MULTI-AGENT SIMULATION FOR ANALYSING INLAND CONTAINER TERMINAL NETWORKS

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ABSTRACT
Using a multi-agent system, representing the nodes in the network of the Austrian inland container terminals, and using system dynamics to depict the terminals' internal structures and processes in an aggregate manner, we perform network flow analyses of intermodal load units in case of unforeseen disturbances. Comprehensive case studies of disturbances and irregularities in the flow of goods in Austrian container transport chains and transport systems are the basis of the definition of several risk scenarios, and are used in order to investigate the robustness of the network.

Keywords: multi-agent simulation, network flow analyses, disruption risks, inland container terminals

1. INTRODUCTION

Ever more frequent disturbances and irregularities in the flow of goods in transport chains and transport systems reflect the need to evaluate transport chain vulnerabilities and risk potential. These disturbances can stem from natural hazards, e.g. flooding or earthquakes, but can also be caused by acts of sabotage on transport chains or their infrastructure. Particularly in Austria, natural hazards like storms, heavy rain, avalanches and floods are responsible for such disruptions.

An intermodal network consists of multi-element transport chains, including pre-carriage of cargo to a terminal, the transshipment to another means of transport and the following actual change of location on that modus. The transportation process ends after a further transshipment and the on-carriage of the goods or containers. Container terminals are therefore essential infrastructure in intermodal networks.

Based on extensive field studies, comprising almost all Austrian container terminals, we have identified additional risk factors to these essential nodes, other than natural hazards or sabotage, for example risks originating partly from upstream and downstream terminals in the chain or from other parties in the transport system such as train operators or infrastructure operators. However, risks emanating from the daily operational business rank among the most prevalent sources of disruption in transport chains (Gronalt et al. 2008).

A longer persisting disruption of a certain stage - respectively a node - of a transport chain can cause massive damages which are hard to quantify. Such an incident can affect the whole supply chain, i.e. from suppliers, who can no longer deliver their goods, to the customers who do not receive them.

Immanent to networks are causal relationships amongst the participants, which include the emergence of negative cascading effects, i.e. one partner waiting for goods or load units (in the case of terminals) to be transferred by another partner, who is suffering a disruption, also experiences severe problems. Hence, these flow problems in the transport chain require information about rerouting possibilities. Based on the mentioned risk potential analysis and developed risk profiles for every Austrian container terminal, we present an agent-based simulation model of the terminal network to evaluate strategies for coping with disruptions.

In our model we consider a terminal as an individual unit in the network, which pursues its main objective of maintaining the maximum throughput. From this perspective, an analogy with software agents in computer science can be drawn. According to Jennings (2000), the crucial characteristic of an agent is its autonomous behaviour; the capacity to make independent decisions is the primary property of an agent. This implies the need for planning and active responses to the environment to achieve their particular objectives. Software agents are used in the areas of object-oriented programming and concurrent object-based systems. The agents are modelled to represent natural entities in the system under consideration, and therefore are applicable for representing network participants.

The operational activities in a container terminal are subject to dynamic causal processes, influenced by the present infrastructure and operational strategies. An aggregate view of these activities can be provided by the modeling approach of system dynamics, which represents real-world processes in terms of stocks, flows between them and the information that determines their value (see Schieritz and Milling 2003).

2. RELATED WORKS

Social processes are a common field of agent-based modeling applications. Even more important than modeling agent behavior, is modeling the agent interactions. The main issues hereby are the questions about which agent is connected to another, and of course, what the governing mechanisms of their interactions are. For social interactions a network interaction topology may provide a more accurate description of the agents' interaction patterns than a cellular one would. Moreover, agent-based modeling and simulation applications range from the areas of business and organizations, economics, crowds, society and culture and biology, to the subject of infrastructure (Macal and North 2008).

A survey of Davidsson et al. (2005) shows that agent technology has been applied to various problem areas within transport logistics, such as (transport) planning and scheduling, fleet management and traffic control and management. The papers reviewed cover the domains of transport, traffic and terminals, as well as the modes of transportation (air, rail, road, sea) and the topic of intermodal transport. The authors come to the conclusion that very little work has been done in the field of strategic decision-making. For intermodal terminals, Henesey et al. (2009) evaluate operational policies for the transshipment of containers, more precisely policies concerning the sequencing of ships, berth allocation and stacking rules.

Related questions to our investigation have been considered in a commodity flow network with arbitrary topology by Weiskircher et al. (2009). The solution of the profit maximization problem for the network with distributed control is implemented by using software-agents representing the network nodes.

In the field of supply chain modeling, numerous computer-based models deploy system dynamics. Größler and Schieritz (2005) demonstrate a combined approach of system dynamics and agent-based simulation to test the stability of supply chain structures under different levels of uncertainty. They judge a combination of both of these approaches which are helpful in the investigation of a supply network structure that emerges from the interaction of at least partly independent companies.

3. SIMULATION MODEL OF THE AUSTRIAN INLAND CONTAINER TERMINAL NETWORK

The aim of our developed simulation model is to emulate the flow of load units between the considered terminals and to analyse the network behavior in case of disturbances, covering the whole range from reduced transshipment performance to a total breakdown of a terminal. It is, therefore, of considerable interest, which other terminal in the network would be able to overtake a certain amount of load units. Furthermore, it is important to know how long it takes for the network to recover and regain initial conditions. In answering these questions, vulnerabilities of the Austrian terminal network can be identified and its robustness and resilience can be assessed. Therefore, the following performance measures for the network are applied:

1. The overall system performance is measured by the throughput of load units per week, since daily fluctuations should balance in this time.
2. The average utilisation of storage and lifting capacities per terminal, disruption and recovery period.
3. The number of days in total runtime, when storage and transshipment utilisation exceed a critical value of 75 percent.
4. The frequency of occurrence of a queue of load units waiting to be processed in a terminal.

3.1. Model structure and components

The main part of the model is formed by the *terminal agents*, which represent the single terminals in the network under consideration. They communicate with each other about the amounts of load units interchanged, and pass on and receive information from the *system dynamics models*, which perform terminal internal operations. An *administrator* manages the whole simulation cycle and structures, and controls the communication between the terminal agents. The scenarios of disturbance events are implemented through the so called *environment*, which emulates potential incidents of different origin in altering the regular flows of load units, or in affecting available storage and transshipment volumes. Figure 1 schematically shows the systems components and their interrelations.

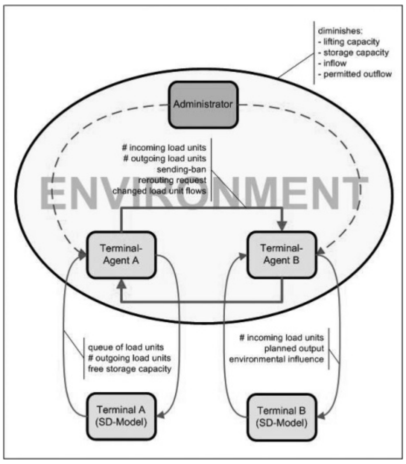

Figure 1: Model Components

The system dynamics models of terminal internal operations

The central elements of the system dynamics models are the storage and lifting capacities. The storage capacity is a stock variable, which is determined by the amount of the daily incoming and outgoing load units. The actual admission to storage results from the amount of the everyday incoming load units, the share of direct turnover to other means of transport without interim storage, the available lifting capacities and of course the storage capacity. Likewise, the daily outcome derives from the planned amount of outgoing load units, the direct turnover, the lifting capacity and the existing stock. The theoretical lifting capacity of all the various transshipment equipment is dependent on the terminals' operating hours and reduced by the necessary reshuffling moves. Incoming load units which cannot be moved to the storage yard form a queue, and can be considered as prestow capacity.

The system dynamics models receive information about up-to-date incoming volumes and current planned outgoing amounts of load units from the associated terminal agent, as well as constraints on the storage and lifting capacities, passed on from the environment through the terminal agent. Vice versa, the information flow contains data about available storage capacities, the queue length and the actual output.

The terminal agents

The main function of the terminal agents is the coordination among themselves in case of deviations in the planned network flows by rail. Each terminal's interest is to fulfil its quotas and to provide for an alternative itinerary when it cannot complete its tasks. There are several scenarios which require terminal agents' action:

- The terminal could not process the planned number of outgoing load units e.g. in consequence of a lack of lifting capacity. So the other terminals in the network have to be informed about changed amounts of incoming load units, and furthermore, these quantities have to be processed additionally in the subsequent periods.
- Due to a deficiency in the storage capacity a queue of load units arose. In order to allow the queue to be processed, delivery bans have to be sent out for the next period.
- Incoming messages from the environment, which signify changes in the incoming or outgoing load unit flows or declines in lifting or storage capacities, will likely entail modifications in the network flows and therefore demand agents' actions.
- Given a ban from another terminal to send load units, the terminal agent tries, according to its focus on maintaining the maximum throughput, to reroute that quantities to another terminal in the network.
- As a reaction to the aforementioned situation, an agent has to accept these load units according to its capacities, which again alters the transshipment amount in the subsequent periods.

The environment

Based on previous work on risk analyses and vulnerability assessment of the Austrian inland container terminals, the environment emulates risk scenarios, which (negatively) influence the operational activities of a terminal. The terminal's turnover capability can thus be affected in terms of a reduced lifting or storage capacity, or changed conditions caused by altered amounts of incoming or outgoing load units.

The administrator

The administrator is responsible for the control of the whole simulation run, i.e. it determines the sequence of the terminal agents activities and the system dynamics components. To avoid problems due to concurrency issues, only one agent can be active at any given time, all other agents are inactive or in a waiting position. For this reason, the administrator additionally determines the order in which the terminals are allowed to conduct the different actions and coordinates their communication.

3.2. The communication of the model components

The communication structure of the agents is of considerable impact on the network performance. This is because the decision to reroute strongly influences the outcome of the simulation run, since these rerouting possibilities are then no longer available to another terminal, which might make a request later. Correspondingly, the rules for announcing bans on incoming load units, and selecting the terminal which is affected by changed outgoing amounts, can result in considerable discrepancies in the overall network performance.

The communication between all agents is implemented as follows. On the one hand, information is transferred by the type of message they send each other, and on the other hand by the carried content. The terminal agents and the system dynamics components are interconnected through interfaces in the form of variables. The different types of messages are:

- Activation of the environment by the administrator.
- Activation of a certain function of a terminal agent by the administrator.
- Announcement of a (partial) ban on incoming load units from one terminal agent to another.
- Request of rerouting possibilities and the corresponding answer among two terminal agents.
- Terminal agents give out information to the others about reductions in the flows of load units, and ask for operability in case of additional amounts and receive accordant reply.
- Confirmation of finished actions to the particular communication partner.

3.3. Activity scheduling

One total run of the models functionality represents the actions in a certain time period, so that it can be applied in a more or less aggregated way for a certain period of time, split into cycles representing data with different levels of aggregation. As mentioned before, the sequence in which the terminal agents get their turn for different actions in a cycle may change the outcome of the simulation, as the decisions of one agent can limit the options for the other agents later in the sequence. We choose their sequence randomly in each cycle.

At the beginning of every cycle the system dynamics components prepare the data basis for the terminal agents' actions. Next, the environment provides the risk driven influencing factors for the period in question, which are adjacently processed by the terminal agents. Afterwards, potential queues are checked, in case necessary bans for incoming load units are announced for the subsequent cycle. Obviously, in the random turn sequence, the reaction of all terminal agents to delivery bans is to demand rerouting opportunities. The sequence of asking the other terminal agents to take over the load units is again chosen at random. This situation is one of several, when one terminal agent has to wait for the response of another one, in order to continue its actions.

Next, the agents check whether modifications emerged in the planned number of load units to be sent or to be received. Deficiencies in the outgoing amounts only have to be announced. However, when additional transport is demanded, the intended recipient can refuse to accept them due to a lack of capacity.

The final action for the terminal agent is to calculate the actual values for the number of incoming and outgoing load units for the next cycle as input parameter for the terminal internal processes, realised in the system dynamics components.

3.4. Proposed model assumptions

The simulation is executed on a daily basis, so the flows of load units are the aggregated amounts of incoming and outgoing units per day. The depicted flows are the amounts to and from the other terminals in the considered network, as well as the cumulative volume of the inflows and outflows per truck and ship, and the other terminals which are not represented in the model, e.g. the flows to and from overseas.

The possibility of asking other terminals for the opportunity to reroute is limited by a certain probability, and their sequence taken by chance.

Basically, the acceptance of a rerouting demand is reliant on free storage capacities and actually accepted requests. Even provided sufficient storage capacities, a terminal is not obliged to accept a rerouting request. Therefore, a probability distribution is used to make this decision.

Every other terminal in the network not having announced a sending-ban, is an option for a rerouting request, as well as for processing additional volumes evoked through certain events in previous periods. Their order is also determined randomly.

No capacity constraints with regard to the links between the terminals are considered.

4. COMPUTATIONAL EXPERIMENTS

For our analyses a group of three representative Austrian terminals were chosen, later referred to as terminal A, B and C. Two of them hold an important strategic position for and in the Austrian terminal network, as they take over the function as a gateway and hub respectively, and belong to the biggest Austrian terminals measured in terms of their yearly turnover. The third terminal has been selected due to its strong interlinkage of transport volumes to the other ones, and, because of its geographical position, inland transport and also transit traffic along the arterial Austrian transport links are covered.

4.1. Data basis and model parameters

As already mentioned, the simulation and investigation of the network performance is done for aggregated daily flows, whereas empty container volumes are not taken into account, and neither are the corresponding capacities for storage and transshipment. The following assumptions are made regarding the model parameters:

- The daily amount of incoming and outgoing load units, given as number of load units, is an average value of the total transshipment volume per year, but also considers fluctuations in the different days of the week.
- Load unit interchange takes place between the modeled terminals, it is also implemented for the "terminal-environment" using aggregated volumes.
- The storage capacity is set for charged containers, measured in TEU (twenty-foot equivalent unit).
- The cumulated lifting capacities per simulation cycle result from the possible moves per hour and equipment, totalized for the terminals operating hours, and reduced by the moves necessary for empty container movement.
- Another limiting factor for the actual available lifting capacity is the share of unavoidable reshuffling moves, which depends on the utilisation of the storage capacity and the number of tiers.
- To convert the number of incoming and outgoing amounts of load units into the storage capacity measure TEU, the average length of stored load units and the share of not stackable load units are applied.
- Not every incoming load unit is put into (interim) storage. This fact is taken into account by implementing a certain share of direct moves per inflow.
- The initial filling degree of the storage yard is estimated at the rather low value of 65 % for two of the terminals; for the third, the actual utilisation of 56 % is taken.

4.2. Disruption Scenarios

The analysed disruption scenarios comprise diminished storage capacities, diminished lifting capacities and constraints on the planned amount of outgoing trains (in fact batches of load units) to the terminal-environment.

Capacity reductions are assumed with 50 and 100 percent respectively, the third type of disruptive event is defined to an extent of one and three trains for each terminal. All disruption scenarios were simulated with a time dimension of one, three and five days of suffering the disruption for every terminal. Every scenario is analysed under ceteris paribus conditions, so that no events occur contemporaneously. Consequentially, a total number of 55 scenarios (one reference scenario without incidence plus 54 disruption scenarios) were calculated. Table 1 provides an overview about the 18 scenarios applied for the first terminal.

Table 1: Disruption Scenarios using the Example of Terminal A

disruption scenario		*duration (days)*	*intensity (% / number of trains)*	*scenario number*
DISRUPTION TERMINAL A	reduction of storage capacity	1	50	1
			100	2
		3	50	3
			100	4
		5	50	5
			100	6
	reduction of lifting capacity	1	50	7
			100	8
		3	50	9
			100	10
		5	50	11
			100	12
	reduction in number of outgoing trains	1	1	13
			3	14
		3	1	15
			3	16
		5	1	17
			3	18

4.3. Simulation results and analysis

The simulation run was carried out for one year, presuming five operating days per week and 50 operating weeks per year. The performance measures for all scenarios were calculated by the average of 20 replications each. To ensure a justification period and to sufficiently observe disruptive events' consequences, the occurrence points in runtime were defined permissible starting four weeks after the start of the simulation, to allow for a system warm-up, until four weeks before the end of runtime, to allow for an observation period of the consequences. During this period, disruptions happen randomly according to a uniform distribution.

Every disruptions' consequences to the network are assessed for the time spans of 5, 10 and 15 days after occurrence, by means of averaging the already mentioned performance measures utilisation of storage capacity, utilisation of lifting capacity and the number of days exceeding their critical value, as well as the emerging of a queue of load units waiting to be processed. As a reference, the average values of a simulation run without a disruption is applied. In the following, we employ selected scenarios to show how certain disruptive events affect the performance of the single nodes, and accordingly disperse in the considered network.

Example 1: Diminishment of lifting capacity at Terminal B

The impact of a total breakdown of the transshipment equipment in Terminal B for a time period of five days on the average utilisation of the lifting capacities of all three terminals is shown in Figure 2. Apparently, the utilisation in the concerned Terminal B rises immediately. This effect lasts up to 10 days after the occurrence of the disruption with the same severity, until the recovery phase sets in. In the same period the effects on Terminal A and Terminal C start to become visible. Terminal A shows an increase in lifting capacities utilisation of about 10 percent and Terminal C shows an increment from about 11 percent to 14 percent. Several things can be shown to be responsible for this development. On the one hand, the other two terminals have to take over additional transport volumes from the system until the recovery of Terminal B has completed, on the other hand, the processing of the arisen queue of load units in Terminal B after its recovery, implies extra workload for the other network nodes. In the course of time, utilisation values drop again.

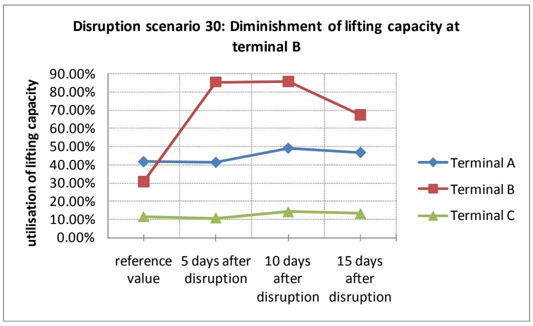

Figure 2: Diminishment of Lifting Capacity

Example 2: Reduction in number of outgoing trains at Terminal C

An incidence concerning the flow of load units to the external, not explicitly modeled, network emphasizes the role of Terminal C as an important gateway for the Austrian terminal network. As a real world example, this can be a situation in which maritime transports from Austria have to wait at an Austrian node located close to the border, because of capacity bottlenecks in the German railway network.

The infrastructure of Terminal C is of sufficient dimension to cope with such a situation, resulting in an extraordinary burden on storage capacities without markedly impairment of its lifting capacities. Effects on the other two terminals keep within limits, both due to the internal capacities of Terminal C and the fact that not every rerouting possibility is reasonable. As shown in Figure 3, efficiency curves of Terminal A and B remain unaffected.

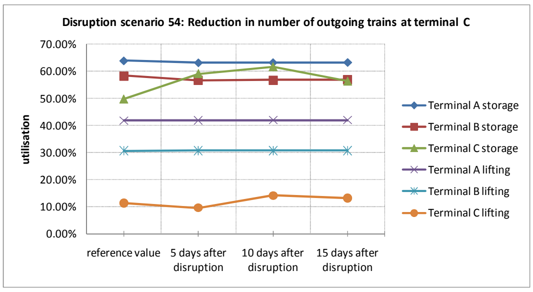

Figure 3: Reduction in Number of Outgoing Trains

Example 3: Comparison of consequences according to the network role of a terminal

According to the role of a terminal in the network, varying from a local node to a gateway or hub, distinctions can be made between the consequences of a disruption for the terminals that are only indirectly concerned. Figure 4 shows the effects of all events occurring at Terminal B and Terminal C on the other terminals, measured in the number of days their respective storage utilisation exceeds its critical value.

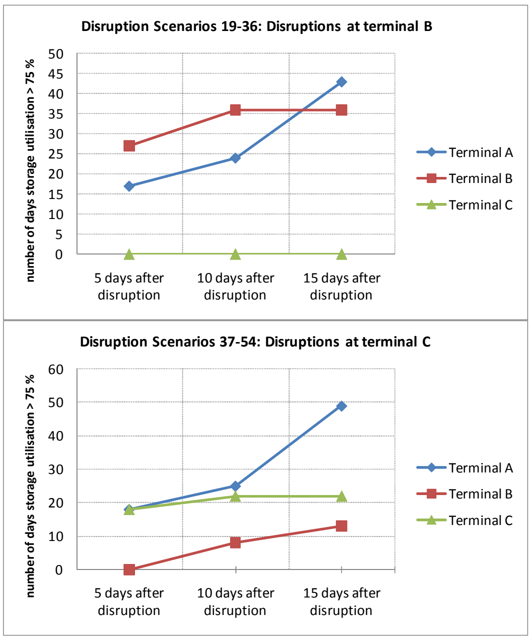

Figure 4: Comparison of Consequences on the Network

Given disruptive events at Terminal B, a considerable increase of the storage utilisation of Terminal A can be seen, whereas Terminal C is hardly affected. On the contrary, disruptions at Terminal C influence both other nodes, but Terminal A encounters stronger impacts than the others. Herefrom, conclusions about mutual interrelationships and dependencies can be drawn.

5. CONCLUSION

The implemented simulation experiments and findings that have been gained from it, conspicuously show that disruptive events in the (here considered) Austrian terminal network can be handled properly. The particular terminals have enough capacities in order to cope with disruptions of either terminal external or internal origin. Where this is not the case, there exist enough rerouting possibilities to geographically closer or otherwise connected terminals anyway.

Another, always feasible coping strategy with disruptions, is to use redundancies in transport routes and (re-)deflect transport from rail to road if necessary. However, limitations of the capacities of these links in the network have to be taken into account. These factors have not yet been considered in this study but are currently being considered in follow-up research works by the authors.

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