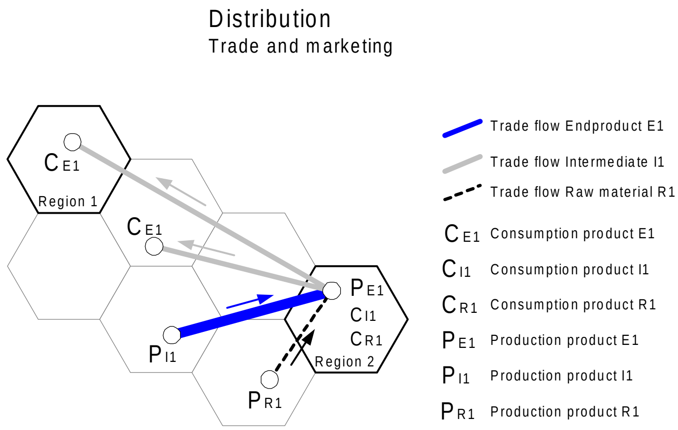

Figure 7: Distribution Phase

Next step is the logistic structure. Depending on product characteristics it is decided if the product is distribtuted through a distribution center or directly delivered[3]. This choice process is very important if freight transport flows are considered, because the shift in transport flows between regions can be considerable (see figure 8)[4].

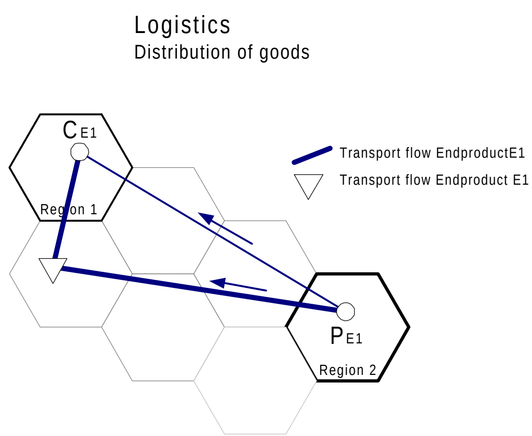

Figure 8: Transport flows

Final step in the calculation is the route and mode choice. In the model a multimodal network is used, where the infrastructure is characterized by means of the possible routing options between origin and destination. These include direct transport, where goods are transported by one mode, without transshipment, as well as intermodal chains. We use a deterministic model of mode choice [Baumol&Vinod, 1970] applied in a multimodal network [Guélat, et al., 1990; Tavasszy, 1997; Groothedde, 1997]. After these four steps are finished the data is imported back in into the system dynamics models per region as illustrated in the figure below.

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3 Not yet implemented in the model.

4 From interviews and surveys, done in 1997 and 1998, there can be concluded that about 40% of all products is being distributed in the Netherlands through distribution centers, so this step in the modelstructure is very influential [TNO Inro, 1998].

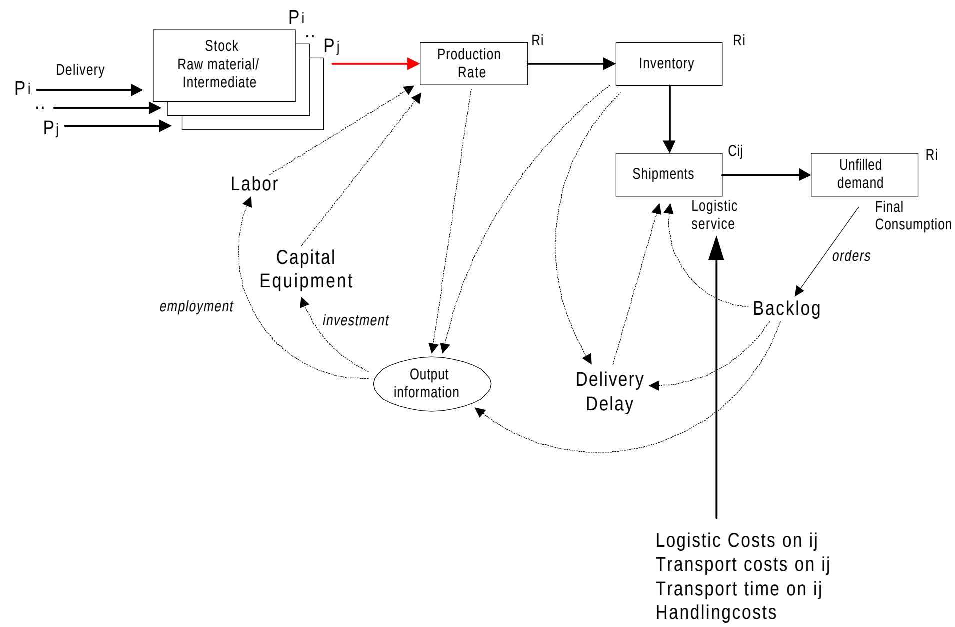

Figure 9: production chain plus feedback from conventional *models*

Behavior

In the previous paragraph the structure of the model being developed, is discussed. We described a model structure that combines economic, trade and logistic factors in a integral manner. This model structure was implemented into Matlab, which made it possible to develop a demo-version of the model. In this paragraph some behavioral aspects of the model will be discussed. This behavior will be illustrated by an example. In this example we consider a single sector in region 1 and 2 that produces Endproduct E1, using intermediate I1, produced in two other regions. Sector I1 consumes raw material R1 (see figure 10).

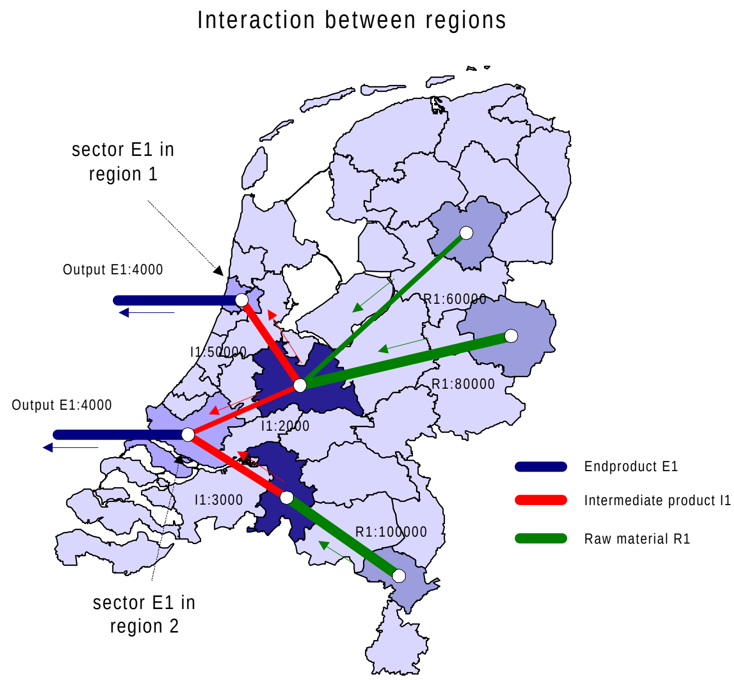

Figure 10 : Example Production Chain

We focus on the region 1 and 2 producing product E1. In these regions the sector E1 produces to supply a foreign region (with an exogenous consumption pattern). But the two regions compete with each other. In this example all four steps described in the previous paragraphs are calculated yielding the behavior illustrated in the figures 11 and 12 below.

Regions 1 and 2 compete with one another price. The price of product E1 consists laborcosts, capital-costs, supply-costs (Intermediate I1 and Raw material R1), logistic and transport-costs. In this example only the logistic and transport costs vary between the two regions. In the figure below the production sector exhibits a sequence of fluctuations typical of normal business cylces. Intervals between peaks vary around five years. Relative timing of backlog, production rate and inventory are typical of actual industrial behavior. Backlog tends to peak before production (labor), and production tends to peak before inventory. As in real business cycles, successive peaks show different shapes and spacing. The significance of the model behind figure 11 lies in its generation of business cycles without variation in consumer income or capital investment.

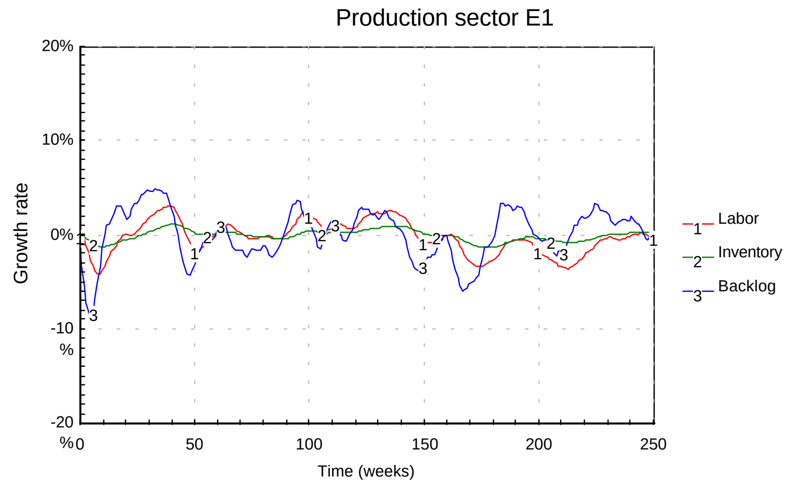

Figure 11: Behavior Sector E1

Both sectors (region 1 and 2) behave in a similar manner, but because of the difference in logistic- and transport costs the production and prices change. In the figure below the production of product E1 in regions 1 and 2, the production of product I1 and product R1 is illustrated. In this figure we can see that the total production fluctuates quite heavily.

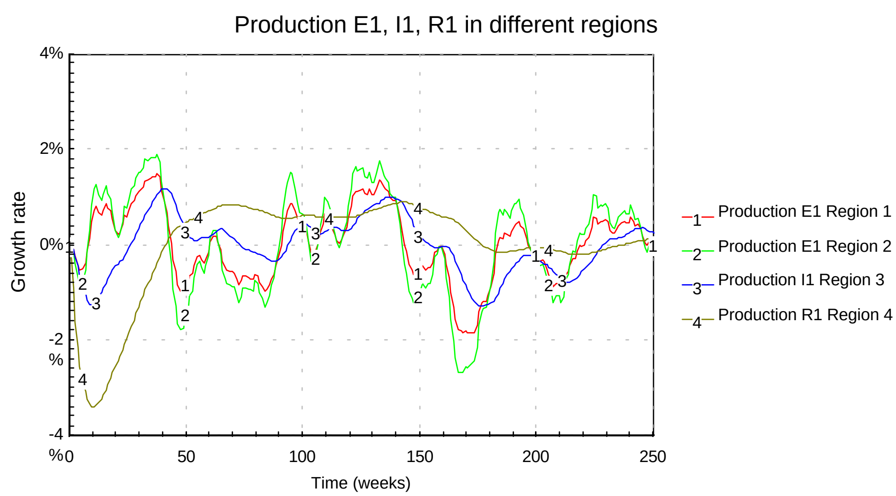

Figure 12: Behavior Sector E1 in region 1 and 2

As trade between the different regions change, because the logistic costs on the different relations fluctuate the price of the product produced in the regions changes. In figure 13 the logistic costs made by sector E1 in region 1 and 2 and the influence of the logistic costs on the price of product E1 is illustrated. Both regions react on changes in demand and the logistic costs are included in the price of the product.

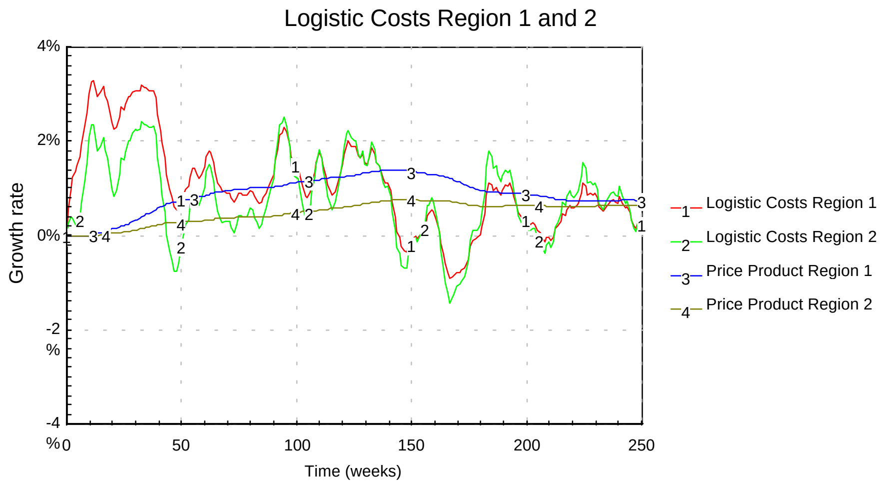

Figure 13: Logistic costs made in region 1 and 2

In addition to the results illustrated in the figures above it is also possible to show results concerning the network flows through time. For an impression of the possible output of the model see figure 14. In these two figures the network flows, for road, rail and inland shipping are illustrated (T=0 and t=250). The intensities shown on the network are the accompanying freight flows of the production network used in the example.

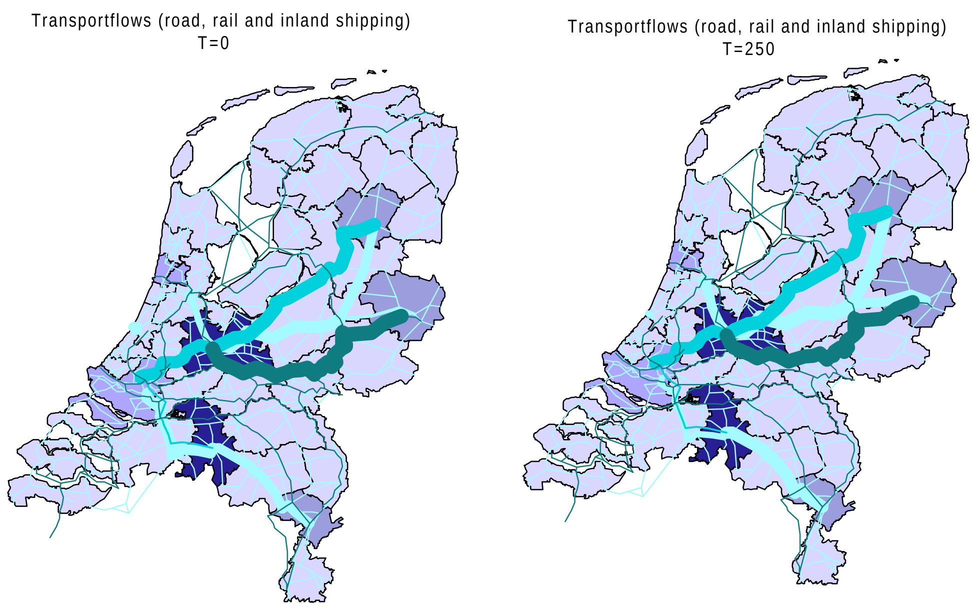

Figure 14 : Transportflows T=0 and T=250 (weeks)

By making a combination of system dynamics and *Conventional* transportation models it becomes possible to gain insight in the spatial interactions between regions through time in terms of trade, distribution and transport flows.

Conclusions

- In this paper we discussed two approaches to gain insight in the complex interactions between economy, logistics and transport. By combining the system dynamics approach with *traditional* models it becomes possible to illustrate the dynamic processes involved in spatial interaction between regions;

- With the development of the model described in the paper two world were combined into one model system, making it possible to treat dynamic processes (using the system dynamics framework) and regions and infrastructure-networks in one model. The model structure described in this paper makes it possible to incorporate the spatial component in a system dynamics model and combine the strength of system dynamics with the network oriented transport models. Using this structure it is possible to analyze spatial logistic chains and changes in the production chain.

- By introducing the production function into the standard production sector makes it possible to consider the specific logistic characteristics of a product and thereby evaluate different logistic strategies (e.g. use of distribution centers, direct delivery, order policy).

Still a lot of work has to be done before the model structure is fully implemented. In the project we used Powersim and Matlab to implement the model structure and the different modules. Recently we finished a demo-version of the model but now we face the task of expanding the model to a national level, where multiple sectors, products and supply chains are considered, taking the described spatial system dynamics model one step further.

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