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**Combining macro-level and agent-based modeling for improved  
freight transport analysis**

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**Abstract**

Macro-level models is the dominating type of freight transport analysis models for supporting the decision-making in public authorities. Recently, also agent-based models have been used for this purpose. These two model types have complementing characteristics: macro-level models enable to study large geographic regions in low level of detail, whereas agent-based models enable to study entities in high level of detail, but typically in smaller regions. In this paper, we suggest and discuss three approaches for combining macro-level and agent-based modeling: *exchanging data between models*, *conducting supplementary sub-studies*, and *integrating macro-level and agent-based modeling*. We partly evaluate these approaches using two case studies and by elaborating on existing freight transport analysis approaches based on executing models in sequence.

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**Keywords:** Multi-agent-based simulation, Macro-level modeling, Freight transport modeling, Combining models

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**1. Introduction**

Freight transportation is known to cause both positive and negative effects on society. Positive effects mainly relate to the economy and social welfare, while there are significant negative effects on the environment. Public authorities, which operate on regional, national, or international levels, are responsible for planning for a sustainable transport system that is capable of fulfilling the transport needs of society. At the same time, they are responsible for reducing the negative effects of transportation. By making use of various types of transport policy and infrastructural measures, it is often possible to influence how transport activities are chosen and executed. However, before implementing measures, it is important to accurately predict what will be the environmental, economic, logistic, and societal consequences, so that undesired and desired effects can be highlighted. Freight transportation is complex, and many aspects need to be considered when assessing the impact of transport policy and infrastructural measures. It is therefore common to use advanced freight transport analysis models for supporting the decision-making in public authorities.

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Macro-level models, e.g., Samgods<sup>1,2</sup> and TRANS-TOOLS<sup>3</sup>, is the predominating type of freight transport analysis models for supporting the decision-making in public authorities. These models are based on highly aggregate data, typically on international, national or regional level, and they do not contain any behavioral aspects. Recently, also a number of agents-based freight transport analysis models have been suggested, e.g., INTERLOG<sup>4</sup> and TAPAS<sup>5</sup>, which belong to the class of micro-level models, where individual entities are represented and the relations between entities are typically studied over time. It should be noted that the agent-based modeling paradigm allows representing different types of entities on different aggregation level in a model. For example, TAPAS suggests to model entities on an individual level; however, it is possible, e.g., to let the same network node and an associated agent represent multiple suppliers and consumers. In an agent-based model, one or more of the entities, often decision-makers, are modeled as agents. An important advantage of agent-based models is that they enable to explicitly model the different actors involved in freight transportation (e.g., transport operators and transport buyers), and the interaction and decision-making processes that lead to activities, thus capturing causality. In general, they enable aspects of time (e.g., timetables, and time-differentiated taxes and fees) to be considered when estimating logistic choices. It is important to include these aspects in order to capture the complexity of freight transportation; however, they are difficult to capture in traditional macro-level models. In addition, it has been argued that the macro-level models currently in use are unable to fulfill the needs for freight transport analysis in public authorities, e.g., due to their inability to capture the logistic complexity in freight transport<sup>6</sup>. However, due to the need for the large amounts of processing power and of input data required in order to model all entities at a micro-level, it is often difficult to use agent-based models for studying large transport systems. Macro-level models are therefore often an appropriate choice in large scale modeling, although they lack the functionality to model the detailed aspects of freight transport.

Due to the respective advantages and disadvantages of macro-level and agent-based models, we hypothesize that improved freight transport analysis can be achieved through combining the two model types. In addition, development of new models typically requires considerable effort, and so it may, in many cases, be more time-efficient to combine existing models rather than developing new models. Even though there are several potential advantages of combining agent-based and macro-level modeling, it has not been common to combine them in freight transport modeling.

In this paper, we suggest three approaches for combining macro-level and agent-based modeling: *exchanging data between models*, *conducting supplementary sub-studies*, and *integrating macro-level and agent-based modeling*. We elaborate on *exchanging data between models* by discussing existing modeling approaches that are based on executing models in sequence with exchange of data. *Conducting supplementary sub-studies* and *integrating macro-level and agent-based modeling* are evaluated using two case studies.

In Section 2 we give an account to related research. In Section 3 we present our three approaches for combining macro-level and agent-based modeling. In Section 4, we describe the models used in our two case studies, which are presented in Section 5, and the paper is concluded in Section 6.

## 2. Related work

As mentioned above, there exist both macro-level and agent-based freight transport analysis models that can be used to support the decision-making in public authorities. However, according to the best of our knowledge, there exist only a few freight transport analysis models that combine the two types of modeling, each of which is discussed in this section. For reviews of models built according to a single modeling paradigm, we refer the reader to<sup>5,7,8</sup>.

The predominant model type for supporting the decision-making in public authorities is the sequential and aggregate four-step approach<sup>7</sup>, e.g., Samgods and TRANS-TOOLS. Four-step models include one or more of the following steps: trip generation, trip distribution, modal split, and traffic assignment. They start out from aggregate data, which is disaggregated in order to enable more detailed estimations of logistic choices (e.g., of vehicle types and consignment sizes). The data is again aggregated before further processing. In that way, the four-step models adopt the so-called ADA (aggregate-disaggregate-aggregate) approach. We refer to the four-step models as macro-level models, mainly since their initial input is highly aggregate, and since they do not contain any aspects of behavior-based modeling. Further, they relate to *exchanging data between models*, since models that operate on different levels of aggregation are run in sequence with data exchange in between.

An agent-based model that integrates some macro-level modeling is TAPAS-Z<sup>9</sup>, in which a few network nodes, with varying locations, are used to model a large number of suppliers and consumers. All consumers in a zone share

inventory, consumption pattern, and ordering policy, although they are separated in space, and all suppliers in a zone share inventory and production facilities. Decisions of when to order are therefore taken centrally, and logistic choices are made based on the location of the supplier and the consumer, which are specific for each shipment.

Cambridge Systematics, Inc.<sup>10</sup>, recently proposed a freight transport model for the Chicago region, where decision-making agents are used to represent firms involved in trade of goods. Three sub-models are run in sequence; a macro-level model is used to generate commodity flow data, which are further evaluated in a (meso-level) agent-based model, and a micro-level model is then used to study vehicle movements in detail.

For passenger traffic analysis, there exist several approaches for combining macro-level and agent-based modeling. For example, Burghout and Koutsopoulos<sup>11</sup> integrated a meso-level and a micro-level traffic model in order to overcome issues with micro-level models, regarding input data management and calibration. Sewall et al.<sup>12</sup> presented a simulation model where individual vehicles are simulated using agents in regions of particular interest, and the rest of the network is simulated using a macro-level model. In that way it is possible to benefit from the performance benefits of macro-level modeling and the flexibility of agent-based modeling.

### 3. How to combine models

We here present our three approaches for combining macro-level and agent-based modeling in order to enable improved freight transport analysis in public authorities (see Fig. 1).

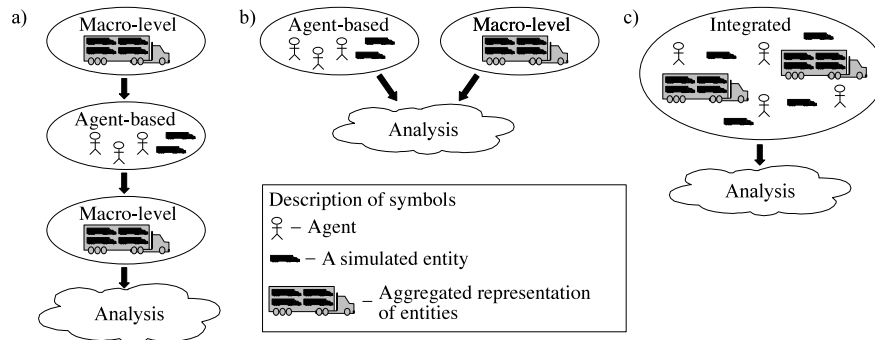


Fig. 1. Our three approaches for combining macro-level and agent-based modeling: a) exchanging data between models, b) conducting supplementary sub-studies, and c) integrating macro-level and agent-based modeling.

*Exchanging data between models.* This approach concerns running models in sequence, and using the output generated by one model as input for one or more other models. Data can be exchanged between models in order to generate input data as part of developing a model or in the execution phase of a study. An important situation where it is relevant to exchange data between models is when necessary data is missing or cannot be used due to poor quality. The generated data can be used in other models exactly as is, or it can be processed either manually or automatically in different ways, e.g., through aggregation or disaggregation.

An example of data that can be generated with a macro-level model and used in an agent-based model is total freight flows, which can be used to model capacity utilization in terminals, and to study congestion and disturbances. Examples of input data that can be generated by an agent-based model and used in a macro-level model are transport elasticities, shipment frequencies, vehicle utilization levels, and new transport chains.

The freight transport analysis model for the Chicago region<sup>10</sup> captures *exchanging data between models*. It uses a (meso-level) agent-based model that operates between a macro-level and a micro-level model. In addition, the traditional four-step approach<sup>7</sup> closely relates to *exchanging data between models*, since sub-models are run in sequence with data exchange; however, four-step models typically do not include any aspects of agent-based modeling. A possible way to enable four-step models to better analyze the logistic processes and relations involved in freight transport is to include more behavioral aspects<sup>6</sup>, e.g., by replacing the logistic model, which is often used for estimation of

choices related to trip distribution and modal split, with an agent-based model. This would make it possible to take into account the more detailed aspects, e.g., concerning interaction between actors, when modeling logistic choices.

It should be noted that we believe there is a risk of transferring errors between models in this approach: incorrect input data used in one model may cause that model to produce incorrect output data, which is later on used in other models. Even though this is difficult to completely avoid, it is important to be aware of this risk so that necessary validation measures can be taken.

*Conducting supplementary sub-studies.* This approach involves using different models in a study and combining the results in the analysis. A situation where it might be relevant to use this approach is when there is a need to use more than one model type to be able to consider all aspects that need to be analyzed in a study. Either there are aspects that cannot be studied at all using only one model type, or a particular model type enables analysis with higher quality of some aspects. For example, detailed aspects concerning logistic choices can be studied using an agent-based model, while general tendencies in a transport network can be studied with a macro-level model. In addition, this approach can be used for validation, by studying the same problem using models of different type.

In comparison to studies that make use of only one model, we expect that *conducting supplementary sub-studies* requires more expertise and effort from the analyst, since results from multiple models need to be jointly analyzed. In particular, when comparing with the other two identified approaches for combining macro-level and agent-based modeling, there is more emphasis on the analysis.

*Integrating macro-level and agent-based modeling.* Integrating macro-level and agent-based modeling concerns incorporating features from both of the paradigms within one model. The expected advantages of this approach are best described by relating to the previously described approaches for combining models, i.e., *exchanging data between models* and *conducting supplementary sub-studies*. By running a single integrated model, rather than multiple models in sequence, there is no risk of loss and accidental manipulation of information when switching between models. In addition, we believe that a benefit of using an integrated model, compared to conducting supplementary sub-studies, is that more of the analysis can be performed within the model, thus reducing the need for complex analysis to be performed by the analyst. However, since more functionality typically needs to be included in an integrated model, we expect that such models will be more difficult and time-consuming to develop than models built around one paradigm.

TAPAS-Z<sup>9</sup> is an agent-based model that integrates some macro-level modeling; the suppliers and consumers, respectively, located in one geographic zone are modeled in such a way that they share inventories. In addition, an example of how it could be possible to integrate agent-based features in a macro-level model is to model agents, representing actors such as producers, consumers, and transport operators, that negotiate over yearly transport demand instead of over single shipments, hence making logistic choices on a macro-level. This is similar to how logistics models in many ADA-based models operate. However, the use of agents can add improved means for negotiation and reaching complex agreements when modeling logistic choices.

#### 4. Descriptions of the models used in the case studies

*Samgods.* The national Swedish model Samgods<sup>1,2</sup> is a macro-level model built according to the principles of ADA. It uses aggregate data specifying production-wholesale-consumption demands, which is disaggregated into firm-to-firm (f2f) demands between firms of three size categories. The f2f-flows are used as input to a logistics model, which determines, e.g., shipment sizes and (multi-modal) transport chains. For each leg in a transport chain, the logistics model determines which vehicle type should be used. The flows produced by the logistics model are then aggregated into origin-destination (OD) flows, which describe the number of vehicles of different types that are assigned to each of the legs in the transport chains. The OD flows are then assigned to the transport network.

Since the standard Samgods logistics model is not capable of modeling railway capacity, Edwards<sup>13</sup> recently developed an alternative Samgods logistics model, referred to as the simplified logistics model (SLM). The Samgods logistics model and SLM is in essence identical; however, SLM can be modified, which is not the case for the Samgods logistics model. Just as the Samgods logistics model, SLM assigns transport flows to the network assuming unlimited capacity for all connections in the railway network. The railway capacity issues can be then iteratively resolved using a railway capacity management model (RCM). We refer to the version of Samgods that uses SLM as “SLM”, and the version that uses SLM and RCM as “SLM+RCM”.

*TAPAS and TAPAS-Z.* The Transportation And Production Agent-based Simulator (TAPAS)<sup>5</sup> is an agent-based freight transport analysis model for simulation of decision-making and activities in transport chains. It can be used for impact assessment of various types of transport policy and infrastructural measures. TAPAS takes into account how transport chain actors are expected to act under different conditions, and the basic premise is that production and transport activities are consequences of the ordering and planning processes that take place in order to fulfill consumers' demand for products. Hence, it is based on causality. TAPAS is built using a 2-tier architecture with a physical simulator and a decision-making simulator. In the physical simulator, all physical entities (e.g., links, vehicles, and products) are modeled, and in the decision-making simulator, six transport chain decision makers (or roles) are modeled as agents. To fulfill the consumers' demands for products, the agents participate in a process that includes ordering of products and a transport solution, selection of which resources and infrastructure to use, and planning how to use resources and infrastructure. The process starts when a customer agent sends an order request, and it ends when products and a transport plan have been booked and confirmed.

TAPAS-Z<sup>9</sup> is an extension of TAPAS, and it is an agent-based model that integrates some macro-level modeling, and hence represents a step towards models that completely integrates macro-level and agent-based modeling. TAPAS-Z follows the same principle as TAPAS, i.e., shipments are simulated between particular transport network nodes representing suppliers and consumers. However, in TAPAS-Z, a few nodes are used to represent a large number of suppliers and consumers of freight, by randomly varying their locations. Hence, it enables to simulate shipments between geographical zones, and in that way it provides extended possibilities to estimate total transport volumes in a larger geographical region. All suppliers and consumers in a geographical zone are randomly located in the catchment area of one logistics terminal, which is used to represent the whole zone. In addition, all suppliers and consumers in a zone are represented by one supplier and consumer node respectively, and by one supplier and customer agent respectively. Hence, all randomly generated consumers in a zone share inventory, consumption pattern, and ordering policy, although they are separated in space. Similarly, all suppliers in a zone share inventory and production facilities. Hence, decisions of when to order are taken centrally, and logistic choices are made based on the location of the supplier and the consumer, which are specific for each shipment.

*TRANS-TOOLS.* TRANS-TOOLS (TOOLS for TRANsport Forecasting ANd Scenario testing)<sup>3</sup> is a four-step model developed within the European Union for various types of transport analysis. An economic model makes a forecast of sectorial development based on a baseline scenario and economics statistics, e.g., GDP. The data produced in the economic model is further processed in a freight demand model using three sub-models that are run in sequence, i.e., trade, modal split, and logistics models. The output of the freight demand model is flows between origins and destinations, which are represented in terms of tons and the number of vehicles for each of the four considered modes of transport (rail, road, inland waterway, and sea). The output from the freight and passenger demand models is passed to a network assignment model, whose output, i.e., traffic flows, is then further processed in an impact model, which generates different types of output, including energy consumption, emissions, and external costs.

## 5. Case studies

In this section we present two case studies (EWTC and HM), which we used for evaluating the approaches *conducting supplementary sub-studies* and *integrating macro-level and agent-based modeling*.

### 5.1. EWTC study: East-West Transport Corridor

The East West Transport Corridor (EWTC) is a land-bridge for transport from China and Russia through the Southern Baltic Sea region further towards the United Kingdom, and it has been the focus of the EWTC projects (see <http://www.ewtc2.eu/>). In a simulation study conducted in the EWTC II<sup>14</sup>, transport in the "EWTC region" (see Fig. 2) was studied using a combined agent-based and macro-level approach. The purpose was to estimate current and future transport volumes in the region, and to assess the impact of three transport policy and infrastructural measures, which may contribute to greener transport in the region. In the EWTC study, we included five scenarios, i.e., CS: Current situation (2010), BL: Base line (2030), BLG: BL + a distance-based road user charging of 0.15 €/km for heavy trucks, BLHH: BL + a fixed link between Helsingborg-Helsingør, and BLSE: BL + a new railway connection between Karlshamn and Älmhult (the so-called SouthEast Link).

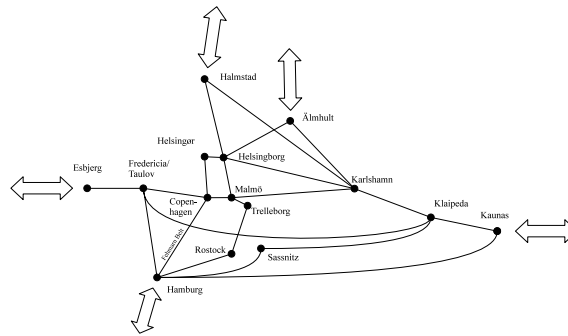


Fig. 2. Overview of the EWTC region, including modeled terminals and connections between the terminals. The arrows represent freight flows entering and leaving the region.

Our main choice was to base the EWTC study on the TAPAS-Z model, due to its abilities to model logistic choices and studying transport between zones. However, since TAPAS-Z does not estimate freight demand, we used TRANS-TOOLS to generate total freight flows in the EWTC region, specified in tons between pairs of zones inside and around the EWTC region. On the other hand, the quality of the logistic choices generated by TRANS-TOOLS has been questioned<sup>15</sup>, which is a reason for instead using TAPAS-Z to suggest logistic choices. For ten OD pairs, and for each of the eleven NSTR commodity types in TRANS-TOOLS, we used TAPAS-Z to simulate a large number of shipments with varying locations of suppliers and consumers. The logistic choices estimated by TAPAS-Z were then combined with the total freight volumes for rail and road suggested by TRANS-TOOLS, and so we were able to obtain total freight flows based on the TAPAS-Z logistic choices.

The principal results used in the analysis are total flows in ton-kilometers for each of the considered connections. The CS and BL scenarios were used as comparison scenarios, and the transport flows in BLG, BLHH and BLSE were compared to the BL scenario to predict the possible impact of the three studied transport policy and infrastructural measures. From the generated freight flows, it was possible to observe some expected trends for future transport in the EWTC region (the detailed output data is presented in<sup>14</sup>):

- It is reasonable to expect a higher share of rail transport than today. This is partly due to the fact that the cost for sea and road transport are expected to increase more than for rail transport until 2030.
- For each of the studied transport policy and infrastructural measures, we observed shifts (when comparing with BL) towards “greener” transport in the EWTC region, i.e., less road transport. One reason is that the studied measures provide additional transport infrastructure (in BLHH and BLSE), and that the kilometer tax in BLG gives incentives to choose greener transport, as all road transport in that scenario is subject to a fee.
- The HH fixed link (BLHH) and the kilometer tax (BLG) shows significant impact on transport in larger parts of the EWTC region, whereas the SouthEast Link (BLSE) shows an influence on transport between the southeast parts of Sweden and locations further north in Sweden. We observed that the importance of the link is expected to increase when it is used for transport with destination or origin further north than Älmhult.

### 5.2. HM study: Railway capacity Hallsberg - Mjölby

The Swedish Transport Administration recently analyzed a set of infrastructure investments for increasing the capacity on the railway link Hallsberg-Mjölby<sup>16</sup>, which is important for freight transport in Sweden. In a simulation-based study (the HM study), we further analyzed the probable impact of an increased railway capacity between Hallsberg-Mjölby, by studying transport in the region in Fig. 3.

Currently, 4-8 daily freight trains between Hallsberg-Mjölby need to be redirected via Katrineholm-Norrköping as a consequence of the current limitation on railway capacity between Hallsberg-Mjölby<sup>17</sup>. This causes an extra transport distance of 100 km, extra transport time for the redirected trains, and robustness problems. An increased railway capacity is expected to result in improved robustness and faster railway transport in the whole region.

We defined two future scenarios, which we analyzed using SLM and SLM+RCM, and with TAPAS:



1. CA - Comparison Alternative (2030). Cost parameters are adjusted for the year 2030<sup>14</sup>. The capacity for the Hallsberg-Mjölby railway connection is identical to the current capacity. However, it is assumed, due to increasing traffic volumes in the whole region, that it will not be possible to redirect trains via Katrineholm-Norrköping.
2. IA - Investigated Alternative (2030). This scenario is identical to CA, except that it includes increased railway capacity between Hallsberg-Mjölby, which leads to faster transport on the Hallsberg-Mjölby railway connection.

For the two scenarios, we used SLM+RCM to estimate total transport volumes within the considered region, considering railway capacity limitations. SLM was used to estimate transport volumes in case of unlimited capacity for all railway connections in the network. In SLM and SLM+RCM, annual freight flows were estimated considering all commodity demands within Sweden, and Swedish import and export. The Samgods sub-study (SLM and SLM+RCM) indicates that the freight volumes that cannot be transported using the Hallsberg-Mjölby railway connection (due to capacity limitations) appear as railway transport via Katrineholm-Norrköping or as road transport, mainly on road 50 and road E4. It is also possible to observe higher flows in CA (compared to IA) for other road connections in the area, e.g., on road 34. Therefore, it is reasonable to expect increased pressure on larger parts of the road network in the studied region in case no railway capacity increasing investments are made. The Samgods study also confirms that the Hallsberg-Mjölby railway connection is a bottleneck, and that the suggested infrastructure investments may even be insufficient for fulfilling the future need for railway transport in the studied region.

We used TAPAS to provide more detailed estimations of shipments in the relation Gävle-Nässjö, which represents important freight flows passing through the studied region. By using TAPAS, it was possible to explicitly take into account the effects of shorter transport times between Hallsberg and Mjölby. We included the rail route Gävle-Hallsberg-Mjölby-Nässjö, and the road route Gävle-Nässjö. There was no route defined for redirection of trains via Katrineholm-Norrköping, as this option was assumed to be impossible in our scenarios. Route choices were studied for three commodity types of different value. For CA, we used a timetable corresponding to the current situation, and for IA we used a modified timetable, which enables faster transport as a consequence of increased railway capacity. In TAPAS, this leads to cheaper transport due to reduced costs for tied up capital. Since it was not possible to find out the exact amount of freight that may be transported on the Hallsberg-Mjölby railway segment, we studied transport demand at two levels. This implicitly gives a sensitivity analysis, and indicates the expected freight flows for different types of commodities under different availability of railway capacity. The TAPAS results indicate that higher value commodity types, to a higher extent than lower value commodity types, tend to be transported by road. This is the case even though the costs for road transport are expected to increase more than the costs for rail transport until 2030. The preferred transport mode for lower value commodity types is rail.

In conclusion, the TAPAS sub-study suggests that the importance of increased railway capacity is higher for lower value commodity types than for higher value commodity types. A reason for this is that the costs for tied-up capital increase with increasing product value, and faster transport on road is therefore often preferred over slower rail transport for higher value commodity types. These results should be considered in conjunction with the results from the Samgods sub-study, which concluded that there is a significant need for railway capacity investments.

## 6. Concluding remarks

We have suggested three approaches for combining macro-level and agent-based modeling: *exchanging data between models*, *conducting supplementary sub-studies*, and *integrating macro-level and agent-based modeling*. We elaborated on *exchanging data between models* by discussing 1) an existing freight transport analysis model for the Chicago region and 2) the sequential four-step approach for freight transport analysis. We partly evaluated the other two approaches using the case studies presented in Section 5. *Conducting supplementary sub-studies* was captured in both of the case studies, and *integrating macro-level and agent-based modeling* was captured in the EWTC study. In conclusion, by combining macro-level and agent-based modeling, we have in our case studies managed to analyze more aspects than would have been possible using only one model. We therefore argue that improved freight transport analysis can be enabled by combining the two types of modeling.

In Section 3, we presented some views on expected advantages and disadvantages of the three suggested approaches for combining macro-level and agent-based modeling. From these views, we believe that *integrating macro-level and agent-based modeling* is best from the perspective of conducting analyses, mainly since it is expected to reduce the

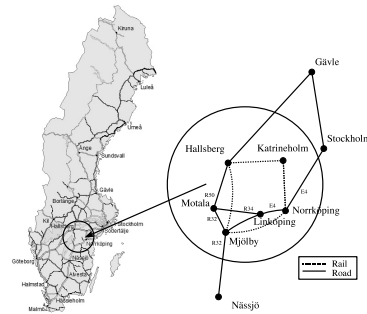


Fig. 3. Geographical region considered in the HM study.

burden of the analyst. From the perspective of developing models, we believe that the other two approaches are more relevant in a short time perspective, due to the expected high efforts required to develop integrated models. However, in a longer time perspective, we believe that there will be integrated models in use.

Future work includes further evaluating the presented approaches, both from the perspectives of using them in freight transport analyses and of how they are perceived by model users and clients. Examples of relevant aspects to consider in such an evaluation are the characteristics of the problem under consideration and the availability of different resources, e.g., expertise and data.

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