DEVS-BASED INTERACTIVE GEOSIMULATION FRAMEWORK FOR PUBLIC TRANSPORT ANALYSIS AND PLANNING

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ABSTRACT
The paper presents a new DEVS-based simulation framework for multi-modal public transport analysis and planning based on the concept of geosimulation that integrates the capabilities of multi-agent modelling and geographical information systems.
The proposed framework provides such important simulation aspects as execution possibilities of large-scale models, the support of user interactivity during the simulation execution process, as well as an effective synchronization between simulation and visualization processes.
Underlying concepts, implementation details and evaluation results of the proposed framework are discussed. The practical importance and application possibilities of the research results are demonstrated by analysing public transport simulation scenarios for the Vidzeme planning region of Latvia.

Keywords: DEVS, geosimulation, public transport

1. INTRODUCTION

In recent years, new forms of simulation have come into popular use in urban, environmental and transportation research, supported by an array of interdisciplinary advances in many scientific areas, especially in the geographical and computer sciences. These models are most commonly based on *Cellular Automata* (CA) or *Multi-Agent Systems* (MAS) formalisms and are often applied to the simulation of spatial systems in dynamic and high-resolution contexts (Ferber and Müller 1996). Modelling systems behaviour with explicit dependency of the geographic space requires a geographic information support that is usually accomplished with *Geographic Information Systems* (GIS).

A relatively new alternative for the research of spatially linked dynamic systems is geosimulation (Benenson and Torrens 2004) that is based on the concept of *Geographic Automata Systems* (GAS), which tightly couples spatial data and process models within a single integrated framework.

Although CA, MAS or GAS are intuitive and relatively straightforward for verification, they have an evident disadvantage – they do not provide any common formalism for model representation.

In the area of passenger transportation, there has been a tendency in recent years to increase investments in public transit projects and to reduce them in road construction (Laporte et al. 2011). Public transit systems or public transportation systems are increasingly complex incorporating diverse travel modes and services. The need to integrate and efficiently operate these systems poses a challenge to planners and operators (Toledo et al. 2010). By using new technologies and applications, as well as development assisting and evaluation tools prior to field implementation in public transportation systems, it is possible to find a solution for this complex problem area.

Simulation models have been established as a primary tool for transportation systems evaluation at the local operational level (Cortés, Burgos, and Fernández 2010). However, traditionally, simulation methods have not played a major role at the regional planning level, but several tools and models developed in recent years (Toledo et al. 2010; MATSim 2014; Behrisch et al. 2011) can assist the decision process and help produce transportation infrastructure designs that can be used by the transportation planners for further evaluation.

The domain of traffic and transportation systems is well suited to an agent-based approach because of its geographically distributed nature and its alternating busy-idle operating characteristics (Chen 2010). Usually, traffic simulation models are macroscopic, mesoscopic or microscopic. In response to the need for models that can capture both local traffic phenomena in detail, and effects on a larger surrounding network, hybrid models have recently appeared integrating macroscopic, mesoscopic and microscopic simulation approaches in different combinations (Burghout, Koutsopoulos, and Andreasson 2006).

The objective of this paper is to present a new DEVS-based simulation framework for multi-modal public transport analysis and planning based on the concept of geosimulation that integrates the capabilities of multi-agent modelling and geographical information systems. The application of the proposed public transport simulation framework is demonstrated by applying it to a public transport system in a territorial-administrative unit of Latvia called Vidzeme Planning Region.

2. GEOSIMULATION FRAMEWORK

The proposed geosimulation framework implements the concept of geosimulation simulation, allowing explicit modelling of each transport participant, such as vehicle or passenger, at a microscopic or mesoscopic level. The mesoscopic simulation considers particular vehicles in some form, but represents their interactions at relatively low detail (Burghout 2004). The microscopic simulation models every single vehicle as an object with its own position, direction, speed, and acceleration.

2.1. DEVS-Based Framework

The *Discrete Event System Specification* (DEVS) (Zeigler 1976, Zeigler, Praehofer, and Kim 2000) is a generic system-theoretical formalism that is provided for the description and definition of discrete-event systems dynamics allowing one to map systems specifications into most classes of simulation models (differential equations, cellular automata, etc.). For each class of model, one DEVS sub-formalism enables specification of one correspondent simulation model. As the specification of complex systems often needs to grasp different kinds of simulation models, connections between the models can be performed using DEVS multi-formalism concepts.

2.1.1. V-DEVS Specification

This paper proposes a new extension to the DEVS formalism called V-DEVS allowing the integration of the geosimulation concept (including CA, MAS and GAS) into a common DEVS-based framework for modelling and simulation of spatially linked dynamic systems at the mesoscopic and microscopic levels. This approach provides the following main advantages:

- Common formalism for model definition and representation of geographical automata systems;
- Unified basis for the integration of systems modelling and computer visualization;
- Seamless component-oriented coupling and synchronization of simulation processes, visualization and user interaction.

An atomic V-DEVS model is defined as the following cortège:

$$AM_{V-DEVS} = \langle X, Y, S, \{RM_r\} \rangle, \quad (1)$$

where

$RM_{r \in \{meso, micro\}} = \{RM_{meso}, RM_{micro}\}$ is a resolution object model set containing DEVS sub-models of mesoscopic and microscopic levels;

$X = X^{meso} \cup X^{micro}$ is an input event set;

$Y = Y^{meso} \cup Y^{micro}$ is an output event set;

$S = RM_{meso}(S) \times RM_{micro}(S)$ is a set of sequential states as a Descartes multiplication of resolution object model states.

Each resolution object model RM_r is based on the classic atomic DEVS model structure (Zeigler 1976):

$$RM_r = \langle X, Y, S, \delta_{ext}, \delta_{int}, \lambda, ta \rangle, \quad (2)$$

where

$X = \{(p, v) \mid p \in InPorts, v \in X_p\}$ is a set of input ports and values;

$Y = \{(p, v) \mid p \in OutPorts, v \in Y_p\}$ is a set of output ports and values;

S is a set of sequential states;

$\delta_{ext} : Q \times X \to S$ is the external state transition function;

$\delta_{\text{int}} : S \to S$ is the internal state transition function;

$\lambda : S \to Y$ is the output function;

$ta : S \to R^{+}_{0,\infty}$ is the time advance function;

$Q = \{(s, e) \mid s \in S, 0 \le e \le ta(s)\}$ is the set of total states;

e is the elapsed time since the last transition.

Equations 1 and 2 provide a formal basis for event-based simulation at the mesoscopic and microscopic levels.

In Figure 1, a general dynamics of V-DEVS atomic model activity is depicted.

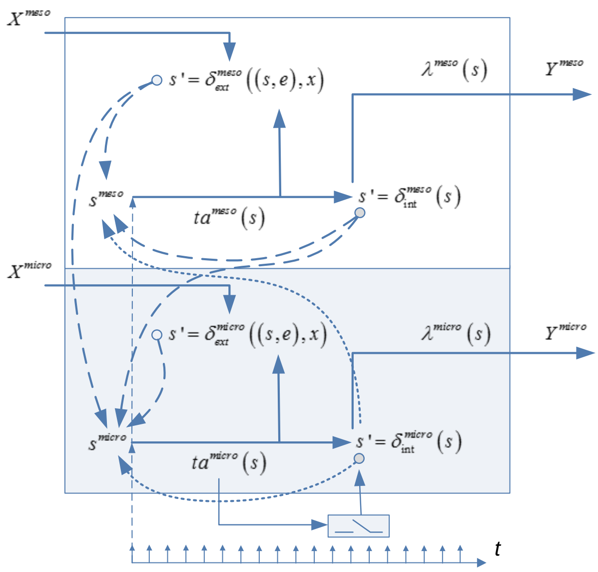

Figure 1: The Dynamics of V-DEVS Atomic Model

An important condition is time synchronization between the mesoscopic and microscopic V-DEVS parts and, therefore, the following inequality should be taken into account:

$$ta^{micro}(s^{micro}) \le ta^{meso}(s^{meso}), \quad (3)$$

if $ta^{meso}(s) \ne +\infty \wedge \delta^{meso}_{ext}(s, x^{meso}, e) \ne \varnothing$.

In the V-DEVS formalism, there isn't directly a confluent transition function defined, as is the case in the parallel DEVS formalism. If the model receives external events together with its internal state transition at the time moment $ta(s)$, then in the V-DEVS formalism a default confluent transition function is used in the same way as in the classical DEVS formalism (Zeigler 1984):

$$\delta_{conf}(s,x) = \delta_{ext}(\delta_{\text{int}}(s),0,x). \tag{4}$$

2.1.2. V-DEVS-Based Formalization of Geosimulation

To interpret geosimulation paradigm with the means of V-DEVS formalism, it is necessary to translate the corresponding geographic automata objects, relationships between them, and the rules of automata behaviour into V-DEVS elements (Equations 1, 2).

Each geographic automata is spatially positioned object, embedded in a GIS layer having a vectorial representation. Each such object can be specified as the following V-DEVS model:

$$AM_A = \left\langle X_A, Y_A, S_A, \{RM_{r_A}\} \right\rangle, \tag{5}$$

where

$S_A = \langle (x,y), VD_A, phase \rangle$ is a set of sequential states;

$(x,y) \in \mathbb{R}^2$ is object position;

VD_A is object dynamic state sub-set including direction, speed, acceleration;

$phase = \{'active', 'passive', 'moving', ...\}$ is the current phase of object dynamic behaviour.

3. FRAMEWORK IMPLEMENTATION

For a simulation to be useful for transportation analysis and planning, it must not only support a wide variety of features, but it must also be applicable to large-scale, real-world applications.

Public transport models developed with the implemented software prototype can be interactively explored in a multi-scenario mode within different simulation time intervals. Currently, the simulator supports two configurable simulation time modes regarding transit routes and trips used by transit operators during summer school holidays or school time.

The following list gives an overview of the main features of the developed transit simulation system prototype:

- Multi-modal simulation of regional and intercity bus and train traffic;
- GIS based infrastructure for spatial data processing;
- Graphical user interface for simulation data preparation, visualization and analysis;
- Interactive real-time simulation and visualization with possibilities of speeding-up the simulation runs by different time scales.

The simulation data preparation, network data visualization, simulation execution, vehicle movement animation and results analysis is managed through the graphical user interface (GUI) (Figure 2).

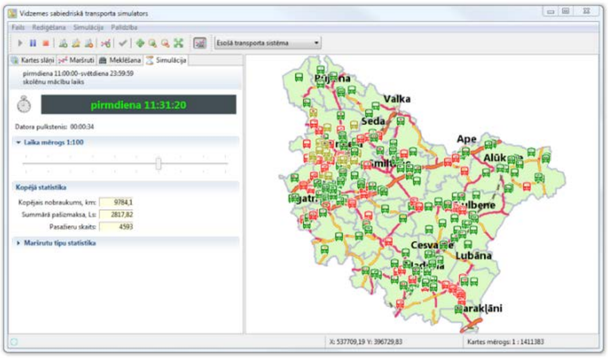

Figure 2: User Interface of Public Transport Simulator

3.1. System Architecture

In Figure 3, a general architecture of the developed public transport simulation system prototype is shown. The geosimulation system uses open source software components based on Java programming tools providing a unified development environment for different operating systems.

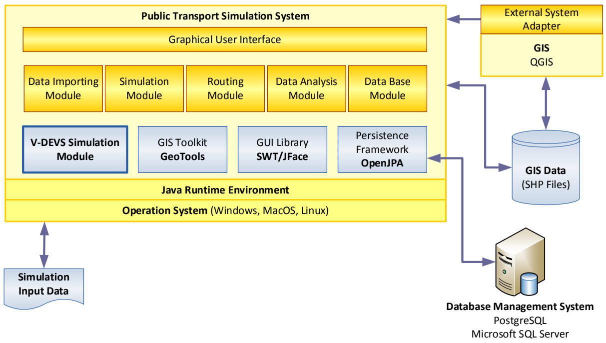

Figure 3: General Architecture of Public Transport Simulation System

For geospatial data processing, visualization and analysis the GIS toolkit called GeoTools (OGC 2014) is used. GeoTools is an open source Java GIS toolkit implementing many Open Geospatial Consortium (OGC) specifications including features for vector and raster data access available in different file formats and coordinate reference systems.

The system includes several integrated interactive analysis features:

- Assessment of route network traffic intensity;
- Assessment of public transport stops availability;
- Assessment of settlements accessibility.

3.2. Simulation Data

Each simulation run needs some initial data, which in the case of transportation simulation usually means a transportation network and the so-called “initial demand”. The initial demand describes the initial day plans of all simulated transportation system participants.

The model database contains both spatial and non-spatial data of different bus and railway routes. The route data are stored and processed in a combination with transit schedules, fares and vehicle types.

The transportation network is represented by nodes and links. The data that describe the simulated network is read from the spatial network database, which includes spatial definitions and related attributes of all the network objects. Nodes are either intersections of several roadways or points of road type change or public transport stops. Each node is represented by its type (intersection, public transport stop, etc.), and a unique identification number. Links are directional roadways that connect nodes. Each link is characterized by its type (freeway, urban street, railroad, etc.), an identification number, and starting and end nodes.

The non-spatial relational database contains 19 tables that store all the necessary information about public transit routes, trip schedules, transit agencies, vehicles, stop facilities, fares, planned passenger counts and transit time modes. For an universal object-relational access to different possible database management systems, the OpenJPA (The Apache Software Foundation 2014) data persistence framework is used.

3.3. Simulation Flow

The simulation flow starts with building of road network (Figure 4). The simulation environment contains a dedicated module that on the basis of the available GIS data automatically generates the network data in a file format necessary for the V-DEVS simulation engine.

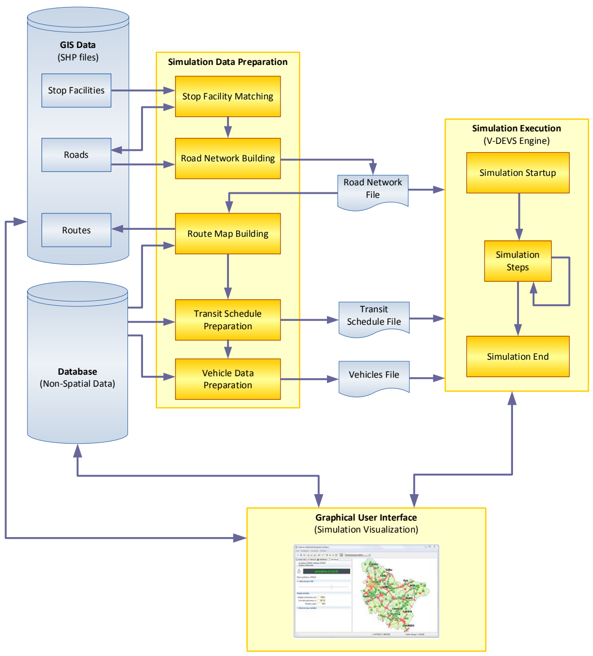

Figure 4: Data Preparation and Simulation Execution Steps

For public transit simulation purposes, the V-DEVS simulation engine requires three specific input files – road network file, transit schedule file and vehicles file. These files are automatically generated by the simulation system in the case when the spatial or non-spatial data that is stored in the database or in shape files is changed. This is the simulation data preparation process.

As previously stated, the road network is a graph consisting of links representing road segments and nodes representing road crossing or road type change point. Only a limited number of vehicles can leave a link per time step corresponding the flow capacity of a link. Nodes do not have a lot of internal logic – in each time step, the foremost vehicles of each incoming link are moved over the node to the next link in their route.

Also the public transport stop facilities are represented by nodes in the road network. Therefore a special module for the conversion of stop facility location data into network nodes is implemented.

3.4. V-DEVS Simulator

Within the proposed framework, a priority queue based V-DEVS simulator algorithm is implemented. The algorithm implements the processing of simulation cycles consisting of event simulation procedures at the mesoscopic and microscopic levels.

The implementation of the priority queue V-DEVS algorithm is based on the principles proposed by (Muzy and Nutaro 2005) and is built in such a way that the simulation efficiency in comparison to the hierarchical simulator algorithm can be improved with respect to the following aspects:

- Abandonment of unnecessary use of simulator and coordinator objects;
- Speed up of event scheduling by processing only active models;
- Abandonment of unnecessary use of internal synchronization messages;
- Abandonment of unnecessary use of event routing messages.

A Root Coordinator is used which executes the main simulation loop until the final simulation time is reached (Figure 5). The priority queue simulator algorithm uses only two simulators for all coupled and atomic simulation models (Figure 6). The processing of mesoscopic events implements the mesoscopic simulator, but the processing of microscopic level events implements the microscopic simulator. Both simulators use priority queue to store future events and are identical in structure. Such an implementation allows one to reduce substantially the overhead of message processing for simulation execution because instead of many coordinator and simulator objects, only two simulator objects are used for all atomic and coupled V-DEVS models.

4. PUBLIC TRANSPORT MODELLING APPROACH

The public transport model is hierarchically composed as a coupled V-DEVS model consisting of statically linked traffic dispatcher, vehicle, traffic monitor and traffic visualizer sub-models (Figure 7). The V-DEVS simulator models vehicles individually but does not represent lanes explicitly. The microscopic simulation level is used for modelling coordinate-based continuous movement of public transport vehicles.

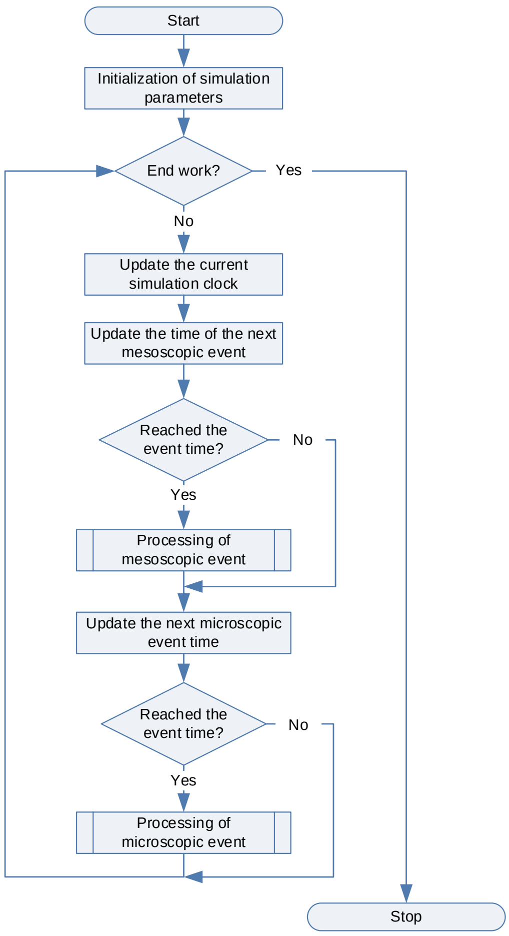

Figure 5: Base Algorithm of V-DEVS Simulator

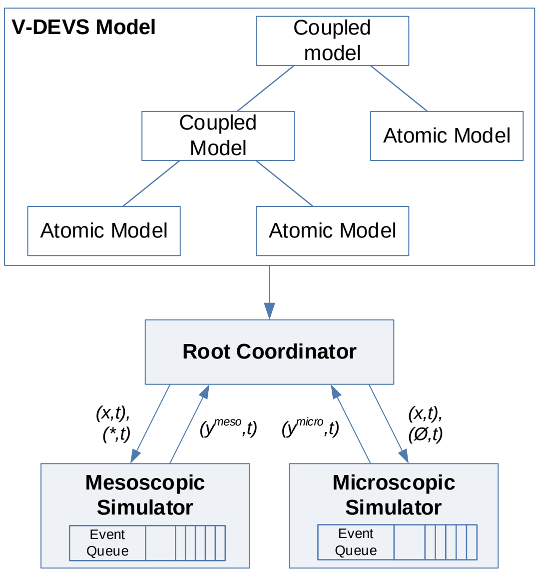

Figure 6: An Overall Architecture of Priority Queue V-DEVS Simulator

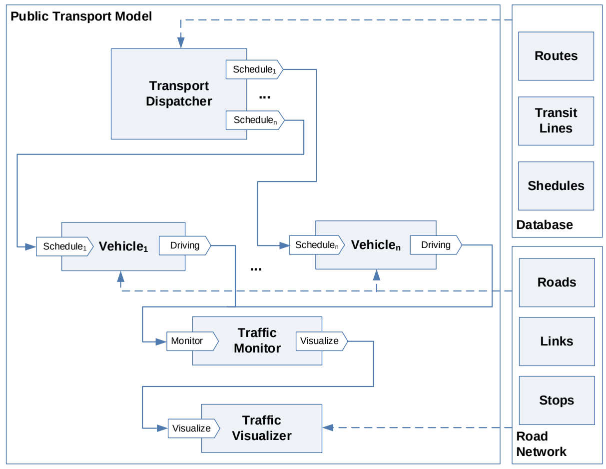

Figure 7: Public Transport Model

4.1. Transport Dispatcher Model

Transport Dispatcher is an atomic model that implements the mesoscopic part of V-DEVS formalism. Transport Dispatcher generates the initial transport demand describing the initial day plans of all simulated transportation system vehicles.

The Transport Dispatcher manages a list of scheduled trips, which allows explicit modelling of trip chaining. The vehicle arrival times are obtained according to the corresponding transit schedules, defined and stored in the trip schedule database table.

4.2. Vehicle Model

Vehicle is defined as an atomic V-DEVS model (Equation 5) that implements both mesoscopic and microscopic levels.

Public transport vehicles follow fixed routes according to a pre-defined timetable provided by the Transport Dispatcher Model.

At the start of the simulation, a list of the transit lines, transit schedules and public transport vehicles that are modelled is read and corresponding vehicle models are created and initialized. To each trip schedule is assigned a corresponding vehicle.

4.2.1. Vehicle Movement Modes

Public transport vehicles follow a fixed route through the network. In order to make the model more realistic, the vehicle moving state between bus stops is divided into three phases: accelerating, constant-speed traveling and decelerating (Figure 8). Three sequential mesoscopic events will be scheduled to model the traveling process, which includes ending acceleration, starting deceleration and stopping at a bus stop.

A vehicle that enters a link on its route checks whether there are stops to be serviced on this link. If there are no stops on the link, the link exit time is calculated at the mesoscopic level, and an event to enter the link is added to the mesoscopic event list. Link travel times are calculated on the basis of planned traveling time between nearest stops and link throughput (road surface type, speed constraints).

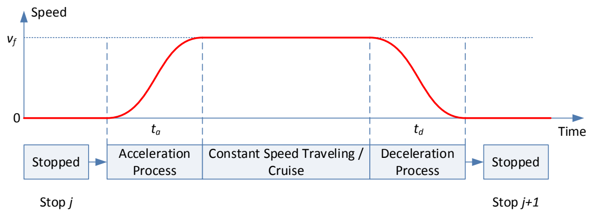

Figure 8: Vehicle Moving between Stops

Acceleration time t_a (in seconds) from a public transport stop implemented in the model is based on the one adopted in the (Akçelik and Besley 2001):

$$t_a = \frac{v_f}{a_{aa}}, \quad a_{aa} > 0 \tag{6}$$

where

v_f final speed in acceleration (km/h);

a_{aa} is average acceleration rate (m/s^2) calculated as follows:

$$a_{aa} = f_{aHV}\left[p_1 + p_2 PWR\sqrt{v_f} + \sqrt{PWR}\cdot p_3 - \right. \\ \left. -\left(p_4\sqrt{v_f} + p_5 Gr \right)/PWR \right]/3.6, \tag{7}$$

where

f_{aHV} is adjustment factor for heavy vehicle (bus) acceleration rates;

Gr is approach grade (%);

$p_1 \cdots p_5$ is acceleration model calibration parameters;

PWR is power to weight ratio calculated from:

$$PWR = 1000\cdot\frac{P_{\max}}{M_{HV}}, \tag{8}$$

where

$P_{\max}$ is maximum rated engine power;

M_{HV} is vehicle mass (kg).

Deceleration time t_d (in seconds) implemented in the model is based on the one adopted in the (Akçelik and Besley 2001):

$$t_d = -\frac{v_i}{a_{ad}}, \quad a_{ad} < 0, \tag{9}$$

where

v_i is initial speed in deceleration (km/h);

a_{ad} is average deceleration rate (m/s^2) calculated as follows:

$$a_{ad} = f_{dHV}\left[p_1 + p_2 PWR\sqrt{v_i} + \sqrt{PWR}\cdot p_3 - \right. \\ \left. -p_4\sqrt{M_{HV}} + p_5 v_i + p_6 Gr \right]/3.6, \tag{10}$$

where

f_{dHV} is adjustment factor for heavy vehicle (bus) deceleration rates;

$p_1 \cdots p_6$ are deceleration model calibration parameters.

Public transport vehicles stop at fixed points along the route to pick up and set down passengers. The stop time for a particular vehicle is sampled from a normal distribution using the mean stop time and deviation.

4.2.2. Passenger Flow Modelling

During the simulation, the vehicle model maintains updated passenger loads and determines crowding level, as well as the maximum number of passengers that can board at each stop.

Passenger flow is represented by the arrival rates at stops of passengers for each transit line and the demand to get off the bus at each stop. The public transport at a regional level is a relatively low-frequency service, therefore the passenger arrivals are assumed to follow a lognormal distribution (Cats et al. 2010):

$$B_{ijk} \sim Lognormal\left(\mu_{ijt_k}, \sigma_{ijk}\right), \tag{11}$$

where

B_{ijk} is the number of passengers wishing to board line i at stop j on trip k;

μ_{ij} is expected arrival time for line i at stop j;

σ_{ijk} is headway deviation on line i at stop j between proceeding bus.

The passenger alighting process is assumed to follow a binomial distribution (Morgan 2002; Cats et al. 2010):

$$A_{ijk} \sim Binomial\left(L_{ijk}, P_{ijk}\right), \tag{12}$$

where

A_{ijk} is number of alighting passengers from line i at stop j on trip k;

L_{ijk} is vehicle load on arrival at stop j on trip k of line i;

P_{ij} is the probability that a passenger on line i will get off the bus at stop j.

4.3. Traffic Monitor and Traffic Visualizer Models

Traffic Monitor model implements the mesoscopic and microscopic parts of the V-DEVS formalism. Traffic Monitor receives input events from moving vehicles and calculates the total statistics of the public transport system including total fuel costs, total passenger count, etc.

Traffic Visualizer is an atomic V-DEVS model linked with graphical user interface that receives and aggregates input events from moving vehicles and manages and synchronizes the interactive animation process of public transport simulation.

5. CASE STUDY

This section describes how the transport simulation was applied in the Vidzeme region in Latvia, detailing the steps for data preparation as well as for configuring and running the simulation. It then analyses the computational capabilities of the large-scale application, as well as estimates the optimization possibilities and enhancement directions of the regional public transport network.

The road network of the Vidzeme Planning Region that is dynamically generated from the available GIS data contains 137521 arcs and 62183 nodes.

The public transportation system of the Vidzeme Planning Region is characterised by the following statistical data:

- 2993 bus stops;
- 2173 bus stop facilities assigned to existing public transit routes;
- 33 railway stations and stops;
- 78 regional intercity routes;
- 222 regional local routes;
- 36 city routes;
- 316 regional intercity trips per working day;
- 1230 regional local trips per working day;
- 162 city trips per working day;
- >74 school bus trips per working day.

The presented study is primarily focused on the evaluation of public transport routes at the network level basing on the transportation social aspect.

5.1. Simulation Scenarios

One of the most important public transportation network efficiency indicators is the trip count per route during a working day or the route traffic intensity. The developed software system contains a module for assessing the route traffic intensity.

Another important indicator for assessment of the public transport quality is the public transport availability. Availability means that the public transport service is within a reasonable distance from where they are and where they want to be.

The performed analysis using the functionality of public transport availability calculation implemented in the simulation system, shows that 59 % of the Vidzeme region inhabitants in average are living within a radius of 2 kilometres from public transit stop facilities. This result is smaller than the public transport stops availability in other planning regions of Latvia. In Figure 9, the map of public transport availability buffer zones located at centres of stop facilities is shown.

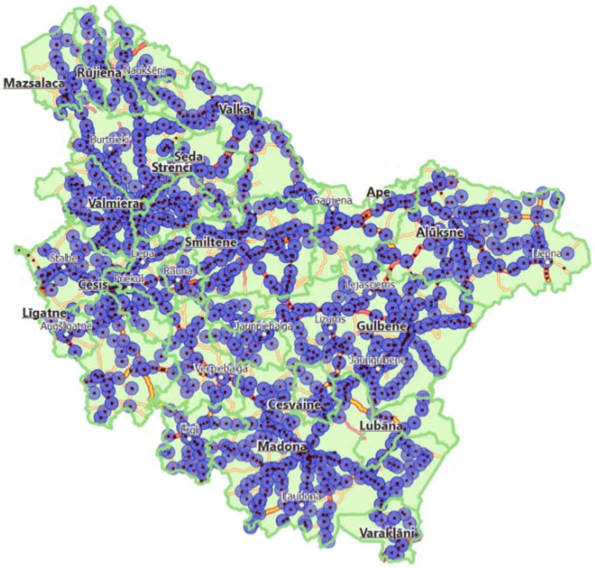

Figure 9: Map of Public Transport Availability in Vidzeme Planning Region

Accessibility is a key element to transport geography (Curtis and Jan 2008), since it is a direct expression of mobility either in terms of people, freight or information. Accessibility is defined as the measure of the capacity of a location to be reached by, or to reach different locations (Rodrigue, Comtois, and Slack 2009). Therefore, the capacity and the structure of transport infrastructure are key elements in the determination of accessibility.

The described simulation system calculates public transport accessibility in the terms of time necessary to reach a chosen destination. By combining the calculated stop facility availability data with public transport traffic intensity it is possible to estimate settlements accessibility time.

In Figure 10, the estimated average passenger count per working day in regional transit lines with largest transport intensity is shown.

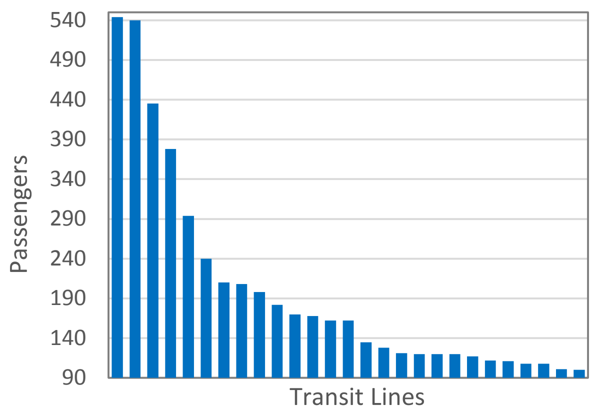

Figure 10: Estimated Average Passenger Count per Working Day in Regional Transit Lines with Largest Transport Intensity

5.2. Simulation-Based Optimization Possibilities

In the performed case study analysis, four optimization alternatives are defined. The initial alternative is to use the existing public transport infrastructure without any changes. The second alternative is related to the improvement of the roads quality and the public transit network density. The third alternative is to increase the count and diversity of public transport vehicles.

During the development of public transit geosimulation system there are performed optimization experiments and scenarios on the basis of the fourth alternative that is related to the improvement of the multimodal public transport infrastructure. This includes the coordination of the railway and bus traffic, planning of the public transport stops layout, modification of the existing routes and optimization of the vehicle trips count. The main goal of the proposed optimization scenarios is to fulfil the social aspect of public transport.

The first proposed optimization scenario is related to the adaptation of the public transport capacity to the number of passengers. The performed data analysis and simulation experiments have shown that in Vidzeme region there exist 166 regional trips of local importance exist where the expected number of passenger per a trip is less than 25. Therefore in these trips it is possible to use buses with smaller capacity and at the same time with smaller fuel consumption (Table 1).

Table 1: Estimated Fuel Consumption Costs For 7 Working Days

Scenario	Costs (EUR)	Cost Savings (%)
Initial alternative: Buses with consumption of 30 l/100 km usage	114,091	-
Buses with consumption of 25 l/100 km usage	107,005	6.2%
Buses with consumption of 20 l/100 km usage	99,908	12.4%

The second optimization scenario is to increase the trip count in routes where the existing trip count per working day is smaller than 2. In the model there are added 18 new trips on 293 bus route kilometres, thus improving the quality of public transport support in these road segments (Figure 11).

The third possible optimization scenario is to improve the accessibility of the region cities by decreasing the stops count within the existing trips. By decreasing route stop count per a trip and at the same time by increasing the distance between stops from 4 to 6 kilometres on average it is possible to improve the accessibility up to 10 %. This alternative can be practically implemented in a real life by using partly express buses.

6. CONCLUSIONS

In this paper, a new DEVS-based simulation framework for multi-modal public transport analysis and planning is presented. The implemented framework is approbated in the Vidzeme Planning Region of Latvia providing a novel solution in the context of regional transportation planning in Latvia. The developed solution is considered as a useful tool in assisting decision-makers in development planning allowing the evaluation of alternative public transit scenarios and planning options.

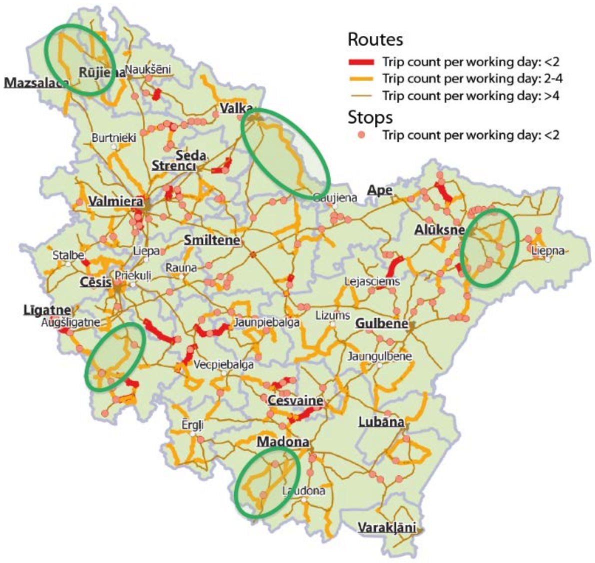

Figure 11: Map of Public Transport Availability and Optimization Possibilities in the Vidzeme Planning Region

The future of the proposed simulation system will include an increasing level of dynamics and accuracy of the modelled transportation infrastructure. The application of modern Web technologies will expand the availability of the public transport simulation to a wide area of users with different knowledge, skills and experience.

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