Multi Agent Based Simulation of Transport Chains

Paul Davidsson, Johan Holmgren, Jan A. Persson, Linda Ramstedt
Department of Systems and Software Engineering, Blekinge Institute of Technology
372 25, Ronneby, Sweden
{paul.davidsson, johan.holmgren, jan.persson, linda.ramstedt}@bth.se

ABSTRACT

An agent-based tool for micro-level simulation of transport chains (TAPAS) is described. It is more powerful than traditional approaches as it is able to capture the interactions between individual actors of a transport chain, as well as their heterogeneity and decision making processes. Whereas traditional approaches rely on assumed statistical correlation between different parameters, TAPAS relies on causality, i.e., the decisions and negotiations that lead to the transports being performed. An additional advantage is that TAPAS is able to capture time aspects, such as, the influence of timetables, arrival times, and time-differentiated taxes and fees. TAPAS is composed of two layers, one layer simulating the physical activities taking place in the transport chain, e.g., production, storage, and transports of goods, and another layer simulating the different actors' decision making processes and interaction. The decision layer is implemented as a multi-agent system using the JADE platform, where each agent corresponds to a particular actor. We demonstrate the use of TAPAS by investigating how the actors in a transport chain are expected to act when different types of governmental control policies are applied, such as, fuel taxes, road tolls, and vehicle taxes. By analyzing the costs and environmental effects, TAPAS provides guidance in decision making regarding such control policies. We argue that TAPAS may also complement existing approaches in different ways, for instance by generating input data such as transport demand. Since TAPAS models a larger part of the supply chain, the transport demand is a natural part of the output. Studies may concern operational decisions like choice of consignment size and frequency of deliveries, as well as strategic decisions like where to locate storages, terminals, etc., choice of producer, and adaptation of vehicle fleets.

Categories and Subject Descriptors

I.6.5 [**Simulation and modeling**]: Model Development – *Modeling methodologies*

General Terms

Experimentation.

Keywords

Multi agent based simulation, transport chains, supply chains.

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1. INTRODUCTION

In this paper we present the Transportation And Production Agent-based Simulator (TAPAS), a general tool for micro-level simulation of production and transportation of products. The purpose is to provide a brief technical description of TAPAS and to illustrate its use. In TAPAS, the individual actors of a transport chain, such as, producers, transport operators, and customers are modeled explicitly. It incorporates the complexity of transport choices with respect to consignment size, route and mode, as well as taking into account both timetabled and non-timetabled (demand driven) transports. This makes TAPAS more powerful than traditional approaches to transport simulation as it is able to capture the interactions between individual actors of a transport chain, as well as their heterogeneity and decision making. Whereas traditional approaches rely on assumed statistical correlation between different parameters, TAPAS relies on causality, i.e., the decisions and negotiations that lead to the transports being performed. In addition, TAPAS is able to capture time aspects, such as, the effects of timetables, arrival times, and time-differentiated taxes and fees. To closer model reality, TAPAS also assumes stochastic consumer demand, transportation time, and production lead time.

We will illustrate the use of TAPAS by describing a case study concerning prediction of the effects of an introduction of a kilometer tax. As a decision support system, it can give governmental policy makers indications on how companies will react to proposed transport policies and what the economical, quality, and environmental effects will be. Other possible applications of TAPAS include assisting companies in making tactical and operational decisions such as choice of consignment size and frequency of deliveries, as well as strategic decisions like choice of producer, adaptation of vehicle fleets, and where to locate storages and terminals. In particular, TAPAS could be used for the generation of input data for new markets where information regarding transport demand is not available. Since TAPAS models a larger part of the supply chain (also production and storage are simulated), the transport demand is a natural part of the output (generated from the product demand).

In the next section we describe the TAPAS model which is followed by some reflections on its implementation and validation. Then a case study is described. Finally, conclusions are presented together with suggestions of future work.

2. Simulation model

Traditionally, transport systems have been studied using macro-level models, such as SAMGODS [17], ASTRA [16] and SISD [19]. This type of models is taking a societal perspective and is based on aggregated course-grained data on the national level. A problem with these models is that they do not take the logistical processes into account, e.g., choice of carrier type and ordering strategies, and thus fail to model the level where the decisions regarding the actual transports are taking place. Models that take logistical aspects into consideration are for example SMILE [18], GoodTrip [4], SLAM [19], and the one suggested by de Jong and Ben-Akiva [10]. However, since individual actors within transport chains are not modeled, the complex interactions, such as negotiation, between these actors from which the transport solution results are not captured. Moreover, these models cannot capture aspects related to time which are crucial when coordination between logistical decisions are made.

Due to (increased) cooperation between actors in transport chains (e.g., producers, customers, transport operators) and their ability to adapt to new situations, there exists a significant flexibility of how to carry out their operations in different scenarios. We believe that more precise predictions regarding the effects of transport policies can be achieved using micro-level models, i.e., transport chain level models, that capture also the decision making of the actors in the logistical processes. Agent-based models seem appropriate since they can deal with the above issues. There exist agent-based simulation models aimed at studying transport chains, see for instance [7] and [8]. However, these models assume a pre-determined transport demand, why changes in transport demand due to changes in logistical structures, etc. cannot be captured.

In general, a transport chain can be organized in a number of different ways with respect to the owner of the products at different locations and to the decision makers organizational belonging, e.g., the transport could be carried out by either the seller, buyer or third party logistics operator. The decision making in transport chains is subject to both short- and long-term planning implying that the time dimension of the decisions needs to be considered when modeling the transport chains. We assume that the actors in our model are cost minimizers locally with virtually no exploration of potential cost savings achievable by cooperation in the transport chain. However, due to a hierarchical decision structure with some knowledge of production and transportation alternatives, some global optimization occurs. This appears to be rather typical in transport chains today, e.g. only a limited amount of information is shared.

TAPAS uses a two-level architecture with a physical simulator and a decision making simulator (see Figure 1). This design is motivated by the fact that entities in the physical simulator (e.g., vehicles and products) are considered passive while entities in the decision making simulator (the decision makers) act independently and potentially proactively. The two layers are connected by letting the decisions taken in the decision making simulator initiate the actions in the physical simulator.

2.1 The Physical Simulator

The transportation network is modeled as a directed graph with a set of nodes and a set of directed links. A link, with average speed and length, is a directed connection between two nodes. A node can either be a consumer depot, a producer (factory) depot or a connection point in the transportation network. Further, TAPAS models a set of product types and a set of vehicles. Each product type has mass, volume and value, and each vehicle has maximum speed, fuel type and emissions (e.g., NO_x, CO and CO_2) per distance unit. Also, a vehicle has fuel consumptions for empty and fully loaded transports respectively. The actual fuel consumption is computed as a linear function of the current load.

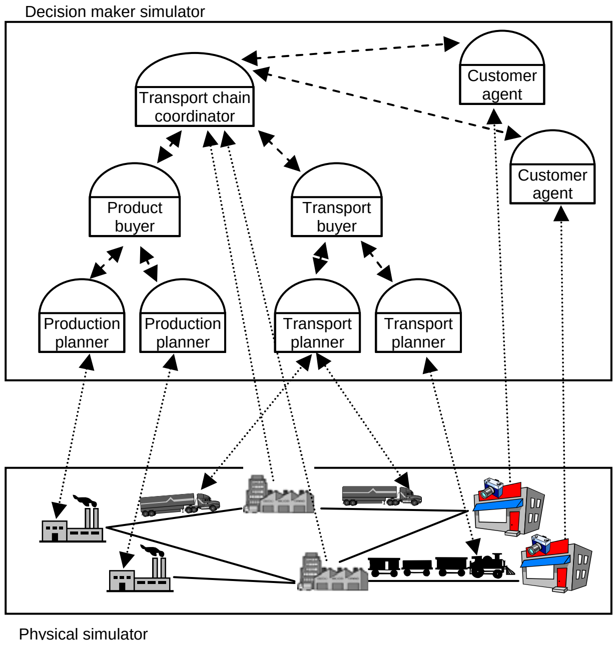

Figure 1. The TAPAS simulation model.

2.1.1 Transportation

A vehicle has a transportation mode (road, rail or sea) and can only travel links with the same mode and it is either controlled by a timetable (with fixed departure/arrival times) or by the departure time of a transport solution.

Transport costs consist of

- time based costs (e.g. driver, capital, and administration),
- distance based costs (e.g. fuel, vehicle wear, and km tax),
- link based costs (e.g. road tolls).

Travel times are stochastic and the time it takes for a vehicle to travel a link is assumed to follow a probability distribution which, for instance, can be lognormal [12].

2.1.2 Production

The production is performed in factories located in the producer nodes. Each node has exactly one factory with a set of individually scheduled production lines. For each product type that can be produced there is a maximum batch size, a production cost per time unit and a batch production time. Delays can occur since production lead times are stochastic. They are assumed to follow a probability distribution, e.g., a normal distribution [14].

2.1.3 Terminals

Times for loading and unloading at terminals are expressed in terms of fixed and variable times. Fixed times are used for the times it take to prepare a vehicle for loading or unloading. Variable times are given for each product type and denote the times for loading or unloading one unit of a product. There are also costs for loading/unloading a vehicle that are given as cost per time unit.

2.2 The Decision Making Simulator

A number of decision makers, i.e., transport chain coordinator (TCC), product buyer (PB), transport buyer (TB), transport planner (TP), production planners (PP) and customers (C), were identified in previous work [3].

2.2.1 *Customer (C)*

Each customer node is operated by a customer agent who is responsible for keeping inventories at reasonable levels by sending order requests (to the TCC). An order request contains a delivery node, a product type, a single order quantity q and a delivery time window.

The ordering behavior based on the principles of the EOQ (Economic Order Quantity) model [1]. In EOQ, the calculation of the quantity q is based on fixed order (transport) cost and inventory holding cost, but the presence of different vehicles, with different transport costs makes it difficult to estimate this quantity. Instead, we let the order request contain a number of different quantities. For the offers (one for each q) returned to the customer, it chooses the best one from a cost perspective including cost of inventories.

Another problem is that the customer needs knowledge about lead time from order to actual delivery, to be able to deduce the order point. Such information is however inaccessible to the customer since lead times are different for different transport modes and dependent on departure times for timetabled transports. To deal with this problem, we let the customer use estimated lead times (chosen as an upper bound) and safety stock levels for the different products. This corresponds to integrating the knowledge built from experience by real customers. Details of how the order quantity and order point are computed can be found in [9].

2.2.2 *Transport Chain Coordinator (TCC)*

The TCC has a central role and it is responsible for receiving order requests, sending product and transport requests and receiving the corresponding proposals. For an order request from a customer it finds the cheapest offer (via requests to the TB and the PB) for production and delivery for each order quantity and sends order proposals back to the customer.

2.2.3 *Product Buyer (PB)*

The PB operates between the TCC and the PP:s and is responsible for handling production related communication with these decision makers. When a product request is received it forwards it to all PP:s and when the production proposals are returned, it sends them back to the TCC for further processing. It also takes care of product bookings received from the customer via the TCC.

2.2.4 *Production Planner (PP)*

Each production node is operated by a production planner. Upon the reception of an order request from the PB, it creates a production proposal with a cost and the earliest time when the products can be ready for pickup. It is assumed that the products can be produced and scheduled for pickup later but not earlier than this time. At the reception of a booking message (of a production previously given as a request), it communicates the booking to the factory.

2.2.5 *Transport Buyer (TB)*

The TB is responsible for compiling transport solutions from producers to consumers to fulfill order requests initiated by customers and communicated to the TB via the TCC agent.

The problem of creating an optimal transport solution from a production node to a delivery node contains the following complicating factors:

1. The capacities of the vehicles are restricted.
2. Some vehicles follow time tables, while others do not.
3. Delivered products must be unloaded at the customer depot inside a time window.
4. Previous bookings must be considered before booking new transports and productions.

The problem of how to find the cheapest transport solution can be seen as a shortest (cheapest) path problem, in the transportation network, with additional constraints for handling timetables and time windows. We were unable to find any existing research on how to address the problem, and therefore we had to develop and implement our own customized search algorithm.

For a transport request containing a production node, a delivery node, a product type, an order quantity and a delivery time window, the TB uses a set of precompiled transportation paths between the production node and the delivery node. For each link (or connection) in each path, the TB sends a transport request to all TP agents, containing a start node, an end node, the requested product type and quantity and some time interval which is calculated from the earliest possible production time and the preferred delivery time window.

After the receipt of all requested link transport proposals, the TB combines them into one transport proposal for each precompiled path using a tree-based search algorithm. The best path proposals are then sent for validation to the customer via the TCC. Details about how transport proposals are created and selected can be found in [9].

2.2.6 *Transport Planner (TP)*

Each TP controls a vehicle fleet which operates some set of network nodes. Upon the reception of a transport request between two nodes, it generates proposals for the requested product and quantity with departure and arrival times inside the requested time window. Since timetable controlled vehicles have fixed departure and arrival times which are repeated within some certain frequency, and non timetabled transports only departs when they are booked, the corresponding transport proposals are different. For a timetabled transport, a transport proposal is generated for each departure with departure no earlier than the start of the interval and arrival no later than the end of the interval, and for non timetabled transports, the TP generates one proposal, containing the actual travel time (without departure and arrival times), for each vehicle type in the fleet. The cost returned to the TB includes all costs associated with the transport.

2.2.7 *Interaction Protocol*

In this section we present the communication framework aiming at matching valid transport and production proposals to fulfill a customer order. When we developed the interaction protocol we had to deal with a number of challenges.

- Transport and production cannot be booked simultaneously, one must be booked before the other,
- a production cannot be booked without matching it with a valid transport and vice versa,
- the computations needed to find the cheapest combination of production and transportation that fulfils the order might be very time consuming.

In the first version of the simulator, products were booked without considering the possibility to match a transport. A standard contract net negotiation was used to buy the cheapest products before using a second contract net negotiation to buy the cheapest transports. However, it can be risky to assume the existence of valid transports for an already booked production. In the framework presented below, where a negotiation requires two steps, a production is booked before a transport but bookings are preceded by production and transport requests to assure valid overall solutions. See Figure 2 for the interaction diagram. Observe that only one production planner and one transport planner are shown to increase the readability of the diagram.

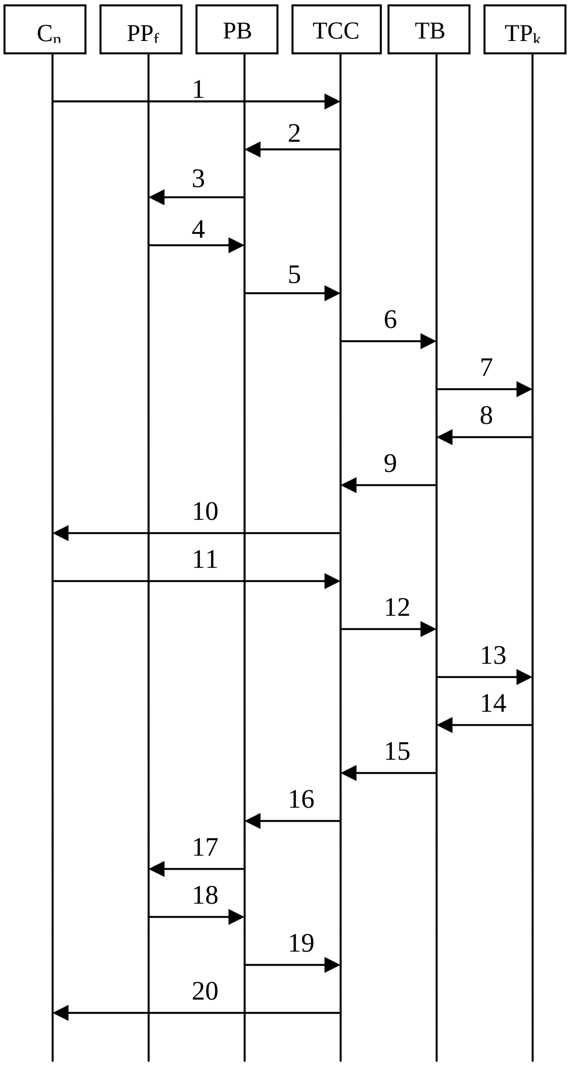

Figure 2. Interaction diagram.

1. (C_n → TCC) A customer C_n sends an order request to the TCC. The order request contains customer identifier, product identifier, a number of quantities and delivery time window for each quantity.
2. (TCC → PB) The TCC receives the order request sent by C_n and forwards it as a production request to the PB.
3. (PB → PP:s) The PB receives the production request from the TCC and sends it to all PPs.
4. (PP_f →PB) PP_f creates a production proposal for each of the requested quantities that can be produced by factory f, including the producer identifier, the earliest time the products can be ready for pickup and the production cost, and sends them back to the PB.
5. (PB → TCC) When all PPs have responded to the production requests sent in message 3, the PB sends them to the TCC.
6. (TCC → TB) After receiving the production proposals from the PB, the TCC sends a transport request to the TB. The transport request actually consists of a transport request for each production proposal, and it contains producer identifier, customer identifier, product identifier and a number of quantities with corresponding delivery time windows and earliest times for pickup.
7. (TB → TP:s) For each transport request received from the TCC, the TB extracts the producer node and consumer node and sends a link transport request for each connection in each precompiled path between those nodes. Each such transport request contains departure node, arrival node, product identifier, quantity and time interval in which the transport must depart and arrive.
8. (TP_k → TB) After receiving a transport request from the TB, the TP_k creates a number of transport proposals and sends them back to the TB. Each link transport proposal contains departure/arrival times, link identifier and transportation cost. Also, the starting time for loading the vehicle before departure and the ending time for unloading after arrival is included to be used if necessary.
9. (TB → TCC) After receiving all link transport proposals from the TPs, the TB uses them to compile one transport solutions for each production proposal sent in message 5. For each producer and quantity, the transport proposal with lowest transport cost is sent to the TCC.
10. (TCC → C_n) After receiving the transport proposals from the TB, the TCC combines them with the production proposals to form one valid order proposal (the cheapest) for each order quantity. The order proposals are sent to C_n for validation.
11. (C_n → TCC) C_n receives the order proposals and accepts the most beneficial proposal.
12. (TCC → TB) After receiving the order acceptance (message 11) from C_n, the TCC sends a transport booking message to the TB.
13. (TB → TP_i) The TB receives the message from the TCC and sends a transport booking message for each link (actually departure) in the transport solution for the accepted proposal to the corresponding transport planner TP_i.

14. (TP_i → TB) TP_i receives the transport booking message from the TB, books the transport with the agreed vehicle and sends a booking acceptance message to the TB.
15. (TB → TCC) After receiving all transport booking acceptance messages from the TPs involved in the transport solution, the TB sends a transport booking inform message to the TCC.
16. (TCC → PB) The TCC sends a production booking message to the PB. This message contains quantity, pickup time and selected producing factory f.
17. (PB → PP_f) After receiving the production booking message from the TCC, the PB sends a production booking message to PP_f.
18. (PP_f → PB) PP_f adds a production order to the factory and sends a production booking inform message back to the PB.
19. (PB → TCC) The PB informs the TCC that the production is booked by PP_f.
20. (TCC → C_n) After receiving the production booking inform message, the TCC sends an information message to C_n that the order has been booked by PP_f and the TPs.

If the TCC receives a reject message from the PB, the TB or C_n, it is forwarded to all involved agents and the negotiation terminates. The same happens if the PB receives rejects from all PP:s, or if the TB receives rejects from all TP:s.

3. Implementation and validation

TAPAS is implemented as a discrete time event based simulator in the Java 1.4 language. The decision making simulator is implemented as a Multi-Agent System with software agents representing decision makers. To simplify the implementation of the agent system, we used the Java Agent DEvelopment Framework (JADE) platform [2].

As noticed in a survey of applications of Multi Agent Based Simulation (MABS) [5], few MABS applications do actually utilize any agent platform. One reason might be lack of knowledge about these platforms and another reason might be that the behavior of the simulated entities is not complex enough to motivate their use and a simpler technology would suffice.

Moreover, it should be noticed that agent platforms often introduce limitations to the system. Even though JADE has many useful properties, it is easy to integrate in Java and it has been used in the development of many other systems, we realized that there are also some problems of using JADE for our particular system. For example, we found it difficult to implement advanced communication protocols, such as the one presented in this paper.

Simulated activities (loading/unloading, departures, arrivals, etc) are all represented by events, which are scheduled in an event list. An activity is actually represented by two events, a start activity event and an end activity event. At the start of a simulation activity (triggered by a start activity event), the execution time of the activity is determined (possibly stochastic) and the end event is created and scheduled. Further, if an activity cannot be started when a start activity is scheduled, e.g. since it might be waiting for some other activity to finish, then it must wait for the blocking activity to terminate before trying again.

TAPAS has mainly been validated by interviews with experts in policy issues and transport modeling, and practitioners in transportation and logistics. Simulation experiments of different scenarios have been performed with TAPAS and the results have been compared to similar studies (cf. [11],[15],[20]) as well as to existing transport chains. Moreover, existing models of transport chain actors and decisions have been compared to our model. The sensitivity for different input parameters has also been examined.

4. Case study

We have chosen to illustrate the usage of TAPAS with a scenario of a transport corridor between the Baltic States and England. The scenario is a part of a larger transport corridor between China and northern Europe studied within a project financed by the European Union (http://www.eastwesttc.org). The transport corridor is interesting since it is possible that larger goods volumes will be transported via the Trans-Siberian railway, instead of with container ships directly from China to northern Europe which is currently the most common way. It is also interesting to predict and influence the mode and route choices made in the corridor from a regional perspective. In this section the scenario design will be described followed by the simulation results and the analysis of the results.

4.1 Scenario

The scenario consists of several possible transport alternatives for transportation of 20 ft ISO-containers from Kaunas in Lithuania to Harwich in England. The transport links considered are:

- Rail transport from Kaunas to Klaipeda.
- Road transport from Kaunas to Esbjerg.
- Sea transport from Klaipeda to Karlshamn.
- Rail transport from Karlshamn to Esbjerg.
- Road transport from Karlshamn to Esbjerg.
- Sea transport from Esbjerg to Harwich.

The containers contain goods with medium value, such as furniture or kitchen appliances. The producer is assumed to be located in Kaunas, and the customer is assumed to be located in Harwich, where there is a customer inventory. This result in three alternative routes (see Figure 3):

1. Kaunas (train) Klaipeda (ferry) Karlshamn (train) Esbjerg (ferry) Harwich
2. Kaunas (train) Klaipeda (ferry) Karlshamn (truck) Esbjerg (ferry) Harwich
3. Kaunas (truck) Esbjerg (ferry) Harwich

More details on the scenario can be found in [13].

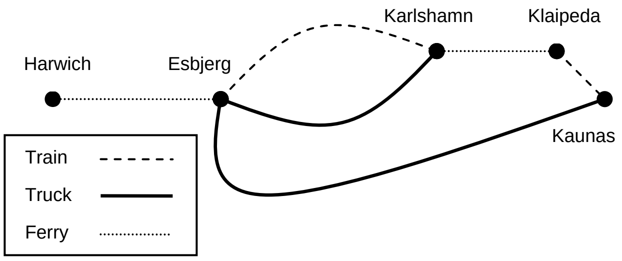

Figure 3. The three alternative routes in the scenario

In the simulation experiments we study the introduction of a kilometer tax on trucks in Sweden and its effects. The tax levels that we are examining are the levels suggested by Swedish Institute for Communication Analysis (SIKA) [6]. The suggested kilometer taxation is differentiated based on the euro class of the truck, as well as on the total weight of the truck. As a compensation for the proposed kilometer taxes, different fuel tax levels are proposed. Different choices of kilometer tax, vehicle differentiation, and fuel taxes are suggested and studied in the following cases:

- Case 0. Current situation, no kilometer taxation and diesel taxation as today (0,36 euro/l).
- Case 1. A high kilometer tax as suggested by SIKA. Differentiation. Diesel taxation is lowered to the minimum level within EU (0,30 euro/l). Marginal cost principle as defined by SIKA is assumed.
- Case 2. A low kilometer tax as suggested by SIKA. Differentiation. Diesel taxation remains as it is today. Marginal cost principle as defined by SIKA is assumed.
- Case 3. The same average level of kilometer taxation is assumed for all vehicle types and euro classes. Diesel taxation is lowered to the minimum level within EU (0,30 euro/l).
- Case 4. A high kilometer tax as suggested by SIKA, including differentiation, but without compensation, i.e., current level of the diesel taxation.

Below some of the input data is given in the tables.

Table 1. Input data for the links.

	Link 1	Link 2	Link 3	Link 4	Link 5
Nodes	Kaunas-Klaipeda	Klaipeda-Karlshamn	Karlshamn-Esbjerg	Kaunas-Esbjerg	Esbjerg-Harwich
Modes	Rail	Sea	Road, rail	Road	Sea
Length (km)	240	537	487, 517	1562	648
Speed (km/h)	19	37	78, 18	70	37

Table 2. Input data for the vehicle types.

	Truck 1TEU Link 3	Truck 2TEU Link 3	Truck 3TEU Link 3	Truck 1TEU Link 4	Truck 2TEU Link4	Train Link 1	Train Link 3	Ferry Link 2	Ferry Link 2
Capacity (TEU)	1	2	3	1	2	50	22	374	374
Av. vehicle util.						50%	50%	88%	88%
Time-based cost (euro/h)	40	40	40	40	40	18	18	1860	1860
Distance-based cost (euro/km per TEU)	0,68	0,39	0,32	0,56	0,31	0,01	0,39	0,64	0,51
CO_2 (g/km/TEU)	675	444	406	691	440	111	109	680	680
Km tax (euro/km) case 1	0,14	0,15	0,16						
Km tax (euro/km) case 2	0,11	0,12	0,12						
Km tax (euro/km) case 3	0,16	0,16	0,16						
Km tax (euro/km) case 4	0,14	0,15	0,16						

Moreover, we use the following values (the same for all different transport modes):

- Loading/unloading cost: 0,39 euro/min
- Loading/unloading time: 60 min/unit
- Preparation loading/unloading time: 60 min/unit
- Weight of a container: 11 tons
- Product value of a container: 20 000 Euro

Around 520 days are simulated and the precision is 1 minute.

4.2 Simulation results

The results from the experiments are summarized in Figures 4-7.

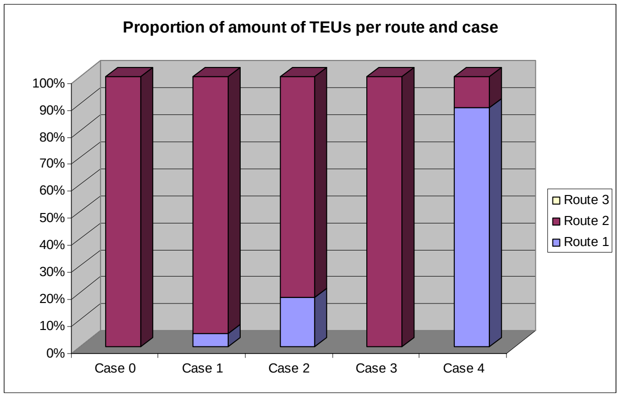

Figure 4. Proportion of TEUs per route and case

From the simulation experiments it is possible to see the breakpoints concerning choice of traffic mode, truck type, transport route as well as the size of the consignments. Also, performance metrics in terms of for instance amount of emissions, the total costs, and the tax income to the public authorities. The simulation results show that the largest modal split from road to rail transportation on the link between Karlshamn and Esbjerg is for Case 4, i.e., the case where the highest levels of kilometer and diesel taxation is introduced. This corresponds to a change of the route choice (Figure 4)

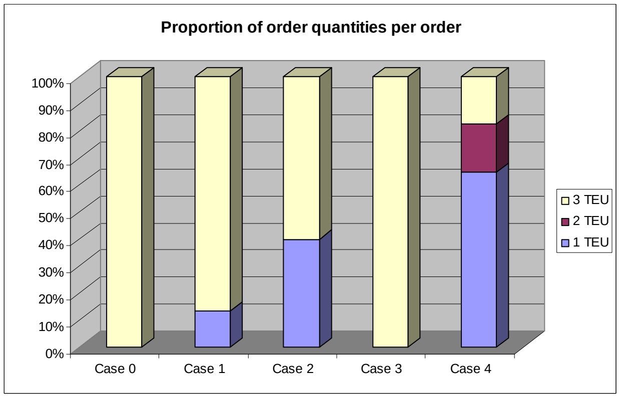

Figure 5. Proportion of orders per order size and case.

Another effect which can be observed is that the order quantities vary in the different cases. In Case 4 where rail transportation between Karlshamn and Esbjerg mainly is used, the order quantities are mostly 1 (Figure 5). The reason for this is probably that the cost per TEU for the customer is lower when choosing to have three containers on a large truck, while the costs per container for all order quantities are equal for the rail alternative between Karlshamn and Esbjerg.

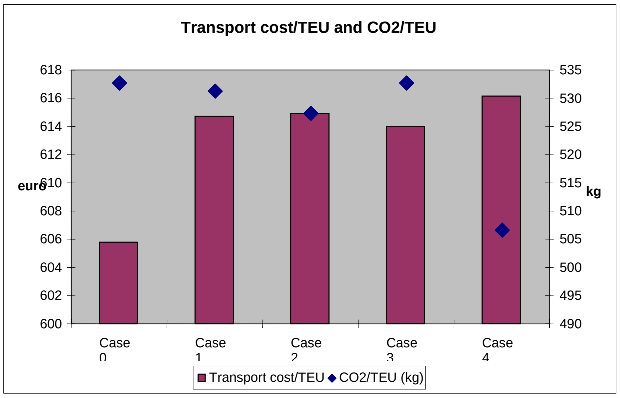

Figure 6. Transport costs (euro) per TEU for the customer per case and CO_2 per TEU.

In Figure 6 the transport costs per TEU for the customer and the amount of CO_2 per TEU are illustrated. The highest costs for the customer appear with the highest taxation, while the lowest costs appear for the current situation with no kilometer taxation. If delays from the planned arrival time to the customer occur, a delay cost will occur in terms of larger time costs. However, in these simulation experiments no delays occur. Concerning the environmental performance in terms of CO_2, as expected, the lowest amount of CO_2 appears in Case 4 where rail transportation is used more frequently instead of road transportation (which also is the case where the transport cost is the highest).

Finally, we studied the tax income (kilometer and diesel tax) to the public authorities in Sweden. It was concluded that the lowest tax income occurs when there are fewer road transports due to a large amount of rail transports.

4.3 Analysis

The simulation experiments have shown that it is possible to observe several effects of an introduction of a kilometer tax, e.g., concerning order quantity, mode choice, route choice, etc. However, there is a need to analyze the simulation results in more depth, as well as to validate the results more. In the scenario we explored the following functionalities of TAPAS among others:

- Intermodal transportation, i.e., transportation with several traffic modes with the same load carrier. Also, changes between vehicles types with the same traffic modes are possible.
- Restrictions of vehicle capacities.
- Loading/reloading.
- Timetabled as well as non-timetabled (demand driven) transports.
- Time window for delivery.

Some further experiment using TAPAS including more advanced timing issues, such as synchronization of time tables are presented in [15]. These experiments also include studies of the importance of the storage interest and product value. Other issues that would be interesting to study in the scenario are:

- Changes in prerequisites for the transport chain actors in terms of lower costs and times in nodes. The price sensitiveness of the actors is interesting to study.
- Different aspects of demand and consumption, e.g., a changed demand distribution are relevant to study, as well as different settings of the ordering and consumption behavior.
- There are different vehicle restrictions within the EU. Since the goal is to harmonize the prerequisites for businesses in the EU, it is possible that the maximum allowed vehicle capacity will increase to the Swedish level, i.e., maximum 60 tons.

5. Conclusions and future work

We have presented a micro-level simulator for a rather wide scope of production and transportation. By using agent technology, we were able to simulate the decision making activities as well as the interaction between the actors. This is very difficult, if possible at all, using traditional techniques. We have showed that it is possible to deal with the complexities of mixing timetabled and non timetabled transports in the algorithmic approach. Further, we simulate the principles of EOQ by letting the customer select the best order quantity among a set of possible quantities. Also, the interaction framework is shown to be appropriate for tools such as TAPAS.

However, there is still room for further development of TAPAS. Possible extensions of the modeling on the agent level include:

- The integration of sophisticated optimization algorithms in the agents to improve the quality of their decisions (making the system prescriptive rather than descriptive).
- Allowing agents to learn from experience, e.g., customer agents regarding lead times and safety stock levels.
- Let other costs than the direct ones, such as environmental impact in terms of external costs, influence the decision making of the agents.
- Experiment with other interaction protocols, e.g., allowing agents to initiate and respond to messages outside the interaction framework presented. For example, the production buyer suggests an order quantity that fits some producer.
- Allow the product buyer to discard production proposals that it considers useless instead of returning them to the TCC.
- Additional agents, possibly storage agents and terminal agents (simple storage and terminal behaviors are currently modeled in the physical simulator).

Regarding the physical simulator, we plan to:

- Increase the level of detail, such as, simulate the loading and unloading at the terminals, possibly causing congestion.
- Including external aspects that affects the transports. As an example, to simulate other traffic on the links would allow us to study the effects of link congestion.

Some possible general developments of TAPAS are:

- Performance improvements, such as, more efficient route selection method, and make TAPAS run in a GRID environment.
- Investigate how TAPAS could be used in the context of the Trading Agent Competition, TAC SCM (www.sics.se/tac/)

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