MODELING OF FREIGHT TRANPORT LOGISTICS IN A MESO-ECONOMIC FRAMEWORK

Mikal Holmblad

Danish Transport Research Institute, Knuth Winterfeldts Allé, Building 116 west, DK-2800 Lyngby. *e-mail mhb@dtf.dk, phone +45 45256504*

ABSTRACT

This paper presents a model to convert trade flows to transport flows with emphasis on the use of transport centers. Large-scale operational advantages of transport agents operating in a transport logistics system are assumed by introduction of a heuristic mechanism, where inter-regional generalized logistic unit costs are modeled as being dependent on the inter-regional transport volume. The model is integrated with the computation methodology of the Metropolis algorithm, which generates an ensemble of probable transport solutions from which averaged properties can be determined. In this way the methodology proposes a probabilistic modeling framework that integrates the trade pattern (a production/consumption trade flow matrix) with the behavior (discrete choice) of agents in the transport logistic system of transport centers to compute a likely averaged transport pattern (an origin/destination transport flow matrix).

1. INTRODUCTION

The spatial distributions of trade flows of a commodity and the associated transport pattern are interdependent. The geographical separation of trade partners naturally creates demand for efficient transport solutions. On the other hand, conditions for transport also influence the structure of the trade pattern.

In economic modeling the trade pattern is commonly described by regional trade flows organized in a Production/Consumption-matrix (PC-matrix). The elements of the PC-matrix express the amount of an aggregate good that is produced in one region (row) and consumed in another region (column). Similar, a transport pattern is represented by an Origin/Destination-matrix (OD-matrix), where the elements represent inter-regional transport flows of goods transported from one region (row) to another region (column). The two matrices are in general not identical for example due to indirect transport associated with the use of transport centers (TC's) in a chain of transports from the production site to the consumer location. Transport via such centers enables otherwise isolated individual transports to be organized in consolidated transports in the vicinity of producers and out-parceling in the vicinity of the final receivers. Indirect transport increases the transport performance, but necessarily the traffic performance. Ultimately indirect transport organized in a transport logistics system may be more cost efficient due to the logistics operators possibilities of scheduling transports for optimum use of the available transport equipment and resources.

The logistic structure in the production-to-consumer chain is complex. Although not truly separable, it is commonly divided in production logistics (location of production, availability of raw materials, sub-suppliers, and subcontractors etc.), and transport logistics (transport solutions given the locations of production and consumption). If at all treated by a freight transport model, the production logistic aspect is usually reflected in a spatial economic model in more or less detail, whereas transport logistics may be treated directly by choice of route in the assignment model to generate the traffic flow pattern. Historically, the transport flow structure and the trade flow structure has nevertheless been taken as approximately the same due to the complexity and need for transport statistical detail that eventual modeling of logistics would add to the model structure. For example, in the present Swedish national freight transport model SAMGODS (SAMPLAN, 2001), national accounts are regionalized with a Furness model to interregional trade flows using zonal data of sector employment to determine regional production and consumption combined with an observed regional OD-transport pattern, which therefore in a sense is employed as a proxy for the PC-matrix structure. In contrast, in the present Norwegian national freight model NEMO/PINGO (Vold et al., 2002 & Ivanova et al., 2002), trade flows are applied as a proxy for the OD-matrix. Possibilities for implementation of a logistics module in both these models are currently being investigated (TFK et al., 2002). At present the only operational national freight model that implements logistics is the Dutch model SMILE (Tavasszy et al., 1998). A recent review of freight transport model systems can be found in De Jong et al., 2004.

Most recent developments to model the complexity of transport logistics are based on bottom-up approaches with rather detailed treatment of transport networks and modes combined with rather complicated models for decision making in the transport chain building. The outset of the model formulation described in this paper is somewhat contrary to this. The modeling approach represents a meso-economic aggregate modeling of transport logistics via regional transport centers formulated as a cost minimization problem. “Meso-economic” means that the modeling is regional and with a transport decision making on a level between micro- and macro-economy. Organization of transports in the transport system involves a heuristic mechanism, where average transport unit costs on links depends on the total link transport volumes. By cost minimization and employing this mechanism the model converts regional trade flows represented by a PC-matrix to regional transport flows expressed as an OD-matrix. Another feature of the model formulation is a representation of the transport system and the transport system network by quite few parameters. The aim of this paper is to present the ideas behind the model and to exemplify by a synthetic data example.

2. THE PCOD-MODEL

The model presented does not address the detailed assignment on physical infrastructure but concerns the transport logistics structure on the regional level i.e. conversion of a trade flow structure (PC-matrix) to a transport flow structure (OD-matrix) with emphasis on possible chains of transports via regional transport centers. The aim of the model is evaluation of the transport logistic behavior of the system based on a meso-economic representation of aggregate transport logistic decisions. As opposed to unorganized direct transport between producer and consumer, agents of transport and logistics operating in a transport system involving transport centers are assumed to be able to supply cost efficient transport chains e.g. as a result of large scale operational advantages. The transport chain building involving transport centers is in the model represented by a heuristic mechanism or economic driving force, where the unit cost of transportation ceases with the total volume of link specific transport. This is for example possible due to expected large-scale operational advantages of the transport operators.

2.1 Matrix formulation of the model

The area of interest is divided in R regions. Directed trade flows between these regions are organized in a PC-matrix, which is an input to the model and has been computed or estimated elsewhere. The elements of the PC-matrix, PC_{rs}, express the quantity of a certain group of goods that are produced in region $r \in R$ and consumed in region $s \in R$.

The transport associated with the trade flows are modeled on a network of directed average region-to-region links each representing several possible physical routes. Transport on these links is organized in an OD-matrix, where each element, OD_{lamb}, describes the quantity of the aggregate good that is transported from region $l \in R$ to region $m \in R$ via the link L_{lamb}. The indices a and b, which identifies the nature of the origin and the nature of the destination of the link, has additionally been assigned in addition to the region indices in order to explicitly differentiate between direct transport and indirect transport, thus providing a more detailed OD-matrix. These indices are in the model either a production/consumption site ($a,b=0$) or transport center site ($a,b=1$). Each region thus has two nodes and the network therefore consists of $N_{link}=4\cdot R^2$ links. An OD-matrix, for example an observed regional transport flow not containing information about the details of the origin and destination, is now in the model decomposed as:

(1) $$OD_{lm}=\sum_{ab} OD_{lamb} \qquad ,\forall\ lm$$

Combining a specific trade flow, PC_{rs} with the links of the transport network it is also possible to define a trade flow specific OD-matrix, which will be termed a PCOD-matrix. It is related to the detailed OD-matrix elements as:

(2) $$OD_{lamb} = \sum_{rs} PCOD_{rs,lamb} \quad , \quad \forall\, lamb$$

The PCOD-matrix elements are connected to the trade flow matrix by the following regional transport flow balances:

(3) $$PC_{rs} = PCOD_{rs,r0s0} + \sum_{m} PCOD_{rs,r0m1} \quad , \quad \forall\, rs$$

(4) $$PC_{rs} = PCOD_{rs,r0s0} + \sum_{l} PCOD_{rs,l1s0} \quad , \quad \forall\, rs$$

(5) $$PCOD_{rs,r0k1} + \sum_{l} PCOD_{rs,l1k1} = PCOD_{rs,k1s0} + \sum_{m} PCOD_{rs,k1m1} \quad , \quad \forall\, rs,k$$

2.2 Unit costs of transport

The cost of transportation from production region to consumption region is determined by the cost associated with the use of links and by the cost of handling in transport centers.

The average unit cost of transport ($\hat{C}$) on a link (L_{lamb}) is assumed to depend on the total volume of transport on the link. The unit cost on a link ($\hat{C}L_{lamb}$) is in general suggested to have the form:

(6) $$\hat{C}L_{lamb} = \hat{C}L^{0}_{lamb} \cdot f(\,OD_{lamb}\,)$$

where f is a decreasing function taking values between 1 and some minimum value f_{min}. The function f represents the proposed mechanism that the link unit cost of transport is reduced when the total transport volume on the link increases. The volume independent term is assumed to be associated with a reference cost of driving trucks from region l to region m. This generalized cost can for example be expressed in distance and time dependent terms as:

(7) $$\hat{C}L^{0}_{lamb} = b_{length} \cdot Length_{lamb} + b_{time} \cdot Time_{lamb} + b_{0}$$

but may include additional terms such as penalties of delay, damage etc..

The unit cost of transport via transport centers, $\hat{C}TC_{k}$, can be treated in a similar way as the link unit costs to be dependent on e.g. the total volume of transport through the transport center:

(8) $$\hat{C}TC_{k} = \hat{C}TC^{0}_{k} \cdot g(\sum_{la} OD_{lak1}\,) \quad , \quad \forall\, k$$

where the function g has similar properties as the link function f.

Equations 1-8 describe the general idea and structure of the modeling approach. The following section 2.3 provides an example of formulation of the unit cost functions. These are implemented in the computation methodology described in section 3. An illustrative example simulation with a synthetic trade flow matrix is given in section 4.

2.3 Formulation of the unit costs functions

In the present model implementation organized transport providing unit cost reductions as modeled by equation 6 is possible only for transports between transport centers. Therefore, for direct transports between production and consumption, for transfers between production and transport centers, and transfers between transport centers and consumption, equation 6 reduces to:

(9) $$\hat{C}L_{l0m0} = \hat{C}L_{l0m1} = \hat{C}L_{l1m0} = \hat{C}L^{0}_{l0m0}$$

Between transport centers however the expression for f given in equation 12 below is applied.

The decreasing unit cost can for example be thought of as resulting from the transport operators being able to better exploit truck capacity as the transport demand increases. In this case, $\hat{C}L^{0}_{lamb}$ could be considered the average unit cost per kilometer of the transport operators associated with driving the necessary number of trucks with average truck load factor of V_0 on the link to meet a given transport demand. The unit cost of transporting as a function of load factor can for example be expressed as:

(10) $$\hat{C}L_{lamb}(x) = \frac{C^{oper}_{lamb}}{V(x)} = \hat{C}L^{0}_{lamb} \cdot \frac{V_0}{V(x)}$$

where $V(x) \in [V_0, 1]$ is the average truck load factor, the variable $x \geq 0$ is a measure of the total transport volume on the link, and C^{oper}_{lamb} represents the transport unit cost with fully loaded trucks. If the average truck load factor is arbitrarily given the functional form:

(11) $$V(x) = 1 - (1 - V_0) \cdot exp(-a \cdot x)$$

we obtain the following expression for the function $f(OD_{lamb})$ in equation 6:

(12) $$f = \begin{cases} 1 & , if \quad 0 \leq OD_{lamb} \leq PC_{lm} \\ V_0 \cdot \left(1 - (1 - V_0) \cdot exp(-a \cdot \frac{(OD_{lamb} - PC_{lm})}{PC_{lm}}) \right)^{-1} & , if \quad OD_{lamb} > PC_{lm} \end{cases}$$

The transport volume measure x is expressed as a threshold for unit cost reduction given by the volume of trade between the regions as well as normalization to this volume. This represents a kind of pivot-point formalism in accordance with f being a measure of the transport cost on the link relative to the cost corresponding to the unit cost of unorganized direct transport in a situation, where transport centers are not available. Consequently it would make no sense to allow for the unit cost of direct transport also to be dependent on volume.

In the simplified example of truck loading, $f(0)=1$ relates to unit cost of transport corresponding to truck traffic with average truck loading factor, $V(0)=V_0$. As the transport demand x increases and becomes infinitely large f approaches $f_{min}=V_0$ corresponding to full truck capacity use, i.e. $V(\infty)=1$.

In the current implementation of the unit cost of using transport centers, equation 8, is for simplicity reduced to equal a constant for all transport centers:

(13) $\hat{C}TC_k = \hat{C}TC_k^0 = constant \quad , \ \forall k$

3. COMPUTATION METHODOLOGY

Let Ω be the set of possible states of the entire system. The total cost ($\hat{C}$) of the transport system being in a specific state ($\Omega_w \in \Omega$) is computed as:

(14) $\hat{C}\Omega_w = \sum_{lamb} OD_{lamb}^{(w)} \cdot \hat{C}L_{lamb}(OD_{lamb}^{(w)}) + \sum_{lam1} OD_{lam1}^{(w)} \cdot \hat{C}TC_m$

where the cost of transporting via transport centers are assigned to the transport centers in the downstream regions of the links.

Formulated by the equations (3)-(13) and with the objective function equation (14), the OD-matrix can be computed as the system equilibrium of a non-linear programming (NLP) minimization problem. However, this constitutes several problems associated with the existence of comparable solutions with small cost differences, computational complications originating from the non-linear nature of the problem, and possible existence of multiple local minima (Holmblad, 2003). Although the model in its formulation is quite simple it becomes rather complex since the cost or disutility of transporting using a specific link between transport centers ceases with the total usage of this link in the transport system making the problem non-convex. Cost minimization and the NLP approach ideally computes only one unique solution (global minimum), whereas many different transport solutions (local minima) with insignificant cost differences may exist. Also, the system cost function may be very smooth around a specific minimum, but the underlying details of transport system solutions may be rather different. Related to this question of specifying what is meant by a solution, the NLP-approach does not allow for variation due to details not treated by the model. This is frequently treated by random utility methods. A computation approach is proposed in the following section 3.1, which integrates the PCOD-model with simple random utility theory.

3.1 The probabilistic PCOD-model

The invoked computation methodology involves Monte Carlo (MC) simulation employing an algorithm (Simulated Annealing) originally evolved in materials physics known as the Metropolis algorithm (Metropolis et al., 1953). The algorithm has parallels to the formulation of a simple logit discrete choice model. The costs ($\hat{C}$) of transport alternatives are similar to the energies of particles, and the scale of the stochastic terms (m) is parallel to the inverse temperature of a physical system. Implementation of the PCOD-model in this simulation framework provides a methodology that integrates meso-economic cost minimization with logit discrete choice modeling of the aggregate decision makers and the transport chain utilities of the system. Observed features of the transport system are in this modeling framework represented by weighted averages of possible system states.

3.2 The Metropolis algorithm

Several strategies can be formulated for generating the Monte Carlo random walk in the space of transport solutions that meets the transport demand. In this paper the solutions are sequentially explored by picking trade flows at random and generating random alternative transport solutions for these trade flows from a specified set of possible trade flow specific transport solutions. The alternative transport solution is then compared to the current transport solution in use and accepted or rejected according to the Metropolis algorithm equation 15 below. In the implementation of the Metropolis algorithm the relative cost change is applied. Thus the algorithm decides to accept or reject a randomly generated state according to:

$$(15)\quad P_{ab} = \begin{cases} 1 & , \; if \quad \Delta\hat{C}_{ab} \leq 0 \\ exp\left(-m \cdot \dfrac{\Delta\hat{C}_{ab}}{\hat{C}_a} \right) & , \; if \quad \Delta\hat{C}_{ab} > 0 \end{cases}$$

If the alternative system state b is rejected, the current system state a is accepted once more. Accepted system states are added to an ensemble of states from which average properties can be evaluated. Using the system cost equation 14 above in the formulation of the algorithm corresponds to a simulation of system equilibrium, whereas using the trade flow specific cost equation 18 below in the formulation corresponds to a simulation of user-equilibrium.

The cost of e.g. the total system becomes an average property computed as the direct mean of the N system states in the ensemble of accepted states:

$$(16)\quad \left\langle \hat{C}\Omega \right\rangle = \frac{1}{N} \sum_{i=1}^{N} \hat{C}\Omega_i$$

Likewise, the average transport pattern is given by:

(17) $\langle OD_{lamb} \rangle = \dfrac{1}{N} \sum_{i=1}^{N} OD^{(i)}_{lmab}$

3.3 System equilibrium formulation

Let Π_{rs} be the choice set of possible transport chains between r and s. The transport cost of using a transport chain a, $\hat{C}\Pi^{a}_{rs}$, bringing the trade flow PC_{rs} from region r to region s is computed as:

(18) $\hat{C}\Pi^{a}_{rs} = PC_{rs} \cdot [\sum_{lamb \in \Pi^{a}_{rs}} \hat{C}L(OD_{lamb}) + \sum_{lam1 \in \Pi^{a}_{rs}} \hat{C}TC_{m}]$

In a logit discrete choice model formulation the probability of using this transport chain is:

(19) $\hat{P}\Pi^{a}_{rs} = exp(-m_1 \cdot \hat{C}\Pi^{a}_{rs}) \Big/ \sum_{b} exp(-m_1 \cdot \hat{C}\Pi^{b}_{rs})$

which also applies to the PCOD-model when all other transports are considered static at a particular step in the simulation. The probability of a specific state of the entire transport system, $\hat{P}\Omega_w$, can not be written as a simple product of the trade flow state probabilities equation 19 since the trade flow state probabilities or costs are in general interdependent through equations 6, 8, and 18. However, similarly to equation 19, we can tentatively write the probability in the discrete choice model look-alike form:

(20) $\hat{P}\Omega_w = exp\left(- m_2 \cdot \hat{C}\Omega_w \right) \Big/ \sum_{q} exp\left(- m_2 \cdot \hat{C}\Omega_q \right)$

although the concept or definition of a decision maker for the system becomes somewhat blurred. The relative probability of two system states is:

(21) $\hat{P}\Omega_{ab} = \hat{P}\Omega_b \Big/ \hat{P}\Omega_a = exp\left(- m_2 \cdot (\hat{C}\Omega_b - \hat{C}\Omega_a) \right) = exp\left(- m_2 \cdot \Delta\hat{C}\Omega_{ab} \right)$

which in a simulation framework can be interpreted as a transition probability from one system state to another corresponding to the Metropolis algorithm equation 15.

4. A SYNTHETIC TRADE FLOW EXAMPLE

The behavior of the model and of the MC simulation methodology has been addressed computing transport patterns with an artificial trade flow matrix, where all trade flows are set equal: $PC_{rs} = 100000 \ tons, \forall rs$. The symmetry of the PCOD-model and the diagonal symmetry of the trade pattern means that the diagonal symmetry should be preserved in the average transportation pattern. This can be considered as a qualitative indicator of convergence in the simulation. Also the costs of transportation between region and transport centers, $\hat{C}L^{0}_{lamb}$, used in the example are synthetic although derived from a matrix of representative region- to-region distances reflecting the Danish regional geography shown in figure 1. Distance is simply used as a proxy for transportation cost and: $\hat{C}L^{0}_{lamb} = Length_{lamb} \cdot 1.0 \; DKK \; per \, ton \; per \, km$. The 15 regions are based on the Danish counties, and transport centers are in the computation example made available in the regions: 1, 2, 4, 5, 8, 11, 12, 13, and 15. The unit cost of transporting via these is set to: $\hat{C}TC_{m} = 40.0 \, DKK \; per \; ton$.

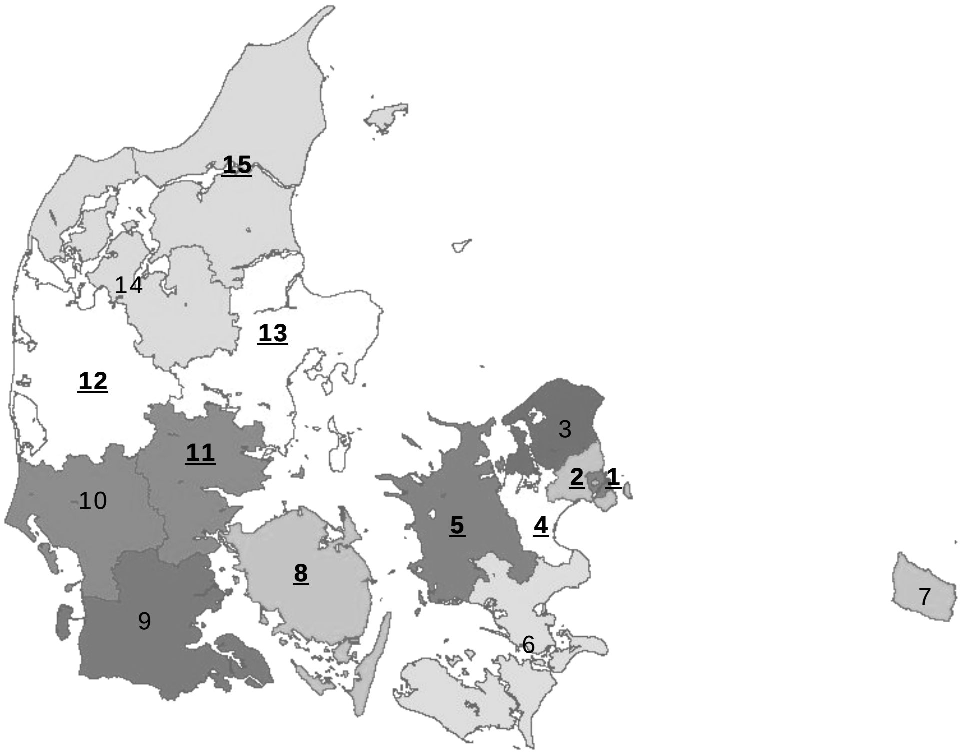

Figure 1. Regional geography of Denmark.

An example with the uniform PC-matrix computed as system equilibrium with parameters $a = 0.5$ and $V_0 = 0.6$ is shown in table 1 as the total average OD transport in units of 1000 tons. The parameter $1/m$ or the "temperature" of the transport system in the simulation is 3x10^{-4}, corresponding to a 4 percent probability (equation 15) of accepting a relative system cost increase of 0.1 percent.

ODij	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Oi
1	577	580	232	490	225	134	357	166	7	6	459	9	5	2	1	3.249
2	563	666	253	765	323	186	323	233	8	6	688	69	9	2	87	4.180
3	237	260	100	407	273	80	88	26	7	6	7	2	6	2	2	1.500
4	550	858	450	1.015	588	306	345	642	16	11	816	276	160	5	3	6.039
5	210	312	246	522	1.025	147	145	366	23	17	619	103	193	7	5	3.940
6	134	195	80	281	159	100	83	120	66	65	71	42	41	40	23	1.500
7	361	335	87	315	159	83	100	26	5	6	3	2	2	2	13	1.500
8	143	266	25	678	307	119	24	1.043	296	261	381	196	180	156	131	4.206
9	7	9	7	13	26	72	7	295	100	100	492	108	99	86	79	1.500
10	6	7	5	12	21	61	5	258	100	100	506	147	92	92	88	1.500
11	454	576	5	838	641	69	4	375	499	504	1.177	589	523	437	385	7.075
12	2	76	2	279	39	40	2	203	109	147	603	623	151	326	235	2.838
13	3	38	4	358	142	39	1	167	99	92	477	142	703	141	252	2.658
14	2	2	2	4	7	37	3	159	87	93	439	305	159	100	101	1.500
15	1	2	2	61	5	27	14	127	79	89	337	225	334	102	603	2.008
Dj	3.249	4.180	1.500	6.039	3.941	1.500	1.500	4.206	1.500	1.500	7.075	2.837	2.658	1.500	2.007	45.193

Table 1. Computed example of OD-matrix showing total transport quantities.

It can be inferred from table 1 how trade flows within the regions east (region 1-6) and west (region 8-15) of the Great Belt are primarily associated with direct transport, whereas trade flows across the Great Belt involve consolidations in transport centers and indirect transports. For example there is almost no transport directly from region 3 to region 15.The trade flow between these regions is initially consolidated with other trade flows between east and west in the transport centers of the eastern region. This is more clearly evident from the detailed PCOD- and OD-matrices (not shown).

5. DISCUSSION

The example computation above with the uniform PC-matrix generates an OD-matrix qualitatively resembling the structure of the OD-matrices found in statistical surveys of national freight transport by Danish trucks (Statistics Denmark, 2003), which indicates that the model approach, despite its coarse formulation, apparently is able to reflect features of transport logistics. The more quantitative comparison starting with realistic trade flows and tuning of parameters has at present not yet been possible due to inadequate statistical information or processing of available data on especially Danish foreign trade and international transport, which needs to be included in order to be comparable with the national freight transport surveys. Such data are fortunately in the process of being established in connection with an ongoing project developing a Danish national freight transport model (Fosgerau et al., 2003 and Hansen, 2003).

Also the implementation of the model needs further development. Firstly, the example presented in this paper is computed as system equilibrium and thus based on the choices made by an imaginary system decision maker. Regional decision makers corresponding to a regional user-equilibrium simulation is expected to be a more realistic modeling approach. However, this raises the question of defining trade flow specific transport costs. When testing an alternative transport solution to a given trade flow this can treated as price-setting and result in new average transport costs on the links for all trade flows using the involved links. Instead the alternative transport solution can be treated as price-setting for the particular transport volume on the involved links, however the transportation costs of other trade flows using the links will only be adjusted later in the simulation, when eventually testing transport solutions involving these links. The latter price-setting resembles a kind of renegotiation of transport contracts and the approach seems the more realistic. Secondly, in the present computer implementation of the probabilistic PCOD-model, the space of system states is discrete, since the generation of random changes of the system is performed by shifting entire regional trade flows from one transport chain to another. At present, the consequence of this on the impact of the transport volume dependent cost formulation, and the efficiency of the simulation, is unresolved. Future development of the combined model and computer implementation of the simulation model will address these questions.

6. CONCLUSION

In this paper a transport logistics PCOD-model methodology is illustrated, which on the basis of an input trade flow matrix computes a transport flow matrix taking into account possible indirect transport associated with transport chains and the potential use of transport centers. It appears that the simple model formulation involving a heuristic representation of large-scale operational advantages in a transport system has the potential to imitate basic features of overall transport logistics. Combination of the PCOD-model and Monte Carlo simulation using the Metropolis algorithm provides an integration of the NLP-formulation with random utility modeling of alternative transport chains by a logit discrete choice method.

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