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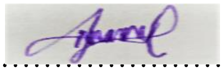
Writer: Fitsum Asrat Zemedkun	 ………………………………………… (Writer's signature)

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Assessing Bus way Operation for City Transportation System using Simulation Approach

By

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Abstract

Public bus transportation service has a significant benefit in society's daily life by facilitating a more natural movement way from place to place. To provide a punctual and a shorter travel time service, Stavanger municipality had a plan to change mixed-traffic bus routes into bus rapid transit systems in the Rogaland area. However, complicated zoning plans and cost cuts have made the BRT infrastructure project subject to several changes along the way. Due to these changes and uncertainties regarding possible decisions on a future solution for the remaining infrastructure projects, the mobility provider company becomes unreceptive to their future service.

Therefore, the purpose of this thesis is to make an assessment and demonstrate the effect of different parameters on the BRT system's future operation. The effect is measured in terms of bus frequency, travel time, and the number of buses needed for various scenarios in the network. A combination of agent-based, system dynamic, and discrete event simulation model is developed using AnyLogic simulation tool. The route between Stavanger and Sandnes, with an arm to ForusNord has chosen as the model case study. In addition to the reference model, three different scenarios are built.

The findings showed that the punctuality was about 70%, with 31% bus bunching if the routes operate in a full BRT system. When there is a change in the system and buses have no priority in only two roundabouts, the bus punctuality degrades by 14%, and bus bunching increases by about 11%. Also, the result showed a rise of approximately 18% and 20% in travel time for buses operating in route2 and route3 if only the first 2.18Km of the route is operated in mixed traffic. Furthermore, the findings indicated an improvement in punctuality and bus bunching with an increase in bus rate.

This thesis provides an insight into the possible effect of the changes made on parts of the BRT system in terms of the relationship between bus frequency, travel time, and bus rate. Thus, it can be used to support decision-making on planning and optimizing the bus transportation system's future operation.

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"…and whatever you do, whether in word or deed, do it all in the name of the Lord Jesus, giving thanks to God the Father through him." Colossians 3:17

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List of abbreviations

BRT	Bus rapid transit
SD	System Dynamic
DEM	Discrete Event Model
Min	Minute
Km/Hr.	Kilometer per Hour
Stavangerhpl10	Stavanger holdeplass10
Bus2R1S1	Bus2Route1Station1
Bus2R1S2	Bus2Route1Station2
Bus2R1S3	Bus2Route1Station3
Bus2R1S4	Bus2Route1Station4
Bus2R1S5	Bus2Route1Station5
Bus2R1S6	Bus2Route1Station6
Bus2R1S7	Bus2Route1Station7
Bus2R1S8	Bus2Route1Station8
Bus2R1S9	Bus2Route1Station9
Bus2R1S10	Bus2Route1Station10
Bus2R1S11	Bus2Route1Station11
Bus2R2S1	Bus2Route2Station1
Bus2R2S2	Bus2Route2Station2
Bus2R2S3	Bus2Route2Station3
Bus2R2S4	Bus2Route2Station4
Bus2R2S5	Bus2Route2Station5
Bus2R2S6	Bus2Route2Station6
Bus2R2S7	Bus2Route2Station7
Bus2R2S8	Bus2Route2Station8
Bus2R2S9	Bus2Route2Station9
Bus2R2S10	Bus2Route2Station10

Bus3R1S8	Bus3Route1Station8
Bus3R1S9	Bus3Route1Station9
Bus3R1S10	Bus3Route1Station10
Bus3R2S1	Bus3Route2Station1
Bus3R2S2	Bus3Route2Station2

1. Introduction

A reliable public transport system has a pivotal role to play in city life. Implementing quality transportation enhances social relevance and people's lives by creating viable access to their day-to-day destinations. Besides, with growing concerns about net carbon reduction and cutting of the emissions, the ease of availability of reliable will contribute to decreasing the greenhouse effect by reducing the number of private car usage. Therefore, the public transportation sector needs to persuade people to use bus transportation as their primary means of travel. Customer trust increases if the bus services are punctual, and it avoids taking the longest route, which increases the travel time considerably.

To provide punctual service, it is essential to prioritize bus service in the roadways, for example, in case of roundabouts, which is not very easy unless there is a particular lane dedicated to the rapid bus transport. Therefore, mobility service providers who operate in the transportation industry often need to model and visualize their service operation. This need for modeling and testing the whole bus operation increases with adding new connections or introducing new routes, infrastructures, and the change in the operating system. Bottlenecks, route capacities, and the distribution of delays must be defined and measured before a decision is made, and action is taken. The solution can find by making an assessment using a simulation modeling approach.

In the following subsections, background and problem presentation, the study problem, objective and relevance, the methodology used, the delimitation, the project time frame, and the full structure of the thesis are described in detail.

1.1.Background and problem presentation

The municipality of Rogaland agreed that a corporation, called Kolumbus, which was previously in charge of bus and boat operation, became a mobility company in June 2017, this means that Kolumbus is responsible for the boat and bus traffic in Rogaland. To optimize their service and simplify the movement of people to their destination without driving their own vehicle, Kolumbus is working on linking trains, motorcycles, biking, and car-sharing effortlessly with buses and boats (Kolumbus, 2019).

Kolumbus owns a total of 450 buses, 10-speed boats, and three ferries operated by firms that work under contract with Kolumbus to make 85,000 daily journeys from Monday to Friday.

Moreover, Kolumbus is working hard to fulfill its goal, creating a better Rogaland by providing green transport by 2024 (Kolumbus, 2019).

Rogaland municipality initially had a plan to implement a full busway system throughout Rogaland. The plan includes upgrading part of the existing route and construction of a new path. However, due to political reasons, part of the project has been decided to be operated in mixed traffic. Due to such changes and uncertainties to political decisions on future solutions for the remaining infrastructure projects, it is essential to analyze and illustrate what kind of impact different parameters can have on future operations of the BRT (Bus Rapid Transit) system.

1.2. Research problem and relevance

Kolumbus is interested in the assessment of the system to cover the following issues of interest:

- The "Korridor 1" infrastructure is initially planned as a dedicated lane for the buses with bus priority through crossings, traffic light, and roundabouts. What would be the effect if parts of the lane system change from a dedicated bus lane to mixed traffic? The result can be presented in terms of total travel time and bus frequency at the selected bus stop.
- All the buses in both lines are supposed to have a timeframe of 3-4 minutes between them. If dedicated lanes are used, how many buses will be required to operate Korridor 1, given the currently planned frequencies, routes, and infrastructure?

The outcome of the model has practical relevance to Kolumbus by providing a way to visualize different scenarios and assess constructed routes and part of the routes that are not yet built. Besides, this work can be further extended and applied for a broader analysis of the BRT system.

1.3. Research Objective

The thesis aims to investigate the impact of the latest decision on the operation of the rest BRT system by adopting a simulation approach and using AnyLogic tool, which will provide a useful perception of changes in travel time and frequency and number of buses required in the system for various scenarios.

This work analyzes the effect of various factors for bus operation and assesses the system by taking various delay factors into account. The analysis also investigates the impact of supporting bus priority in roundabouts and traffic lights. In addition, the effect of running two bus lines in the same Korridor is studied.

1.4.Methodology

During this thesis, different research methods are conducted to solve the research problem and achieve the objective. The author has applied in-depth reading and selected study route visiting to get enough understanding of the problem domain. Several discussions with the case company contact person are carried out to fully comprehend the chosen route, clarify the study requirement, and delimit the work scope. In addition to the process of defining the problem, previous literature has been reviewed. After conducting the above procedures, the required data were identified, collected, and analyzed. The data were collected majorly from the company, GIS map, and further filtering and conditioning are performed to get meaningful data for the model.

Since the problem under study involves a complex system with GIS route, bus operations, and various route delays, a simulation-based approach is found best suited to solve the research problem. In general, simulation helps analyze the result of different scenarios and allow adjustment of system behavior if needed. In this study case, modeling and simulation are performed using AnyLogic tool, which supports various alternatives to create simulation models such as a discrete event, system dynamic, and Agent-based modeling. In addition, the tool allows for mixed modeling methods (The AnyLogic Company, 2020). Moreover, AnyLogic has a built-in library to visualize object movements, geographical points, and provide statistical analysis tools.

1.5.Scope of the thesis

Kolumbus is responsible for the entire public transportation in Rogaland, and it will be vast to implement a simulation model for the whole system. Therefore, it is proposed to narrow the scope of the Master thesis down to specific routes of the BRT system, which is the largest and a very topical project in Bymiljøpakken. The originally planned 50 km Bussveien BRT infrastructure project has been divided into four "Korridors" with priority from 1 to 4. This thesis focuses on Korridor 1, representing the highest priority, which has two high-frequency routes that connect Stavanger with Sandnes with an arm to Forus. Korridor 1 is scheduled to open in the second half of 2023. It has two lines that connect Stavanger to Sandnes, and Stavanger to Forus, and runs in both directions. Part of these routes shares common paths and bus stops. The line from Stavanger to Sandness is run by bus number 2, and the line from Stavanger to Forus is serviced by bus number 3.

"Korridor 1" infrastructure was initially planned for providing dedicated lanes for the buses and bus prioritization in crossings. However, due to complicated zoning plans and cost cuts in the project, the Busway infrastructure project in Korridor1 is subject to changes.

1.6. Project plan

Table 1 shows the tasks and their expected deadline for completing this thesis.

Table 1. Project Schedule

		Feb.		March				April				May				June				July	
	Week#	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Task No.	**Task discription**																				
1	Planning																				
2	Problem formulation including literature review																				
3	Theoretical Frame work and background																				
4	System Analysis																				
5	Data collection																				
6	Conceptual modelling																				
7	Computational modelling																				
8	Scenario modelling																				
9	Verification and Validation																				
10	User Interface development																				
12	Deadline for first submission																				
13	Thesis revision and completion																				
14	Final submission to university																				

1.7. The structure of the thesis

The thesis structure outlines the content of each section. This thesis has seven main sections, which are structured as follows: In the first section, the context of the study problem is defined, and the relevance of the thesis is highlighted. Furthermore, this section includes a description of the methodology used, limitations, delimitations, and the research framework. The second section discusses the related work reviewed, the modeling choices made, and the design of the thesis. The data that is collected and analyzed is described in section three. Based on a case study, detailed system analysis is presented in the fourth section. In section five, computational modeling is discussed. The simulation model that is implemented in the computational modeling is presented in section six. Different scenarios, model verification/validation, and user interface development are discussed in sections seven, eight, and nine, respectively. The study findings are presented and discussed in the tenth section. Lastly, the author concludes this study in section eleven and briefly discusses the conclusion and possible future works.

2. Research methodology and design

This section goes through literature review, methodological approaches that the author applied to the thesis and data collection.

2.1. Literature review

Public bus transportation service plays a vital role in mobilizing people in the community and facilitating travel in cities and municipalities. Public transport sectors need continual optimization of their operation to be predictable and keep high passenger satisfaction. However, various factors can influence the transport service quality. Napiah and Kamaruddin (2011) indicated long waiting periods at bus stops and reduced bus occupancy are the key issues that bus passengers and operators faced. These factors contribute to the poor performance of the urban bus transport system; Thus, people don't choose it as a primary mode of transportation.

Other works from Van der Spek et al. (2017) provided insights into bus operation disturbance by various factors such as traffic jams, traffic light, and passengers loading and unloading, as well as its effect on travel times on the bus route between the towns of Leiden and Zoetermeer. Besides, Wilson (2017) utilized South Africa's rail network as a study case. He showed other factors, such as the mixed operation of old and new trains in the same infrastructure, that pose various operation challenges. Punctuality measurement is crucial in the bus schedule refinement steps, as it is highly correlated with the reliability of the bus transport system and satisfaction of service users.

A study by Yaakub and Napiah (2011) assessed bus operations efficiency using punctuality index, which is one of the performance metrics in regulating reliability or the ability to deliver service as scheduled. Napiah and Kamaruddin (2011) addresses the timeliness and estimated travel time for buses running on an 82,6 km mixed-traffic bus route. The paper assessed and evaluated the timeliness of bus service in mixed traffic, the time of waiting for passengers, and evaluate the punctuality of bus operation characteristics for specific traffic conditions. Tubis and Gruszczyk (2015) presented the influence of selected factors on the trip duration and the frequency of deviations from the timetable. Also, Wilson (2017) followed a simulation approach using AnyLogic. Wilson built a discrete event model to assess other factors that can affect the reliability of the system, in terms of timeliness, such as gradual replacement of the old trains with new trains, by analyzing the number of delays over a defined period.

As mentioned earlier, the complex nature of transportation service requires solutions to assist in operational decisions and actions. Tubis and Gruszczyk (2015) highlighted that bus service providers need means to evaluate the quality of operation, to facilitate an analysis of factors influencing the trip duration and examine the deviations from plans.

The recent advancement in technology has opened new opportunities for computer-based simulation techniques for complex systems such as transport operations. Nikolaev et al. (2017) used an AnyLogic simulation model to assist informed decisions of city transportation. The simulation is developed using a discrete event-based model, with GIS mapping for visualization, providing simulation results that help users to draw conclusions for bus operation planning. The article by Van der Spek (2017) demonstrated a model for the high-frequency bus route in the Netherlands, which can help change bus routes or adjust travel times ahead of time. The model was developed by a combination of agents, and event-based models demonstrated that it could simulate realistic scenarios based on specific model assumptions.

This paper also follows a simulation model approach using AnyLogic software to assess the busway operation for city transportation systems applied to specific routes in Stavanger city.

2.2. Methodology and Design

2.2.1. Simulation and modeling approach

It has been several years since modeling and simulation have become a preferable approach in modeling complex systems such as transportation systems. In such a complicated problem situation, a simulation approach can be very effective by providing evaluations for different traffic conditions (Papageorgiou,2007). Apart from other research approaches, such as those using Excel or linear programming, modeling, and simulation, provide the ability to evaluate the model as it runs. Unlike physical modeling, simulation modeling is computer-based, using algorithms and equations. Simulation software offers a complex environment in which computer models can be studied while running (The AnyLogic Company, 2020). Besides, modeling simulation addresses real-world problems securely and efficiently. It offers an essential analytics approach that is easily checked, communicated, and interpreted. Simulation modeling provides valuable opportunities across industries and disciplines by offering simple insights into complex processes. Simulation permits experimentation on a system 's accurate digital representation (The

AnyLogic Company, 2020). Moreover, simulation modeling provides a visualized output expedite communication and assists decision-making in the planning and management of projects before the proposal is implemented (Nikolaev, 2017).

The fact that the simulation modeling method is an excellent way to study physical and operational behavior, as well as the impact of specific systems involving delays (El-Thalji, 2019), the methodology is preferred to apply for this thesis. Even though various software tools are available, AnyLogic is the most preferred software because it supports users to utilize agent-based system dynamics and discrete event simulation methods seamlessly (The AnyLogic Company, 2020). Most importantly, the tool provides help, tutorial, and library reference guides that aid users in utilizing the tool. Since the author of this thesis considers a multi-method simulation using, AnyLogic software is the right choice to implement on answering the problem on hand.

2.2.1.1. Discrete event model

A discrete event simulation model simulates systems that operate as a series of separate, discrete events in which the system situation changes. Every event occurs in a specific moment and marks a shift in the system condition (Robinson, 2014). Using a discrete event simulation approach, the motion of a moving system from point A to point B can be simply modeled using two different model events that represent a departure and an arrival. The actual movement would be modeled as a time delay between points A and B. Such events and the transition from point A to point B can be smoothly animated (The AnyLogic Company, 2020). AnyLogic Process modeling library supports the creation of a precise discrete-event model. Figure 1 shows some of Process Modeling Library Blocks and their descriptions used during the simulation of discrete events.

Block name	Process Modeling Library Icon	Description
Source		Generates the entities and adds them to them to the process
Sink		Disposes of the entities leaving the model
Queue		Stores entities that cannot move forward in the process immediately
Delay		Delays the entities from moving forward in the process
ResourcePool		Defines and stores the resource unit(s) of a certain type
Seize		Assigns some resource units to the entities passing through; contains an embedded queue
Release		Releases one or more resource units seized by the entity that's passing through it
Service		The block is a combination of three inner blocks: Seize, Delay, and Release that simplifies modelling common processes
SelectOutput		Separates the entities into two groups either probabilistically or based on a condition

Figure 1. Process Modeling Library Blocks (Mahdavi, 2019)

2.2.1.2. System dynamics model

System dynamics is also one of a robust method of modeling that helps to construct systematic computer simulations of complex systems. Unlike Discrete event and Agent-based models, System dynamics is rather an abstract modeling method that provides a broad view of a complex system. Such simulation models can be used for long-term, strategic simulation models and assume a high aggregation level of modeled objects. Implementing causal loop charts, flow charts, and differential equations, SD (System Dynamic) models, represent phenomena in the real world (The AnyLogic Company, 2020).

2.2.1.3. Agent-based model

Agent-based modeling is centered on the single active components of a system. In agent-based modeling, individual agents that could be, for instance, cars, machinery, people, or companies, should be identified and their actions described (The AnyLogic Company, 2020). The use of agent-based models involves a decentralized nature of the problem, where each agent acts within their specific environment according to their objectives. Generally, such behaviors obey basic laws, but they may also be more complicated. Then the system 's global dynamics arise from agent actions and interactions (Jennings,1999). Agent-based modeling is the most recent of the three methods that can be easily combined with simulations of discrete events or system dynamics components (The AnyLogic Company, 2020).

2.2.1.4. Multi-method simulation approach

It is evident that many real-world systems are complex, so explaining the various parts of a system using different approaches is requires. A Multimethod simulation model provides a solution for such requirements by allowing seamless integration of different modeling and simulation methods in a single platform. In addition, a multimethod approach eliminates the shortcomings of individual approaches and to get the most out of each approach. Moreover, combining multiple methods simultaneously gives the flexibility necessary to solve a problem successfully and ensure that models are efficient and manageable without using workarounds (The AnyLogic Company, 2020).

3. Data Collection

It is essential, first, to describe how the required data is collected and explain the data that is utilized to build the model before going into the model itself in detail. This gives an insight into some of the limitations and assumptions that are being made about the model (Van der Spek et al. (2017). In addition, in this section, the author describes the steps taken to pre-process the used data.

Data collection is done mainly from the case company, Kolumbus. The data obtained from the company are GIS point coordinates of bus stops, average loading/alighting time of bus number 2 and 3, at the bus stop, which is collected between 01.01.2020 and 01.02.2020. The sample was taken at 7:00 AM and 12:00 AM that represents the rush hour and non-rush hour traffic time, respectively. In addition to the route maps, the company provided combined zoning plans for Line 2. This information makes it easier for the author to visualize and build the model.

Additional data is collected from the Kolumbus and Statenvegevesen website, as well as roundabouts, traffic lights, and pedestrian crossing counts are extracted from GIS map.

3.1.Loading/unloading Time

Table 2 presents passengers loading and unloading delays to all bus stops on route-2 (Line-2). As described above the time sample was collected for about a month at peak hours (7:00 AM).

To simplify the simulation model, the loading/unloading time presented in Table 2 is processed to suit the model and shown in Table 3.

Table 4 presented the average time taken by the bus to loading and unloading of passengers at selected bus stops for route-2 (Line-2). Likewise, the off-peak hour loading/alighting time data collected for route 2, as well as the peak hour and off-peak hour loading/alighting time of route 3 are adjusted and presented below in Table 3,

Table 4, and Table 5respectively.

Table 2. Peak-hour Loading/unloading delay for bus 2.

BusStop	Loading/Unloading Time (Min)	BusStop	Loading/Unloading Time (Min)	BusStop	Loading/Unloading Time (Min)
Stavanger hpl. 10	1.667	Sørhallet	0.217	Midtbergmyrå	0.200
Stavanger politistasjon	0.217	**Vaulen**	0.083	Løwenstrasse	0.250
Statens hus	0.183	Nålestien*	0.183	Jakob Askelands vei	0.217
Vålandsbakken	0.133	**Jåttåflaten***	0.183	Porsmyrveien	0.267
Lindahlsbakken	0.200	StadionParken*	0.183	**Kvadrat holdeplass 1**	0.250
Strømsbrua	0.267	**Jåttåvågen***	0.183	Seljeveien*	0.183
Hillevågstunnelen	0.217	Gauselvågen	0.283	**Lerkeveien ***	0.183
Hillevåg	0.250	**Gausel sentrum**	0.250	Lurastoppen *	0.183
Kvaleberg skole	0.283	Gauselhagen	0.117	**Altona1***	0.183
Sjøhagen	0.250	Gausel stasjon	0.300	Altona2*	0.183
Eikeberg	0.283	Gamle Forusveien	0.200	Altona3*	0.183
Mariero	0.283	Nådlandsbråtet	0.183	**Sandnes hlp.16**	0.817
Lyngnesveien	0.200	**Forusbeen**	0.167		

Table 3. Average Loading/unloading time of bus 2 at selected bus stops at peak hour.

Selected Bus Stop	Average Loading/Unloading Time (Minute)
Hillevåg	3.133
Mariero	1.100
Vaulen	0.500
Jåttåflaten*	0.367
Jåttåvågen*	0.367
Gausel sentrum	0.533
Forusbeen	0.967
Kvadrat holdeplass 1	1.183
Lerkeveien*	0.367
Altona1*	0.367
Sandnes	1.183

Table 4. Average Loading/unloading time of bus 2 at selected bus stops at an off-peak hour.

Selected Bus Stop	Average Loading/Unloading Time (Minute)
Hillevåg	4.25
Mariero	0.833
Vaulen	0.500
Jåttåflaten*	0.367
Jåttåvågen*	0.367
Gausel sentrum	0.367
Forusbeen	0.750
Kvadrat holdeplass 1	0.900
Lerkeveien*	0.367
Altona1*	0.367
Sandnes	1.550

Table 5. Average Loading/unloading time of bus3 at selected bus stops at peak hour and off-peak time

Selected Bus2 Stop	Average Loading/Unloading Time (Min)
Hillevåg	3.217
Mariero	0.883
Vaulen	0.467
Jåttåflaten*	0.367
Jåttåvågen*	0.367
Gausel sentrum	0.417
Forusbeen	0.750
Forusøst	0.267
Tvedtsenteret	0.417
Forusnord	0.800

Selected Bus3 Stop	Average Loading/Unloading Time (Min)
Hillevåg	4.883
Mariero	0.933
Vaulen	0.450
Jåttåflaten*	0.367
Jåttåvågen*	0.367
Gausel sentrum	0.350
Forusbeen	0.633
Forusøst	0.233
Tvedtsenteret	0.383
Forusnord	1.050

Note that bus stops names that have a star (*) sign refer to bus stops that are positioned on the unconstructed.

3.2. Travel Time

Travel time between two successive bus stops is calculated as a function of average bus speed and the distance traveled, using the well-known time, distance, and speed relationship,

$$T = 60 * \frac{S}{V}$$

Where T stands for Travel time in minutes, S represents distance in Kilometer, and V is the average speed in Kilometer/Hour.

The distance is extracted from AnyLogic built-in route length method. For example, the distance (km) between Stavanger and Hillevåg bus stops is calculated as,

$$\frac{\boldsymbol{Bus2R1S1.length}()}{\mathbf{1000.0}}$$

Where Bus2R1S1: route name between Stavanger and Hillevåg on GIS map.

Table 6 and Table 7 lists distance and travel time of route segments between selected stops, for bus2 and bus3 routes, respectively.

Table 6. Distance and travel time (route 2)

No.bus stop	Route between stops	Distance between bus stops (Km)	Speed(Km/Hr)	Travel time (Min)
1	Stavanger h.pl-10 to Hillevåg	2.181	50	2.617
2	Hillevåg to Mariero	1.634	50	1.961
3	Mariero to Vaulen	0.884	50	1.061
4	Vaulen to Jåttåflaten*	1.000	50	1.200
5	Jåttåflaten* to Jåttåvågen*	0.820	50	0.984
6	Jåttåvågen* to Guasel Sentrum	0.606	50	0.727
7	Guasel Sentrum to Forusbeen	2.411	50	2.893
8	Forusbeen to Kvadrat	1.768	50	2.122
9	Kvadrat to Lekeveien*	0.806	50	0.967
10	Lerkeveien* to Altona1*	1.701	50	2.041
11	Altona1* to Sandnes	1.381	50	1.657
	Sum	**15.192**		**18.23**

Table 7. Distance and travel time (route 3)

No.bus stop	Route between stops	Distance between bus stops (Km)	Speed(Km/Hr)	Travel time (Min)
1	Stavanger h.pl-10 to Hillevåg	2.181	50	2.617
2	Hillevåg to Mariero	1.634	50	1.961
3	Mariero to Vaulen	0.884	50	1.061
4	Vaulen to Jåttåflaten*	1.000	50	1.200
5	Jåttåflaten* to Jåttåvågen*	0.820	50	0.984
6	Jåttåvågen* to Guasel Sentrum	0.606	50	0.727
7	Guasel Sentrum to Forusbeen	2.411	50	2.893
8	Forusbeen to Forusøst	0.881	50	1.057

9	Forusøst to Tvedssentret	1.505	50	1.806
10	Tvedssentret to Forusnord	1.124	50	1.349
	Sum	**13.046**		**15.655**

4. System Analysis

System analysis is carried out for the sake of analyzing the chosen system to provide a clearer understanding of the subject.

4.1. Case study

The Bus Rapid Transit System is part of the Urban Environment Programme and one of Rogaland's main transportation projects. Rogaland municipality owned the project, and the Norwegian Public Road Administration directs the plan and construction of the route. The project is one of the leading projects in the Rogaland area, and it will be 50 kilometers long with 22 stretches, which makes it the longest bus route in Europe. The BRT project aims to enhance the bus transportation system by providing maximum access to the bus traffic so that there will be no delay. The bus route should be reliable, efficient, and attractive, so people prefer to travel by bus instead of driving a car. This will reduce the number of car users and greenhouse emissions (Bussveien | Statens vegvesen, 2019). This thesis focuses on assessing part of the BRT system, called Korridor-1, which is stretched from Stavanger to Sandnes with an arm to Forus nord, in Stavanger.

4.2. System Context

A system context diagram in Figure 2 shows the relationship and interaction of the public transportation system with the consumer need, the resource required to operate the system, the restraints, and the system that will respond to a consumer need.

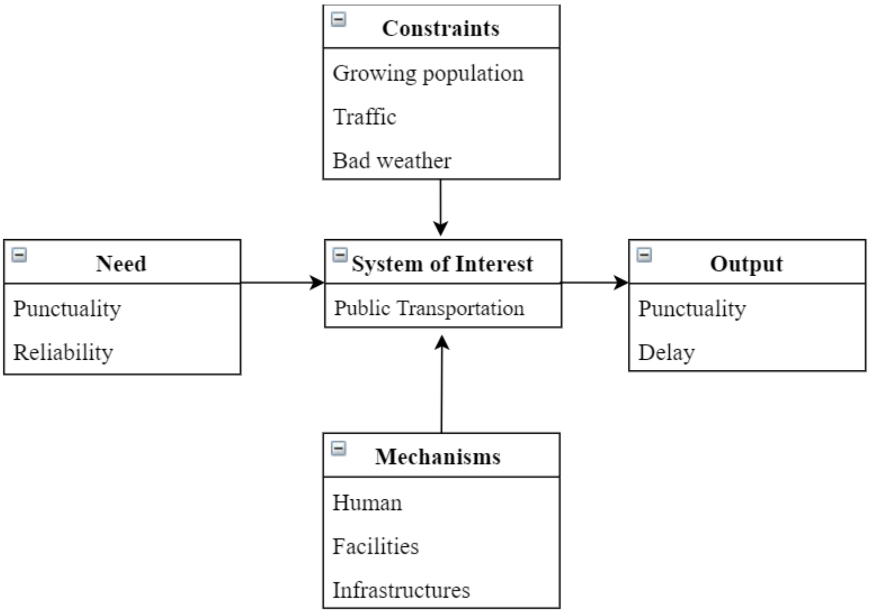

Figure 2. System Context

Major elements that interact with bus transportation are shown in Figure 3.

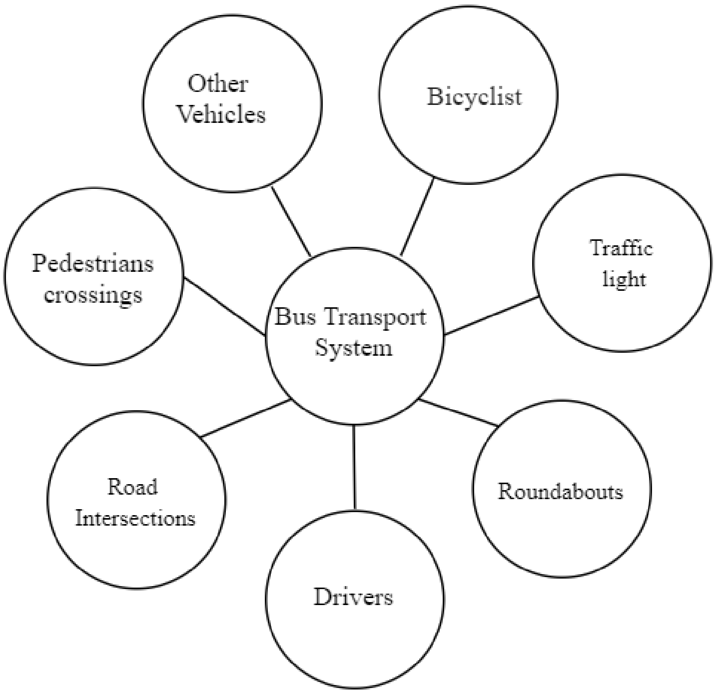

Figure 3 Major elements of the bus transportation system

4.3. System Content

The Korridor-1 network is about 20 km long in total, and bus2 and bus3 share approximately 10 km of the route. It includes two lines, with 73 stops in total, and 26 stops are shared. After the entire construction of the network, 72% of the route will be a dedicated bus lane, and the remaining 28% will be a separately owned route. The dedicated bus lanes are situated in the middle of other traffic lanes. Both route types allow buses to avoid traffic jams (Bussveien | Statens vegvesen, 2019). Figure 4 shows Korridor-1 network for bus2 and bus3 route on a GIS map. Note that some of the routes are already built, while part of the road is not constructed yet.

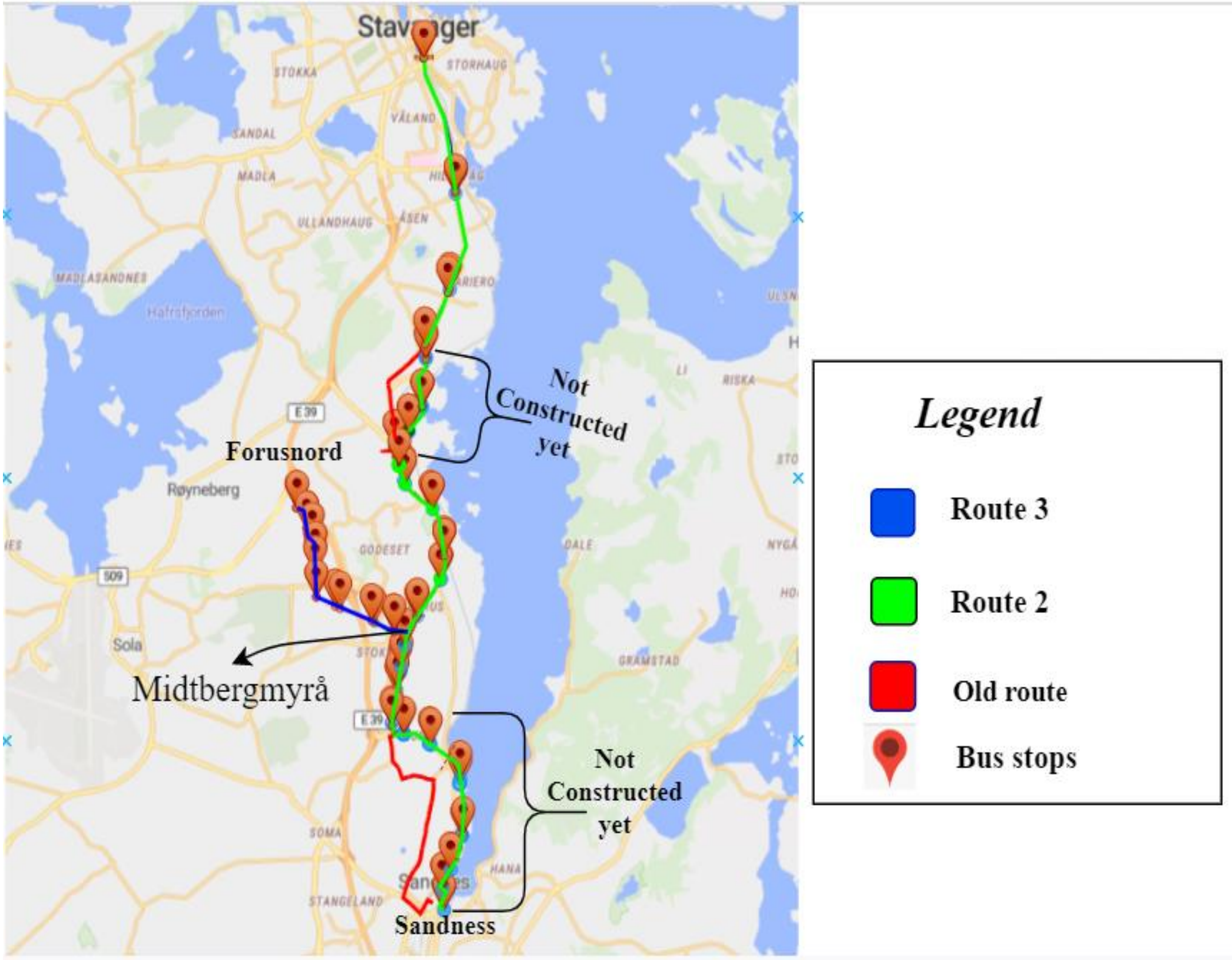

Figure 4. GIS map, Korridor-1 routes

When all the BRT system is implemented, buses will have full priority in intersection, roundabouts and at a traffic light control so that it results in a predictable travel time and bus frequency (Bussveien | Statens vegvesen, 2019).

5. Conceptual modeling

The goal of conceptual modeling is to provide an overview of the inputs that are going to apply in the model, the process, and the expected model output before building the simulation model. An overview of the simulation model is illustrated in Figure 5. The system model takes inputs from route and bus information to generate bus frequency at a given stop and total travel time distribution. Details of the system model are presented in the subsequent paragraphs.

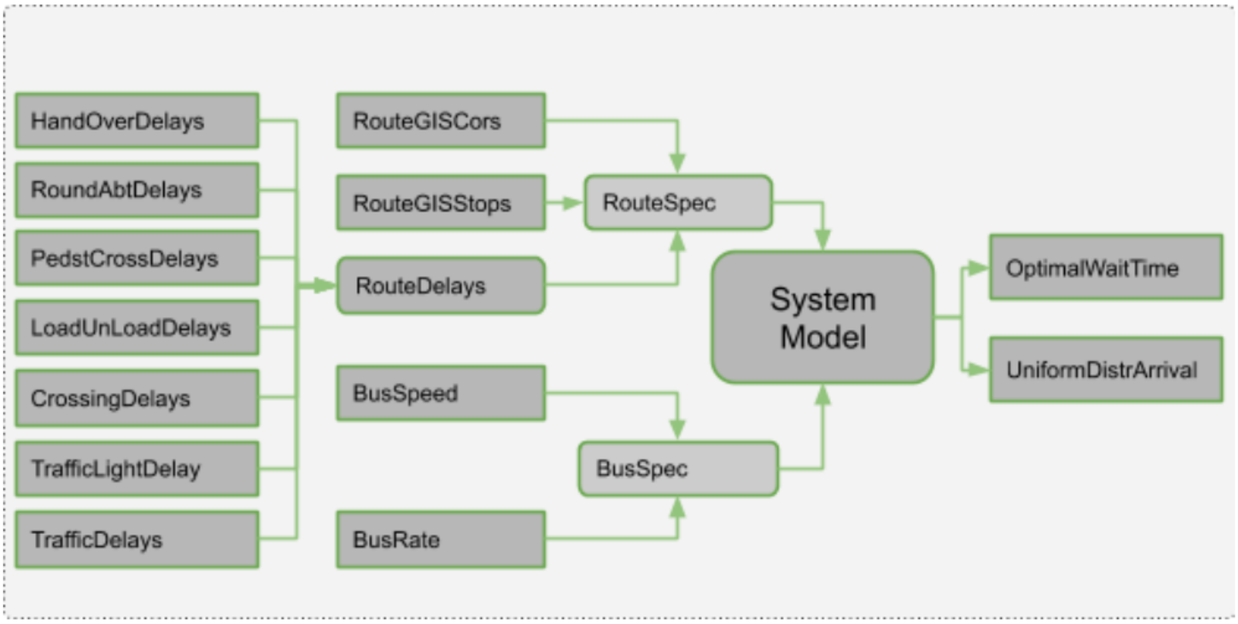

Figure 5. Conceptual model overview

As seen in the system model overview, the first group of the inputs for the model comes from route information. The route information consists of route paths, route stops, and delays. The routes are represented on the GIS map, and the bus stops are placed at particular GIS coordinates. Each bus stop is associated with cumulative route delays between the previous and the current stop.

The route delay is a function of a roundabout, pedestrian crossing, loading/unloading, traffic light, and travel time delays. It is worth noting that the final delay represented at a specific stop is dependent on the route condition; thus, some stops may not include all delay factors into account, and others may have delay only from travel time. Two parameters, bus operation speed and bus rate, are used as inputs to the bus agent. What is more, the system model simulates and presents the desired measurement, such as bus frequency at a specific stop and the probability distribution of total travel time.

6. Analysis and development

6.1. Model Assumptions

The model has made certain assumptions, adjustments to routes, reduced the number of stops by grouping, and created simplified models considering various delay factors.

Constant average bus speed is assumed throughout the routes, together with the route distance, it applies to calculate the bus travel time. The route length between consecutive bus stops is calculated using GIS map coordinates. Bus speed variation due to road conditions and traffic speed limits on the current Korridor are neglected. The thesis also delimits the work by taking consideration of the availability of the buses. All buses that are allocated in this Korridor are assumed to be available throughout operation range, i.e., the models do not take into account factors such as the bus being out of service due to unforeseen events.

Regrouping of bus stops is made to simplify model implementation. Korridor 1 includes two lines with a total (two directions) of 146 bus stops, 52 shared stops. The total number of stops on a bus route is directly obtained from the mobility provider company, Kolumbus. To avoid the model complication, instead of placing all these stops on the GIS map, the stops are grouped into 42 representative stops, and the shared stops are reduced to 8 stops that model the cumulative contributions of all delay factors. Note also that the bus stops in the opposite direction are represented with the same delay values.

The buses' passenger loading and unloading action is conditional. Meaning that the bus may not stop at the bus stops if there is no one waiting for the bus at the bus stop, and if no one is getting off from the bus. Therefore, in the model the delay caused by loading and unloading of passengers is represented as a parameter and has a triangular function.

For reusability, the delay agents are designed as a customizable system dynamic component. The base delay factor is modeled using triangular probabilistic distribution in its range. A multiplication factor is used to calculate the delay at a given stop. As an example, the effective pedestrian delay at a specified stop is calculated by multiplying base pedestrian delay with the number of pedestrian crossing counts. A similar approach is followed to model other types of delays caused by roundabout and traffic lights. Note that in practice, delays are influenced by various factors. Thus, this approximation will be slightly different from real-world situations.

However, such a simplified model is good enough to assess the impact of such delays on overall system performances.

6.2. Model Development

This section discusses the model assumption, the modeling choices made and how these models are enforced.

6.2.1. Model Agents

Figure 6 shows the type of agents applied in the simulation model. Each of these agents are described in the subsequent sections

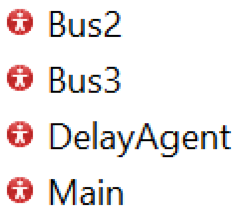

Figure 6. Implemented model agents

6.2.1.1. Agent "Bus2 and Bus3"

Bus2 agent simulates the traffic on route 2. It departs from the first bus stop called Stavangerhpl10, gets the passengers on board, and off at bus stops until it arrives at Sandnes, the final stop. Likewise, the Bus3 agent simulates the traffic on route 3. It departs from the first bus stop called Stavangerhpl10, gets the passengers on board, and off at bus stops until it arrives Forus nord, the final stop.

6.2.1.2. Agent "Delay Agent"

The "DelayAgent" agent contains 23 agents that are found on the main page, simulating the total delay time between and at each bus stop. Each agent locates at the agent simulation location. All delay agents that are used in the model with their content are illustrated in Figure 7. The detail is presented in the next section. As the author mentioned in section 5.1, for the model complication reduction purpose, the author assumes that bus stops in the opposite direction are located parallel to each other. Based on this assumption, bus stops in the opposite direction are represented with the same delay values. Consequently, the total number of delay agents is reduced by half and becomes 23.

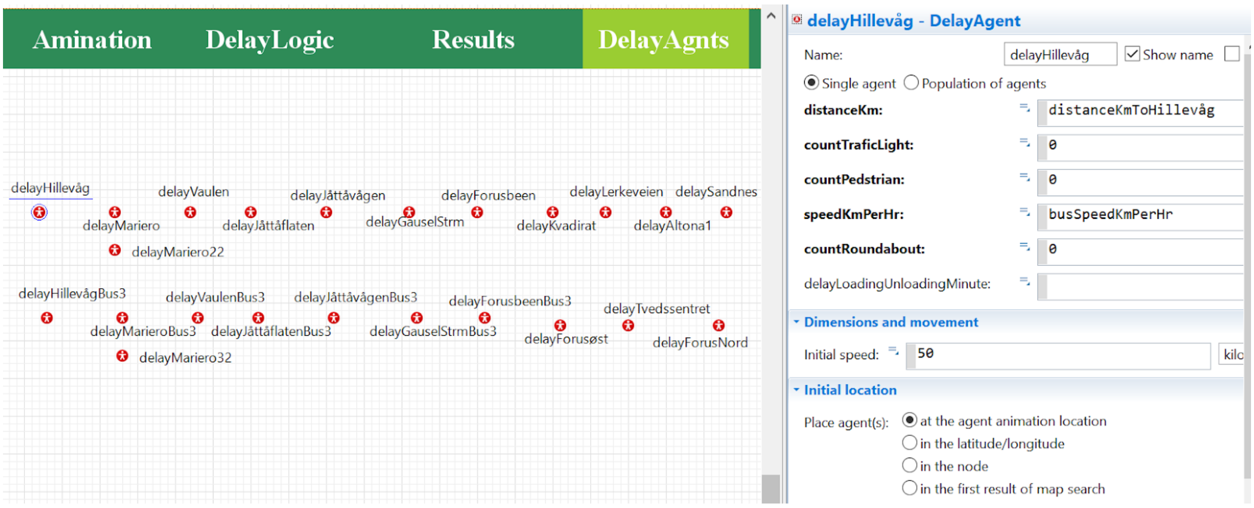

Figure 7. DelayAgent-Agents

The detail information and property of the representative 23 Agents are elaborated in Table 8.

Table 8. DelayAgent-Agents property

Agent Name (Route2)	**Function**	**Description**
delayHillevåg	System dynamic	Calculate total delay time all the way from Stavanger to Hillevåg
delayMariero	”	Calculate total delay time all the way from Hillevåg to Vaulen
delayVaulen	”	Calculate total delay time all the way from Vaulen to Jåttåflaten
delayJåttåflaten	”	Calculate total delay time all the way from Jåttåflaten to Jåttåvågen
delayJåttåvågen	”	Calculate total delay time all the way from Jåttåvågen to GauselStrm
delayGauselStrm	”	Calculate total delay time all the way from GauselStrm to Forusbeen
delayForusbeen	”	Calculate total delay time all the way from Forusbeen to Kvadirat
delayKvadirat	”	Calculate total delay time all the way from Kvadirat to Lerkeveien
delayLerkeveien	”	Calculate total delay time all the way from Lerkeveien to Altona1
delayAltona1	”	Calculate total delay time all the way from Altona1 to Hillevåg

delaySandnes	”	Calculate total delay time all the way from Stavanger to Sandnes
delayMariero22	”	Calculate total delay time all the way from Jåttåflaten to Hillevåg (Towards Stavanger direction)
Agent Name (Route3)	**Function**	**Discription**
delayHillevågBus3	System dynamic	Calculate total delay time all the way from Stavanger to Hillevåg
delayMarieroBus3	”	Calculate total delay time all the way from Hillevåg to Mariero
delayVaulenBus3	”	Calculate total delay time all the way from Mariero to Vaulen
delayJåttåflatenBus3	”	Calculate total delay time all the way from Vaulen to Jåttåflaten
delayJåttåvågenBus3	”	Calculate total delay time all the way from Jåttåflaten to Jåttåvågen
delayGauselStrmBus3	”	Calculate total delay time all the way from Jåttåvågen to GauselStrm
delayForusbeenBus3	”	Calculate total delay time all the way from GauselStrm to Forusbeen
delayForusøst	”	Calculate total delay time all the way from Forusbeen to Forusøst
delayTvedssentret	”	Calculate total delay time all the way from Forusøst to Tvedssentret
delayForusNord	”	Calculate total delay time all the way from Tvedssentret to ForusNord
delayMariero32	”	Calculate total delay time all the way from Jåttåflaten to Hillevåg (Towards Stavanger direction)

6.2.1.3. System Dynamic Model

A System Dynamic model function is chosen to model the “DelayAgent” agent for two reasons. The first reason is it allows the reusability of one delay agent. After modeling the total delay of a single delay agent, it is reused for all delay agents. The second and foremost reason is it reduces model complications. If all delay factors are represented by a delay box, the discrete event model would be complicated. Figure 8 illustrates, the basis delay factor is based on triangular probabilistic distribution within its range. Then a multiplication factor is used. For example, as Figure 8 shows, the delay caused by the roundabout is determined by multiplying the number of roundabout counts by the base roundabout delay. The simulation of certain types of delays caused by a pedestrian crossing and traffic lights follows a similar method.

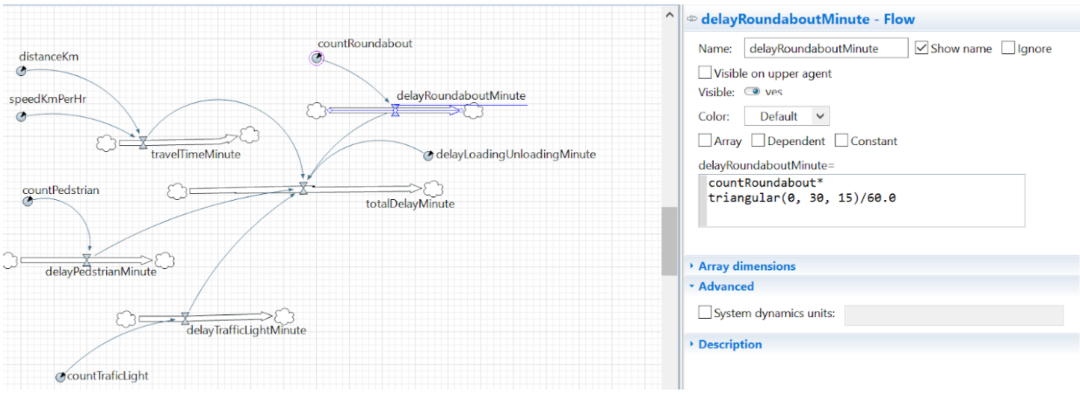

Figure 8. Delay roundabout minutes

Figure 9 illustrates that the total delay at a given stop is a summation of all delay factors which occurs at that stop.

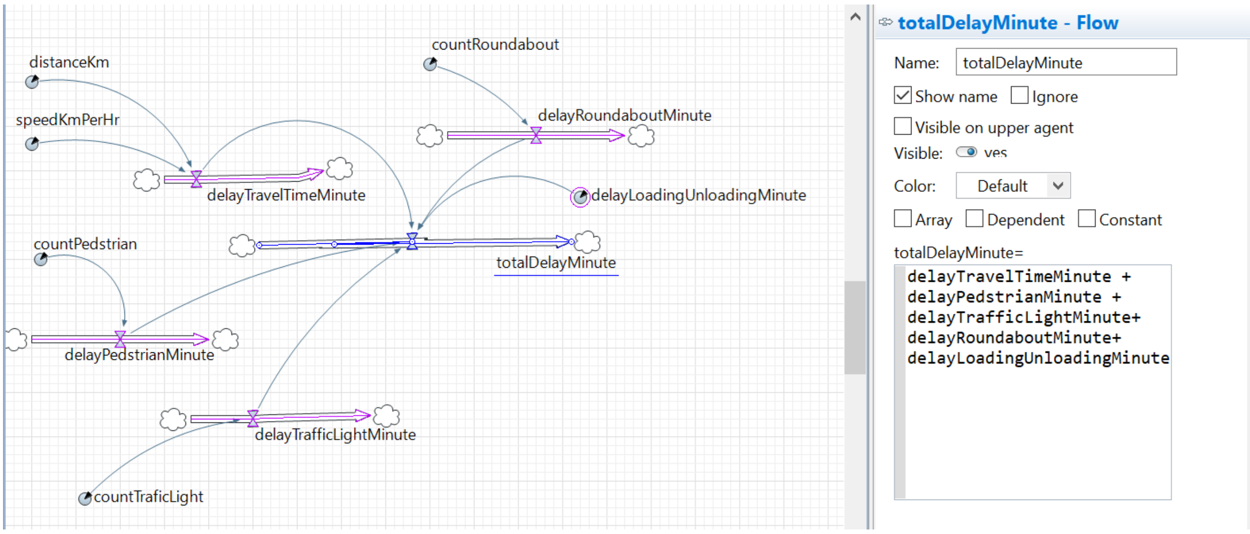

Figure 9. System dynamic total delay in minute

A summary of the system dynamic function parameters and flows in detail is presented in Table 9.

Table 9. System Dynamic Model Parameters

Name	Type	Equation/Function	Description
delayTravelTimeMinite	Flow	(distanceKm/(speedKmPerHr/60.0))	-
delayPedesterianMinite	Flow	countPedstrian* triangular(0, 25, 15)/60.00	A delaytime caused by pedestrian is assumed to between (0,25,15) seconds

delayTrafficLightMinute	Flow	countTraficLight* triangular(0, 30, 15)/60.0	A delaytime caused by traffic light is assumed to between (0,30,15) seconds
delayRoundaboutMinute	Flow	countRoundabout* triangular(0, 30, 15)/60.0	A delaytime caused by roundabout is assumed to between (0,30,15)seconds
totalDelayMinute	Flow	delayTravelTimeMinute + delayPedstrianMinute + delayTrafficLightMinute+ delayRoundaboutMinute+ delayLoadingUnloadingMinute	summation of all delays
distanceKm	Parameter	Eg. Bus2R1S1.length()/1000.0	Bus2R1S1: route name between Stavanger and Hillevåg on GIS map
speedKmPerHr	Parameter	main.busSpeedKmPerHr	It takes the bus speed value from main.
countPedstrian	Parameter	-	Number of pedestrian crossings between two bus stops
countTraficLight	Parameter	-	Number of traffic lights between two bus stops
countRoundabout	Parameter	-	Number of roundabouts between two bus stops
delayLoadingUnloading Minute	Parameter	-	Time to loading and unloading passengers at bus stop

6.2.1.4. Agent "Main"

The "Main" agent is the main page in AnyLogic modeling. In this paper case, the main page contains different elements such as GIS map, view areas, other agents, parameters, and a discrete event model. The GIS map is a critical item that plays an important role. The model building starts from putting the paths and the bus stop locations using GIS Route and GIS Point on GIS Map. Figure 10 displays the implemented GIS map. With the GIS map, people can experience visual animation modeling of bus transportation, the location of bus stops, and the surrounding environment.

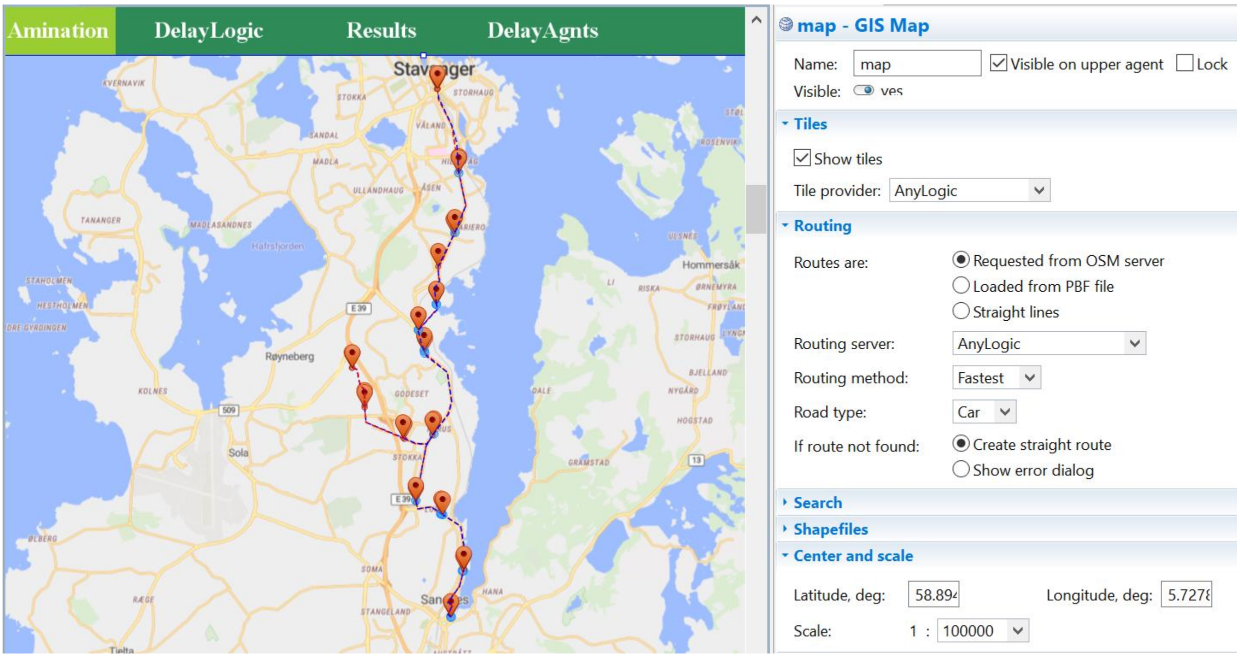

Figure 10. GIS map

Figure 11 illustrates the visualization of the movement of the buses during the model running time. The green and yellow rectangles represent bus2 and bus3, respectively. Where bus2 operates on the Stavanger-Sandnes route, and bus3 gives the transportation service on Stavanger-Forus Nord route.

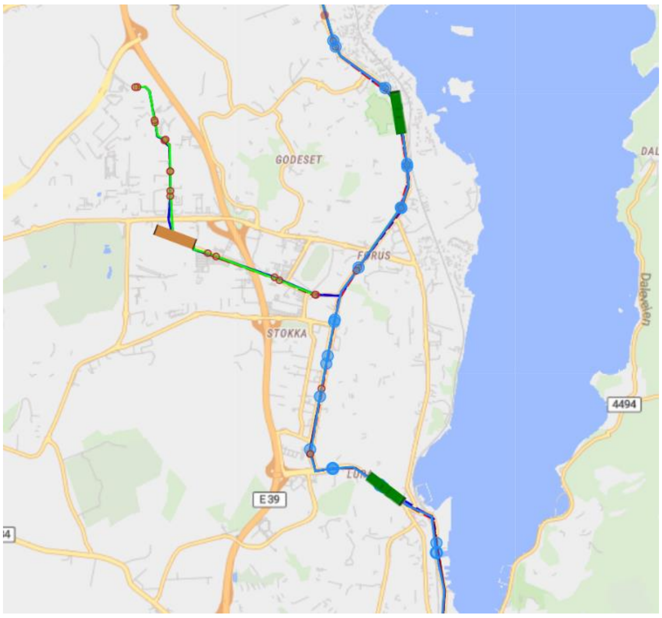

Figure 11. The route, bus stops, and bus movements visualization on the GIS map

All parameters are shown in Figure 12 and their detail information is described in Table 10.

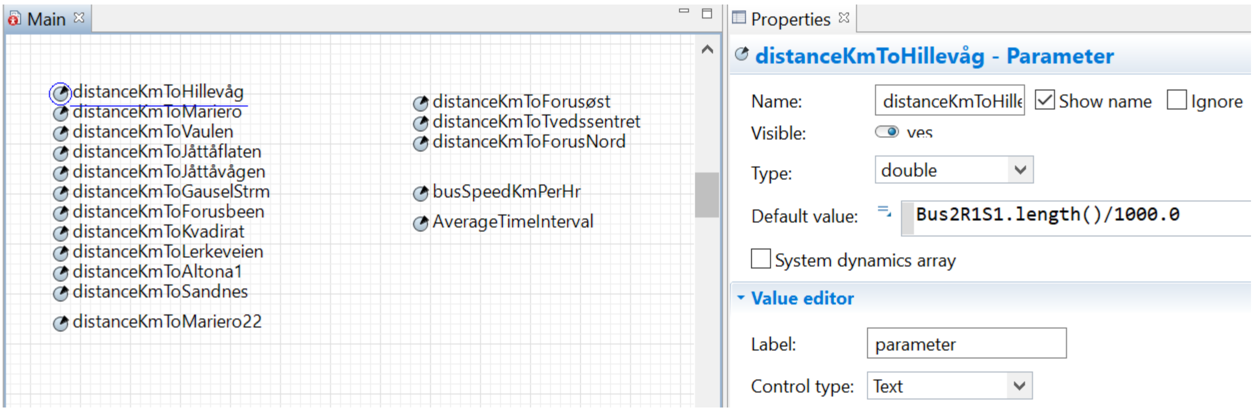

Figure 12. Model parameters that found in Main Agent

Table 10. properties of model parameters

Name	Type	Default Value	Description
distanceKmToHillevåg	Parameter	Bus2R1S1.length()/1000.0	Distance between Stavangerhpl10 to Hillevåg
distanceKmToMariero	”	Bus2R1S2.length()/1000.0	Distance between Hillevåg to Mariero
distanceKmToVaulen	”	Bus2R1S3.length()/1000.0	Distance between Mariero to Vaulen
distanceKmToJåttåflaten	”	Bus2R1S4.length()/1000.0	Distance between Vaulen to Jåttåflaten
distanceKmToJåttåvågen	”	Bus2R1S5.length()/1000.0	Distance between Jåttåflaten to Jåttåvågen
distanceKmToGauselStrm	”	Bus2R1S6.length()/1000.0	Distance between Jåttåvågen to Gausel Sentrum
distanceKmToForusbeen	”	Bus2R1S7.length()/1000.0	Distance between Gausel Sentrum to Forusbeen
distanceKmToKvadirat	”	Bus2R1S8.length()/1000.0	Distance between Forusbeen to Kvadrat
distanceKmToLerkeveien	”	Bus2R1S9.length()/1000.0	Distance between Kvadrat to Lerkeveien
distanceKmToAltona1	”	Bus2R1S10.length()/1000.0	Distance between Lerkeveien to Altona1
distanceKmToSandnes	”	Bus2R1S11.length()/1000.0	Distance between Altona1 to Sandnes
distanceKmToMariero22	”	Bus2R2S8.length()/1000.0	Distance between Jåttåflaten to Hillevåg (Towards Stavanger direction)

distanceKmToForusøst	”	Bus3R1S8.length()/1000.0	Distance between Forusbeen to Forusøst
distanceKmToTvedssentret	”	Bus3R1S9.length()/1000.0	Distance between Forusøst to Tvedssentret
distanceKmToForusNord	”	Bus3R1S10.length()/1000.0	Distance between Tvedssentret to ForusNord
busSpeedKmPerHr	”	50Km/Hr.	The model offers a range from 10Km/Hr. To 80Km/Hr. So that user can change the speed and see the effect.
AverageTimeInterval	”	-	Measures the average time interval between two consecutive buses at bus stop “Vaulen”

6.2.1.4.1. Discrete Event Model

The discrete model illustrates the bus transportation process. It is built up through a source that allows the two bus agents to enter the route. The following discrete event boxes are implemented in the model.

Source: It is a starting point of a process model. In this thesis case, it is the source where the buses generate.

TimeStart and TimeEnd: Calculate the time the buses spend in between them.

Delay box: represents the selected bus stops. It animates bus agents while they are moving along their route, and as stopping at the bus stop for passenger loading and unloading.

Sink: It is an endpoint for the buses in a process model.

The detailed process of the discrete event model will be discussed in the next section.

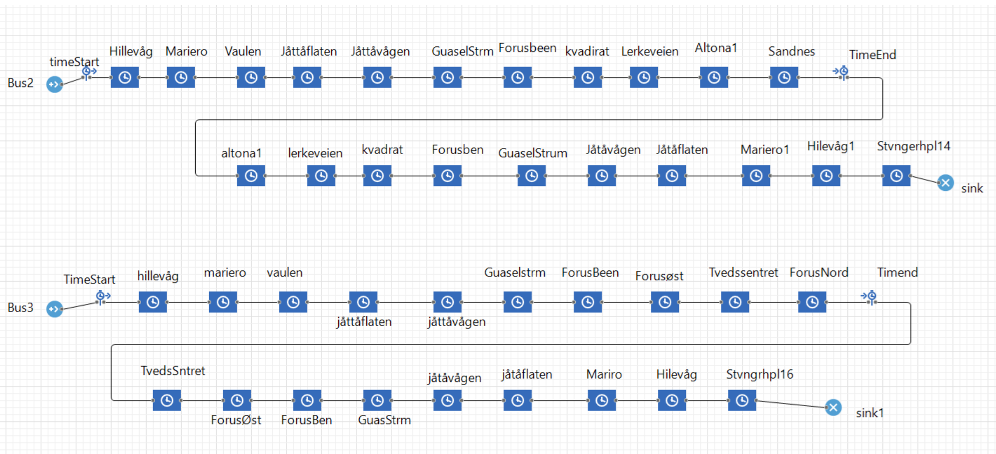

Figure 13. Discrete Event Model

Figure 14. Analysis Charts (Result graphs)

Figure 14 represented one of the view areas called “Results”, which is included in the main agent. In addition to, two other view areas are available in the Main agent. Table 11 summarizes the four agents applied in this model.

Table 11 Model Agents

Agent Name	Function	Description
Bus2	-	Bus which operate on route 2
Bus3	-	Bus which operate on route 3
DelayAgent	System Dynamics	Model and calculate the total delay time at each stop
Main	Discrete event, Agent-based, GIS map, and Graphs	The main simulation page contains all other agents, animation of the two buses, and graphs showing bus frequency and travel time.

6.2.2. Reference Case Model

The reference model is the base model. Regardless of date and time difference, in the reference model case, Korridor-1 is assumed to be a fully BRT system with a consideration of passenger loading and unloading delay. Meaning that the buses have full priority at roundabout and traffic light. In addition, delay caused by pedestrian crossing is ignored. As the author mentioned in the methodology section, the Multimethod approach is applied for building the simulation model and the final analysis is represented by a discrete event model as illustrated in Figure 15 and Figure 16.

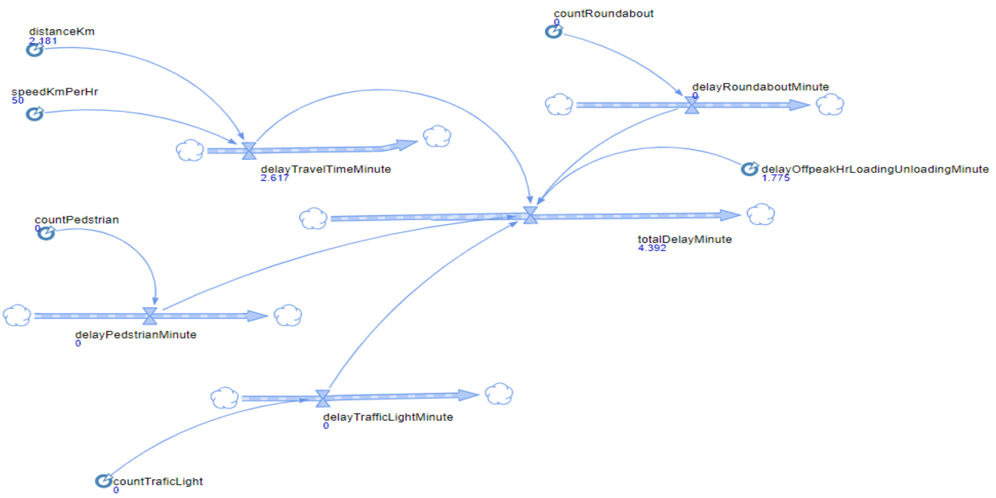

Figure 15. Total delay time at bus stop, Hillevåg

As illustrated on Figure 15, the value of total delay time measured in SD model at Hillevåg, is implemented to the delay box named Hillevåg, which is found in discrete event model. See Figure 16 . Likewise, delay times which are recorded at the bus2 stops using SD model, goes to the corresponding bus stops found in the DEM (Discrete Event Model). So that the whole transportation process is represented by DEM. As a result, the expected bus frequency and travel time result also taken from the DEM. The detailed information of the discrete event model is illustrated by Table 12.

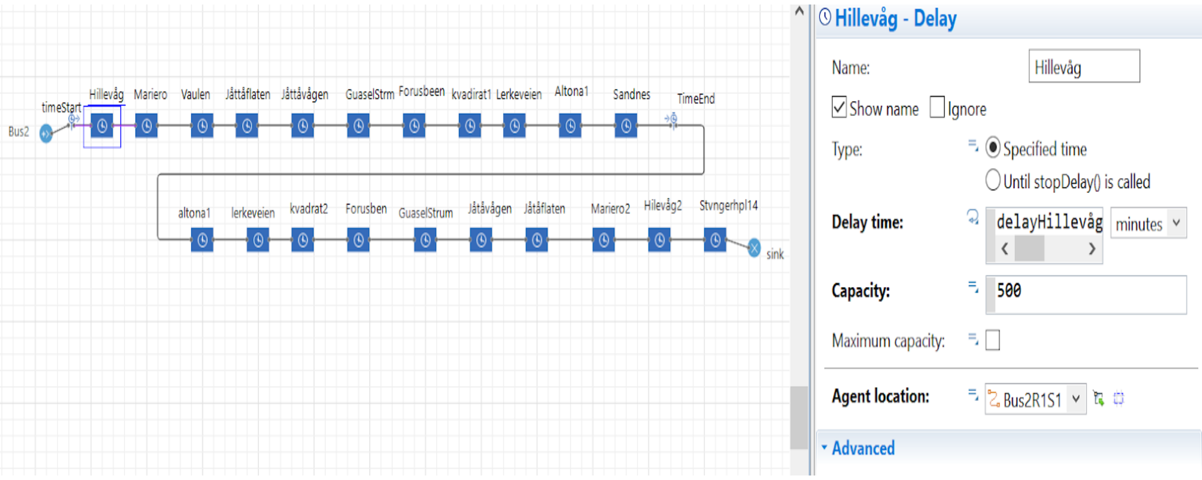

Figure 16. Delay event model for route 2

Table 12. Table of Function in Discrete Event (route 2)

Event Block Name	**Function**	**Time function**	**Agent Location (Route Name)**	**Description**
Bus2	-	-	Stavangerhpl10	It is a source that generates buses
timeStart	-	-	-	Start measuring agent time spend in the system until it reaches TimeEnd block
Hillevåg	Specific time	delayHillevåg.totalDelayMinute	Bus2R1S1	Animate the bus as it travels along the designated route or as it loads and unload at bus stops.
Mariero	”	delayMariero.totalDelayMinute	Bus2R1S2	”
Vaulen	”	delayVaulen.totalDelayMinute	Bus2R1S3	”
Jåttåflaten	”	delayJåttåflaten.totalDelayMinute	Bus2R1S4	”
Jåttåvågen	”	delayJåttåvågen.totalDelayMinute	Bus2R1S5	”
GuaselStrm	”	delayGuaselStrm.totalDelayMinute	Bus2R1S6	”

Forusbeen	”	delayForusbeen.totalDelayMinute	Bus2R1S7	”
kvadirat1	”	delayKvadirat.totalDelayMinute	Bus2R1S8	”
Lerkeveien	”	delayLerkeveien.totalDelayMinute	Bus2R1S9	”
Altona1	”	delayAltona1.totalDelayMinute	Bus2R1S10	”
Sandnes	”	delaySandnes.totalDelayMinute	Bus2R1S11	”
TimeEnd	-	-	-	Measures the agent time spent since it has been through timeStart block
altona1	Specific time	delaySandnes.totalDelayMinute	Bus2R2S1	Animate the bus as it travels along the designated route or as it loads and unload at bus stops.
lerkeveien	”	delayAltona1.totalDelayMinute	Bus2R2S2	”
kvadrat2	”	delayLerkeveien.totalDelayMinute	Bus2R2S3	”
Forusben	”	delayKvadirat.totalDelayMinute	Bus2R2S4	”
GuaselStrum	”	delayForusbeen.totalDelayMinute	Bus2R2S5	”
Jåtåvågen	”	delayGauselStrm.totalDelayMinute	Bus2R2S6	”
Jåtåflaten	”	delayJåttåvågen.totalDelayMinute	Bus2R2S7	”
Mariero2	”	delayMariero22.totalDelayMinute	Bus2R2S8	”
Hilevåg2	”	delayMariero.totalDelayMinute	Bus2R2S9	”
Stvngerhpl14	”	delayHillevåg.totalDelayMinute	Bus2R2S10	”
sink	-	-	-	Disposes buses

Similarly, by implementing a system dynamic modeling method, all delay times at each bus3 stops are recorded, and the value goes to the corresponding bus stops found in the DEM. For example, the total delay time recorded at Forusøst which is presented in Figure 17 feeds to the

DEM illustrated in Figure 18. The detailed information of the discrete event model is illustrated by table 13.

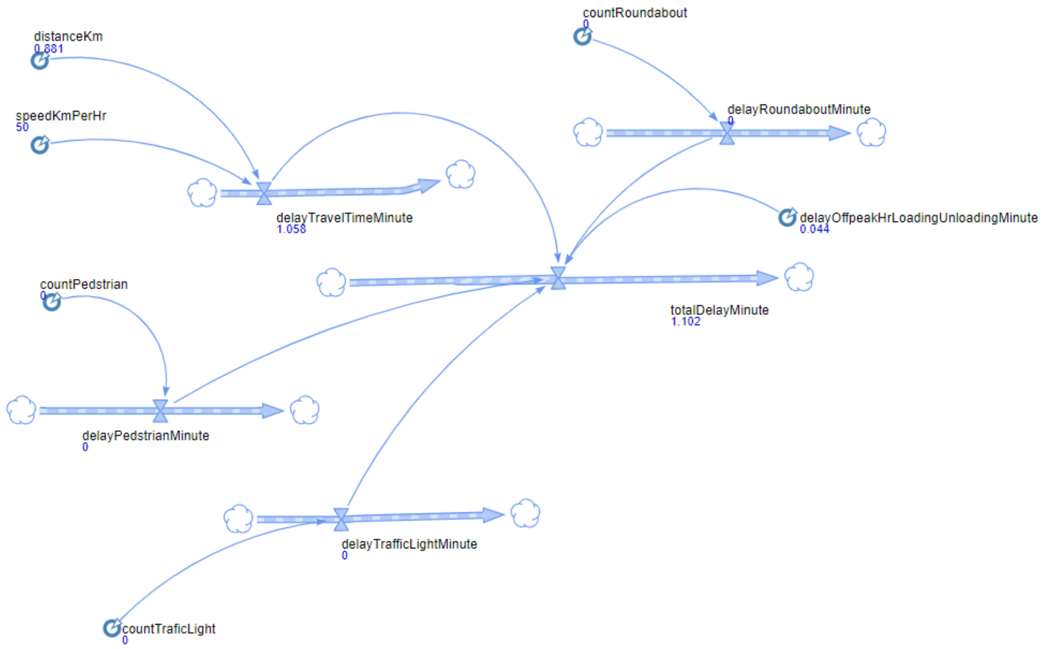

Figure 17. Total delay time at bus stop,Forusøst

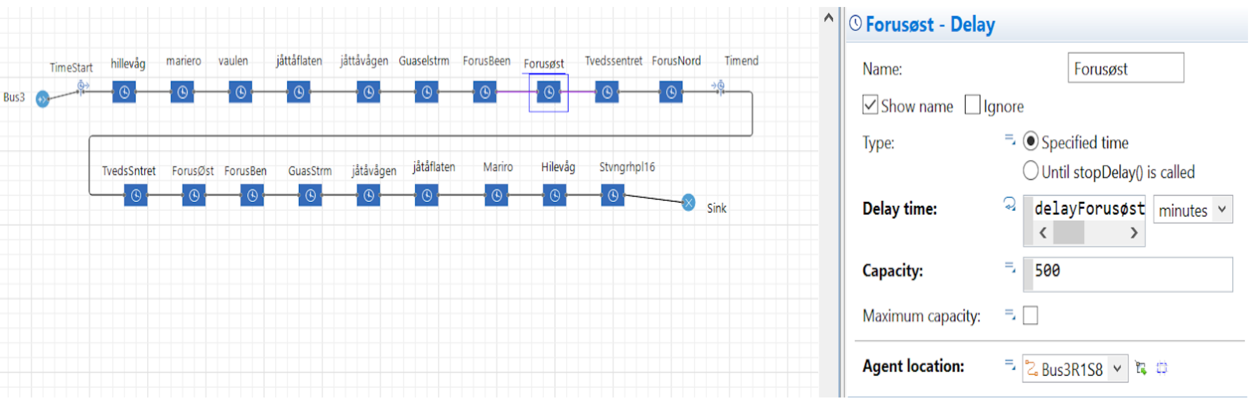

Figure 18. Delay event model for route 3

Table 13. Table of Function in Discrete Event (route 3)

Event Block Name	**Function**	**Time function**	**Agent Location (Route Name)**	**Description**
Bus3	-	-	gisPtStavangerhpl10	It is a source that generates buses
TimeStart	-	-	-	Start measuring agent time spend in the system until it reaches Timend block
hillevåg	Specific time	delayHillevåg.totalDelayMinute	Bus2R1S1	Animate the bus as it travels along the designated route or as it loads and unload at bus stops.
mariero	”	delayMariero.totalDelayMinute	Bus2R1S2	”
vaulen	”	delayVaulen.totalDelayMinute	Bus2R1S3	”
jåttåflaten	”	delayJåttåflaten.totalDelayMinute	Bus2R1S4	”
jåttåvågen	”	delayJåttåvågen.totalDelayMinute	Bus2R1S5	”
Guaselstrm	”	delayGauselStrm.totalDelayMinute	Bus2R1S6	”
ForusBeen	”	delayForusbeen.totalDelayMinute	Bus2R1S7	”
Forusøst	”	delayForusøst.totalDelayMinute	Bus3R1S8	”
Tvedssentret	”	delayTvedssentret.totalDelayMinute	Bus3R1S9	”
ForusNord	”	delayForusNord.totalDelayMinute	Bus3R1S10	”
Timend	-	-	-	Measures the agent time spent since it has been through timeStart block
TvedsSntret	Specific time	delayForusNord.totalDelayMinute	Bus3R2S1	Animate the bus as it travels along the designated route or

				as it loads and unload at bus stops.
ForusØst	”	delayTvedssentret.totalDelayMinute	Bus3R2S2	”
ForusBen	”	delayForusøst.totalDelayMinute	Bus3R2S3	”
GuasStrm	”	delayForusbeenBus3.totalDelayMinute	Bus2R2S5	”
jåtåvågen	”	delayGauselStrmBus3.totalDelayMinute	Bus2R2S6	”
jåtåflaten	”	delayJåttåvågenBus3.totalDelayMinute	Bus2R2S7	”
Mariro	”	delayMariero32.totalDelayMinute	Bus2R2S8	”
Hilevåg	”	delayMarieroBus3.totalDelayMinute	Bus2R2S9	”
Stvngrhpl16	”	delayHillevågBus3.totalDelayMinute	Bus2R2S10	”
Sink	-	-	-	Disposes buses

7. Scenario Modelling

Throughout this chapter, the author will consider three scenarios and discuss the differences these scenarios have with respect to the reference case.

7.1. Scenario-1

The first scenario introduces delay factors to Korridor1. For this purpose, the route segment which stretches from Stavanger to Hillevåg is selected because it is commonly used by bus2 and bus3. In addition, there are many roundabouts, traffic lights and pedestrian crossings that can cause a delay. It is obvious that the delay that occurs at any of the route segments can be propagated and cause a visible traffic flow interruption in the BRT system. For this reason, assessing the effect is very important. Table 14 shows all delay factors that are considered in this scenario.

Table 14. Delay factors on Bus2R1S1

Route Name	**Bus2R1S1 (Stavanger to Hillevåg)**			
Delay Factor	Roundabout	Traffic Light	Pedestrians Crossing	Off-peak hour Loading/Unloading delay
Number of counts	9	3	5	The value is taken from Table 4 and Table 5

A Multimethod simulation method is implemented using a default bus speed (50km/hr.), and 8 bus rates within an hour. The results are collected after simulating the model for 1440 minutes. Figure 19 and Figure 20 illustrates the total delay measured at Hillevåg by System Dynamic function.

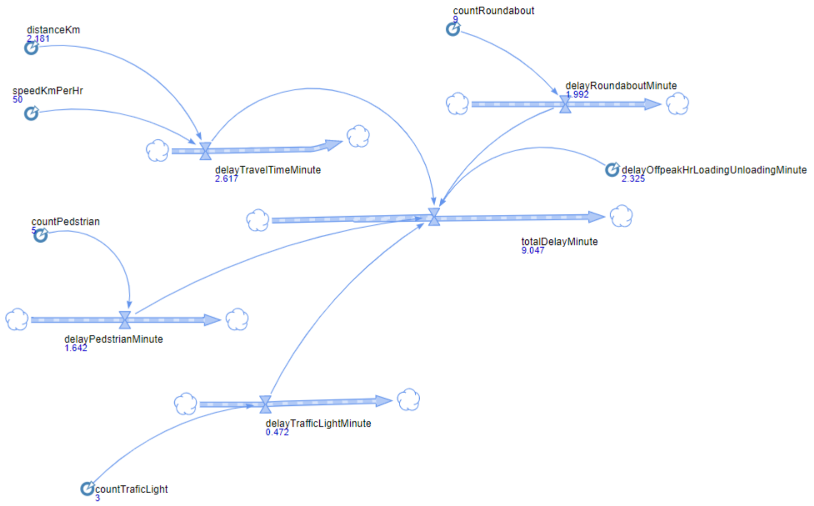

Figure 19. Total delay at Hillevåg (Bus2)

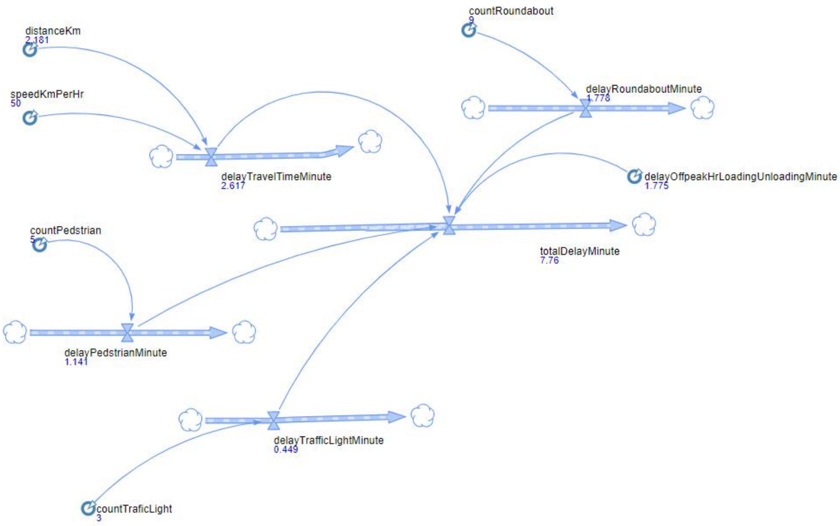

Figure 20. Total delay at Hillevåg (Bus3)

The total delay value, which was found from SD model at Hillevåg, is applied to the delay box which represents the Hillevåg bus stop in the discrete event model. The effect will be presented and discussed in section 9.

7.2. Scenario-2 and 3

Scenario 2 and 3 are scenarios that consider no bus priority at two roundabouts in Hillevåg, and a dwell time that the bus spends for loading and unloading of passengers at bus stops. The two roundabouts, which are illustrated in Figure 21, can be a bottleneck if buses have no priority. Mainly the first roundabout could cause a traffic jam since it is connected with the nearby bridge.

Any delay that occurred at these roundabouts could have an impact on the whole system by affecting travel time and bus frequency.

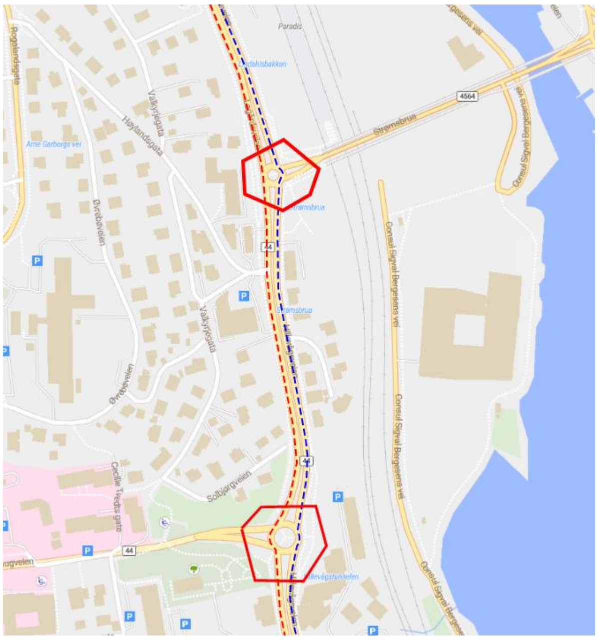

Figure 21. Two roundabouts in Hillevåg

For modeling scenarios 2 and 3, two different roundabout delay times, one with (15,60) seconds, and one with (30,60) seconds is implemented, as shown in the Figure 22 and Figure 23.

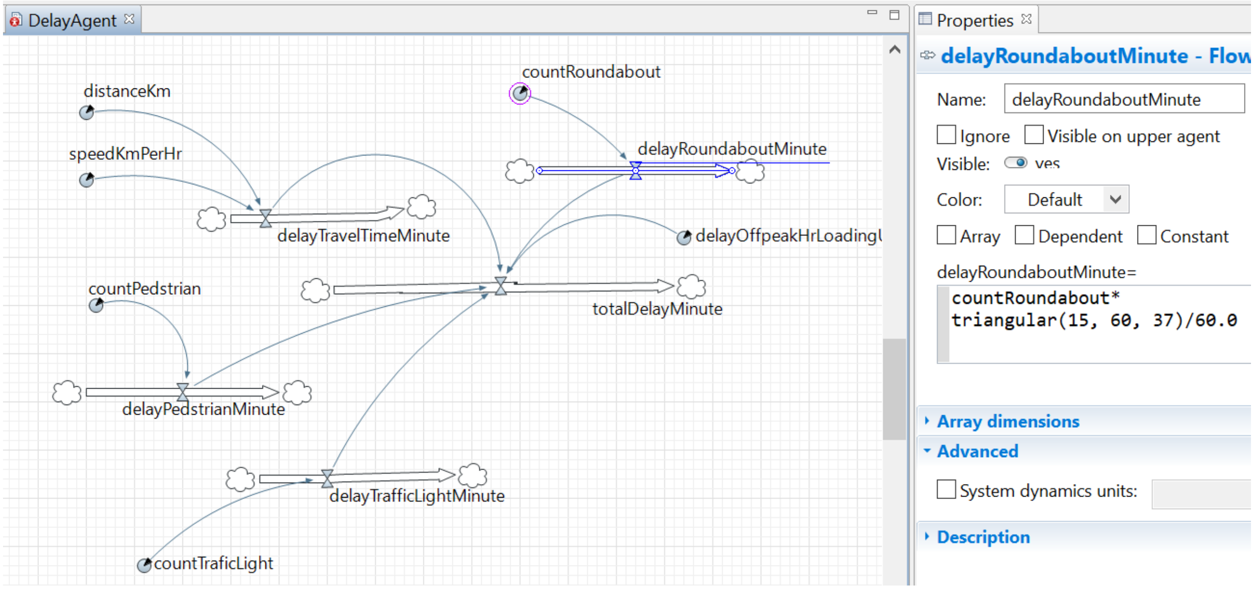

Figure 22. Scenario2-Implemented Roundabout delay time

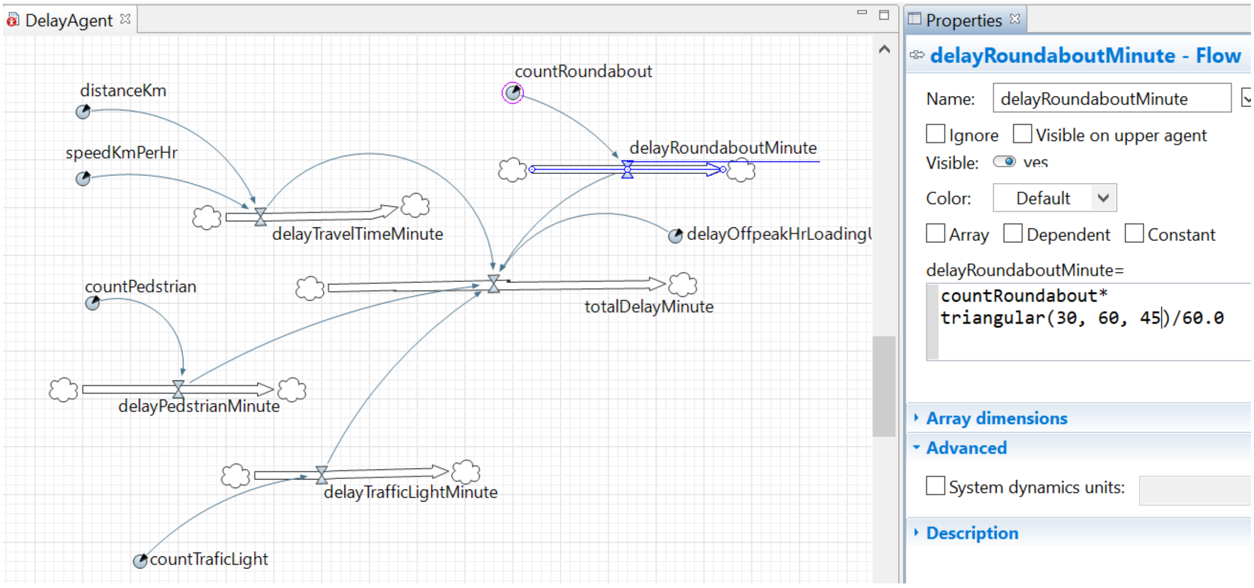

Figure 23. Scenario3-Implemented Roundabout delay time

As illustrated in Figure 22 and Figure 23, the function/equation used to calculate the delay time at these two roundabouts is *countRoundabout* triangular(15, 60, 37)/60.0 and countRoundabout* triangular(30, 60, 45)/60.0* respectively.

8. Verification and Validation

The models have been run and tested several times to check if it is appropriately representing the intended ideal of the conceptual Model. In practice, the bus frequency and travel time are affected by factors such as the system operating condition, bus speed, and rate. The simulation models also show a similar effect. A numerical comparison between a simulation output and estimated travel time has shown the expected correlation. For the ideal scenario, the total travel time expected is 18.23 minutes, which is calculated by taking the ratio of total route distance with bus speed. By configuring and running the simulation model for the ideal scenario, it is confirmed that the total travel matches the calculated value. Also, the result plots are used to verify the simulation model.

The effect caused by introducing delay factors on bus frequency and travel time was analyzed and visually inspected from the result plots. It is expected that, whenever there is an increase or decrease in bus rate, the bus punctuality and travel time are affected proportionally. These relationship between bus rate, punctuality, and travel time was checked during the model run. The result is visually inspected and confirmed that the expected behavior matches the result.

Furthermore, extreme corner case checks are performed by setting parameters such as the bus speed and bus rate to zero. For such conditions, the system is expected to generate zero frequency and travel time. From this test scenario, it is observed that the expected behavior is accounted for by the Model. The model is validated by comparing with a numerically calculated solution. However, it could be better if it was also validated by an expert. The summary of verification and validation process is presents Table 15.

Table 15. Verification and Validation

Aspect	Verification test	Validation test	Comments
Model structure	Ok	Ok	Compared with sample model from AnyLogic Library
Model behavior: (Inputs/ parameters)	Ok	Ok	Verified through the output plots and behaves as expected
Inputs(parameters)	Ok	Ok	Verified by changing parameter values Changes the input shows a change in the output
Processes (rates, functions)	Ok	Ok	Verification based on the output result
Model impact (reference case)	Ok	Ok	Verification through the influenced of some parameter on the behavior

9. User Interface Development

The visual user interface aims to simplify the use of the simulation model for the user. It also provides control to select and visualize the content presented in separate view areas. These separate view areas can be accessed just by clicking their given name such as Animation, DelayLogic, Results, and DelayAgnts. Figure 24 shows the front page that appears when the AnyLogic Model play button is pressed.

Figure 24. Frontpage of Simulation Model

As illustrated in Figure 25, the author also provides a bus speed control slider, which is linked to a parameter called busSpeedKmPerHr.The control slider is available in the Results view area and allows the user to change the speed of the bus by sliding through the button and visualize the difference on the bus frequency and travel time.

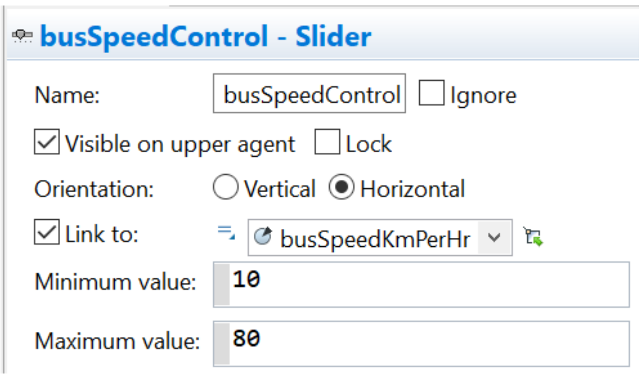

Figure 25. Bus Speed Control Slider

Immediately after pressing the simulation play button, the user starts visualizing the movement of the buses in the Animation view area, which is presented in Figure 26. The DelayLogic, Result and DelayAgnts animated page is shown in Figure 27, Figure 28 and Figure 29, respectively.

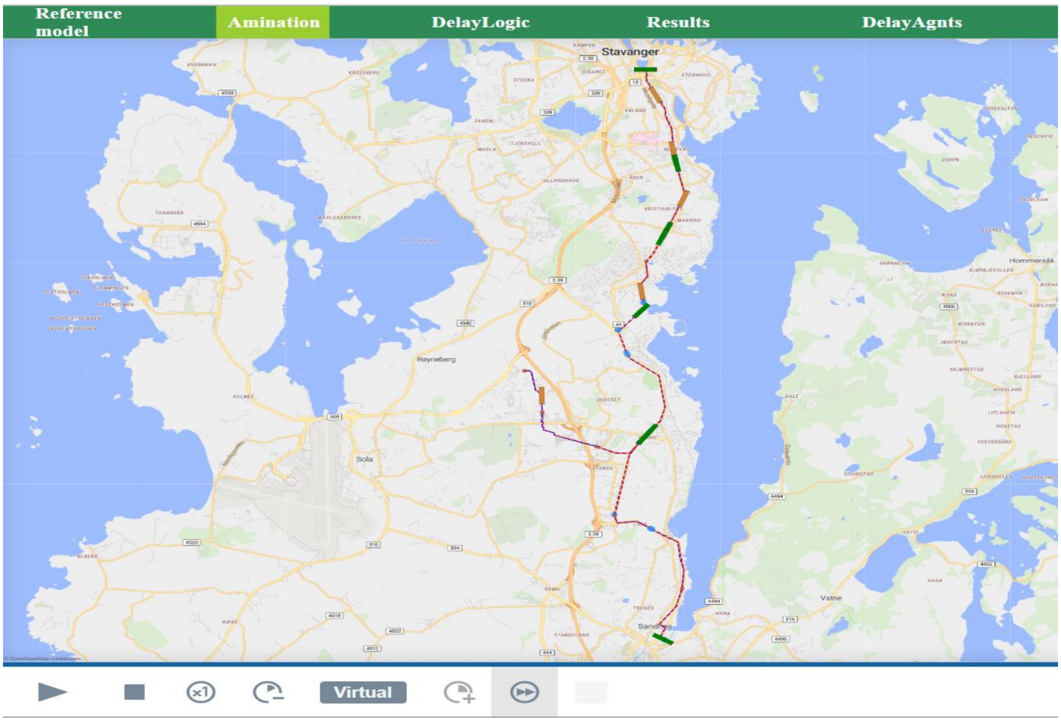

Figure 26. Animation View Area

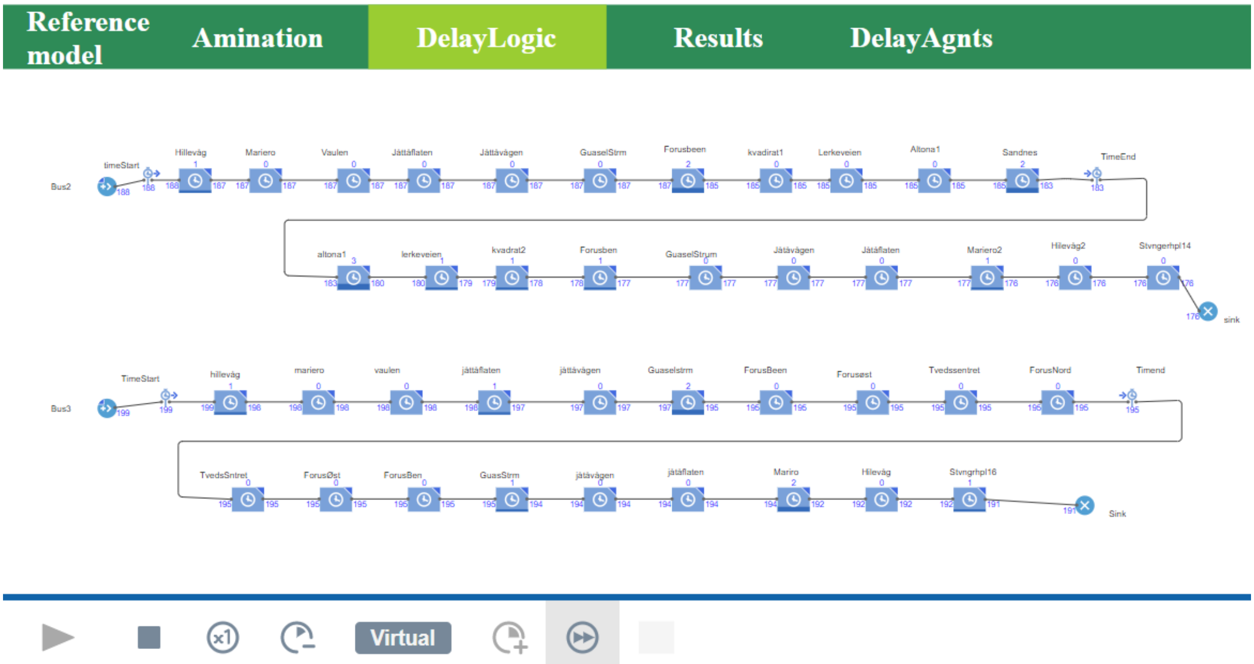

Figure 27. DelayLogic View Area

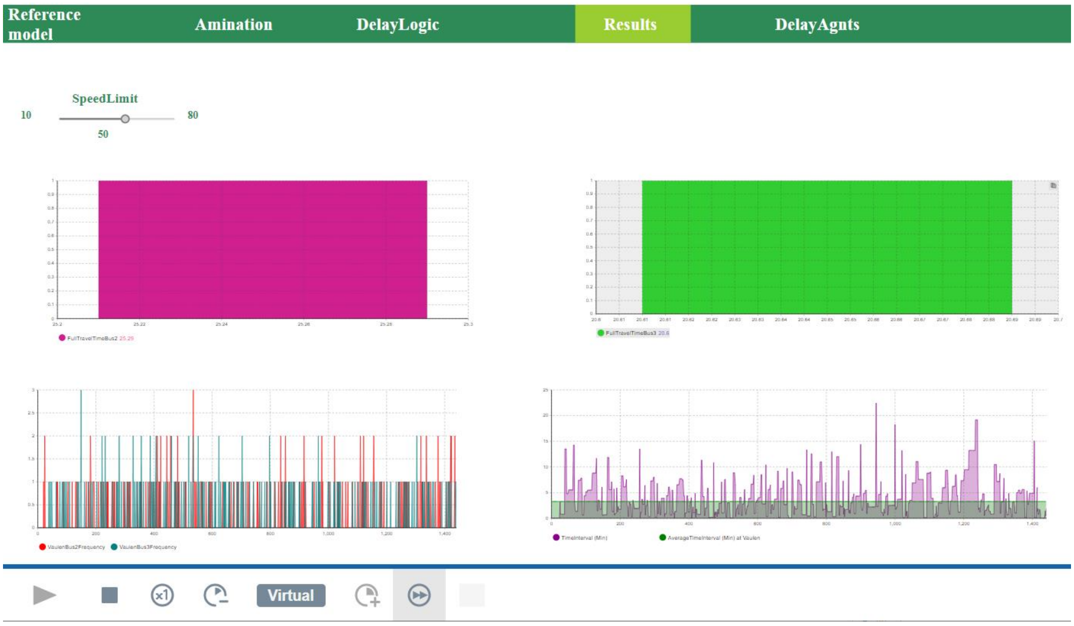

Figure 28. Result View Area

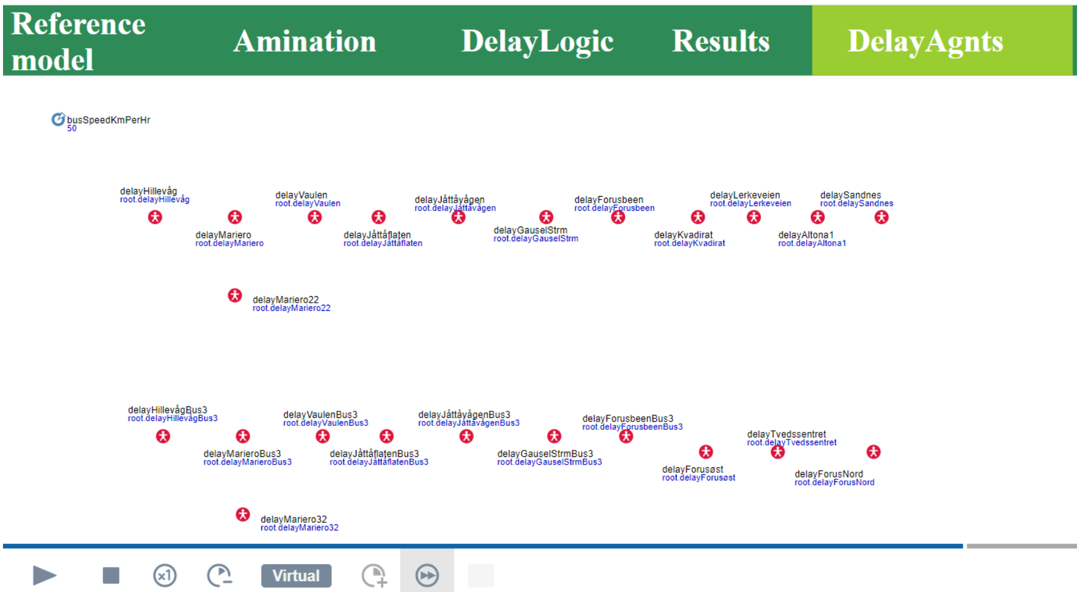

Figure 29. DelayAgnts View Area

Figure 30 shows the view areas for the scenarios model. Everything is identical, only the first text has changed to the name of scenario.

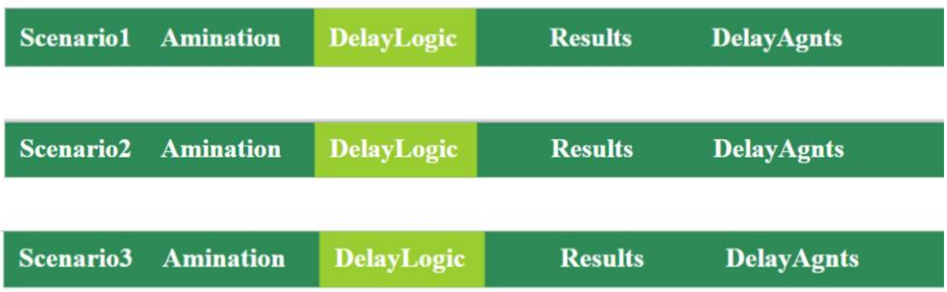

Figure 30. Scenario1-ViewAreas

10. Result and Discussion

The simulation model provides the analysis output in the form of charts. The results are demonstrated for both bus frequency, and travel time taken after running the simulation model for 1440 minutes equivalent to one day span. To check the buses frequency, the third selected bus stop which is called **Vaulen** is chosen.

10.1. Reference Case Model Results

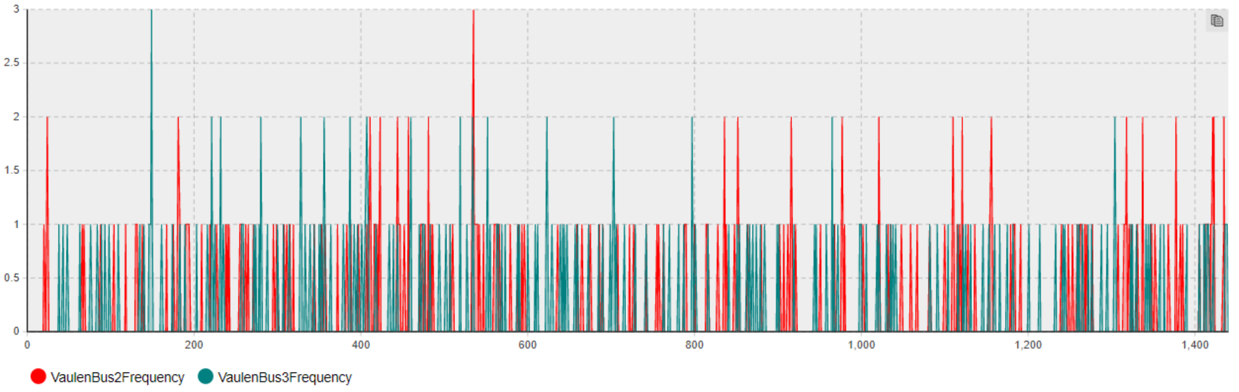

Figure 31. Reference Case-Bus frequency at Vaulen.

Figure 32. Reference Case-Bus frequency at Vaulen between minute 1240 and1440.

Among the selected bus stops, a bus stop named Vaulen is chosen as a bus frequency checking point because Vaulen is one of the bus stops that are commonly used by bus2 and bus3. Therefore, at Vaulen, it visualizes which bus is frequently showing the time difference between two consecutive buses, and most importantly, it shows the number of buses appearing at the same time. In Figure 31 and Figure 32, the blue-green color represents bus3, and the red lines represent bus2. Based on the chart, most of the time, the buses are evenly spaced. Yet, there are also times where the buses bunched at Vaulen. Figure 32 is another version of Figure 31, but the graph time window is reduced from 1440 minutes to 200 minutes so that it gives a clear visualization of the bus frequency.

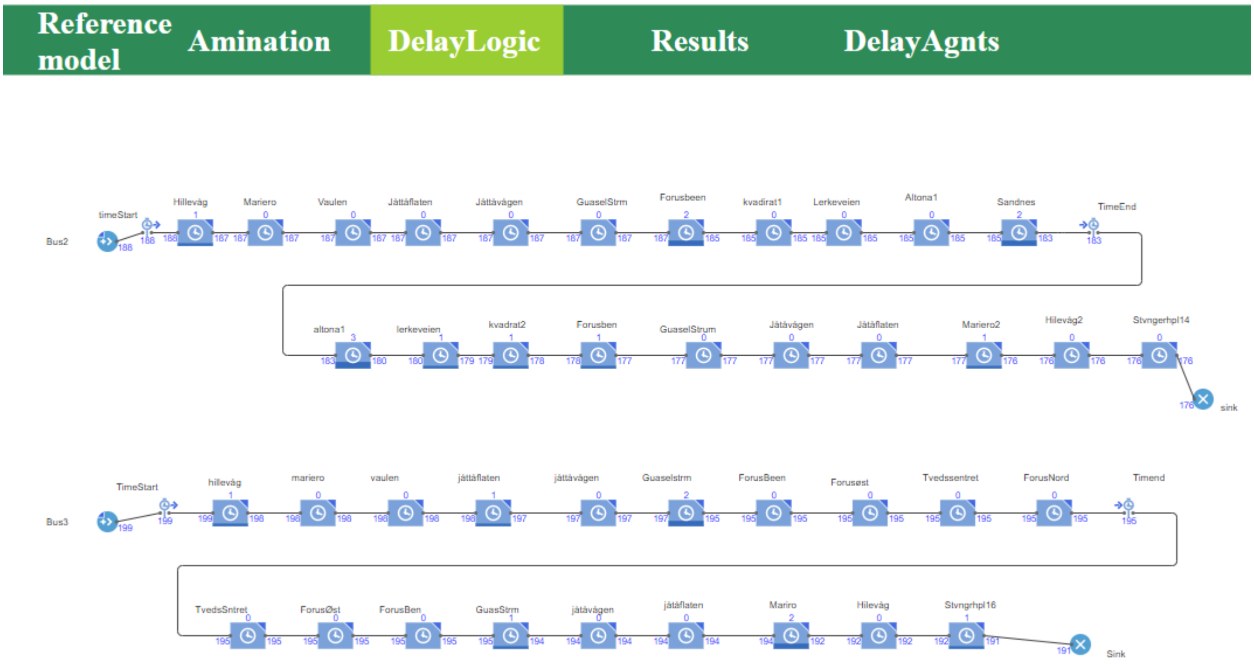

Figure 33. Reference Case-Bus distribution along the route.

Figure 33 demonstrates the number of buses generated from the source, and their distribution along the route. Running the model by making the bus arrival rate equal to eight buses per hour and released from the source, which is Stavangerhpl10, 387 buses are generated and operate on the round trip. Specifically, the figure shows that the number of bus2 and bus3 buses that generated from the source is 188, and 199, respectively. For more clarification, the author also extracted the bus frequency data from the model, conditioned it in Excel and presented as charts in Appendix A. The conditioned data, together with Figure 33, shows that four buses appeared twice, three buses appeared five times, and two buses appeared seventy-five times.

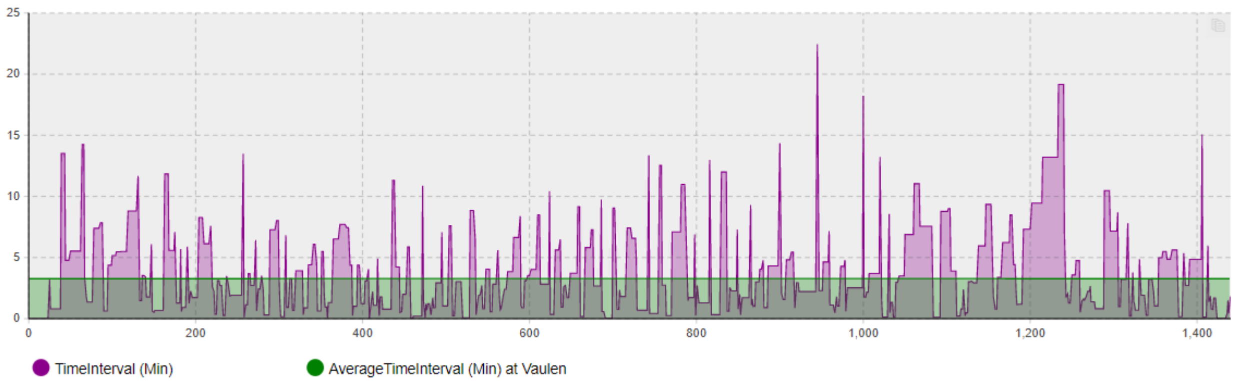

Figure 34.Reference case - Time Interval Between buses at Vaulen

The time interval between two buses that appear at Vaulen is also illustrated in Figure 34. To find the minimum, average, and maximum time interval, the author conditioned the data extracted from Figure 34. Figure 34 and the conditioned data show that the time interval between two buses that are showing up at Vaulen varies within 1 to 22 minutes range, which means that a passenger that is waiting for the bus at Vaulen may have a chance to get the bus every one minute or delayed for 22 minutes. However, on average, a bus shows up at the Vaulen between 3-4 minutes, specifically every 3.277 minutes, as indicated by the green color in Figure 34.

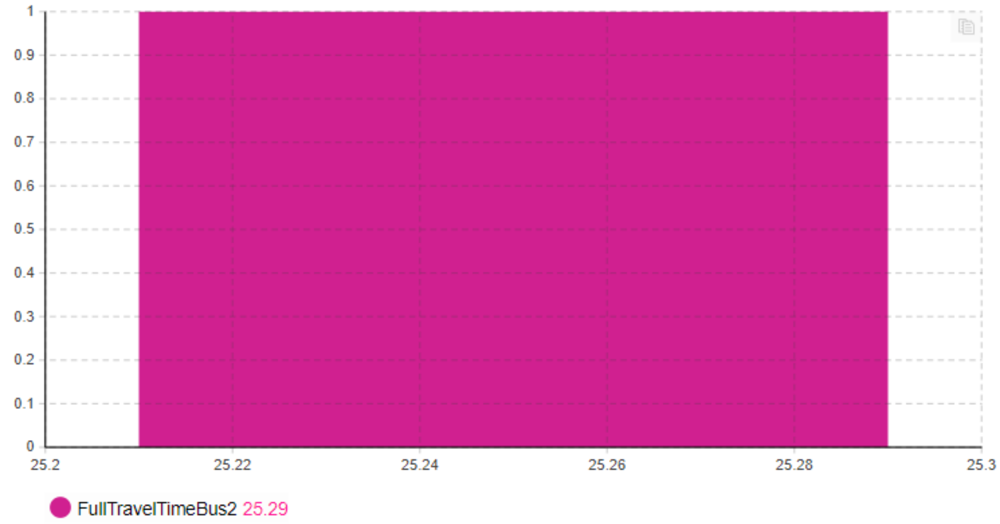

Figure 35. Reference case- Bus2 Travel time.

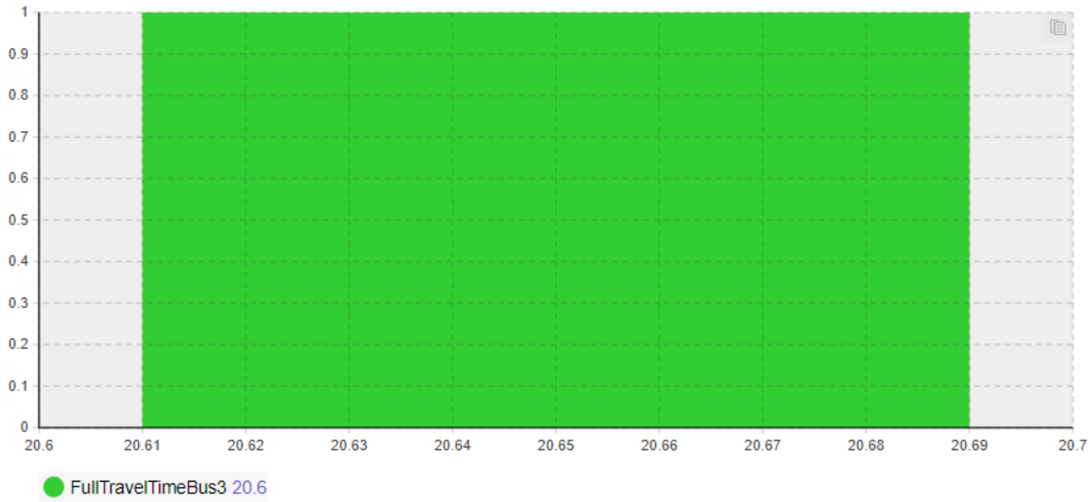

Figure 36. Reference case-Bus3 Travel Time

The travel time of both bus2 and bus3 is illustrated in Figure 35 and Figure 36.Travel time is the time spent by a bus between a starting bus stop, which is Stavangerhpl10 in this case, to the last bus stop, which is either Sandness or ForusNord. As illustrated in Figure 35, bus2 takes 25.29 minutes to travel from Stavangerhpl10 to Sandness. Likewise, Figure 36 shows that bus3 takes 20.6 minutes to drive from Stavangerhpl10 to ForusNord.

10.2. Scenario-1 Results

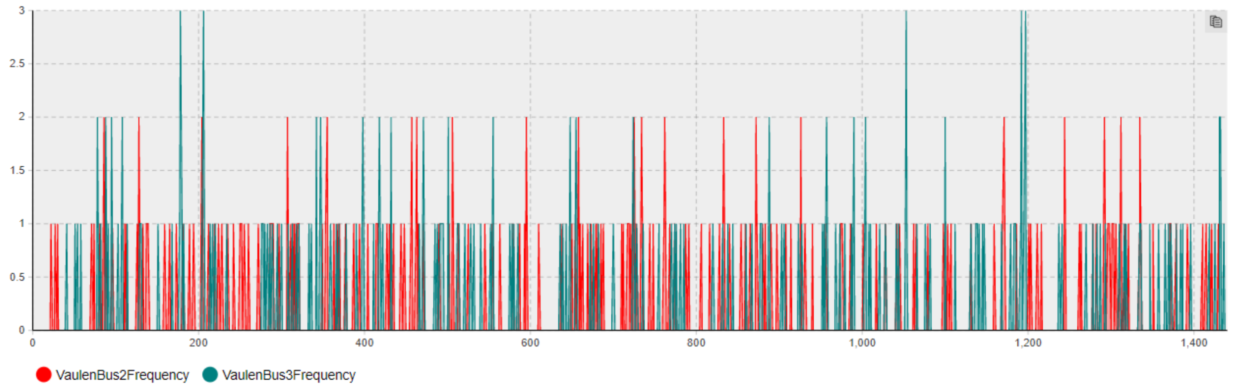

Figure 37. Scenario1 -Bus frequency at Vaulen.

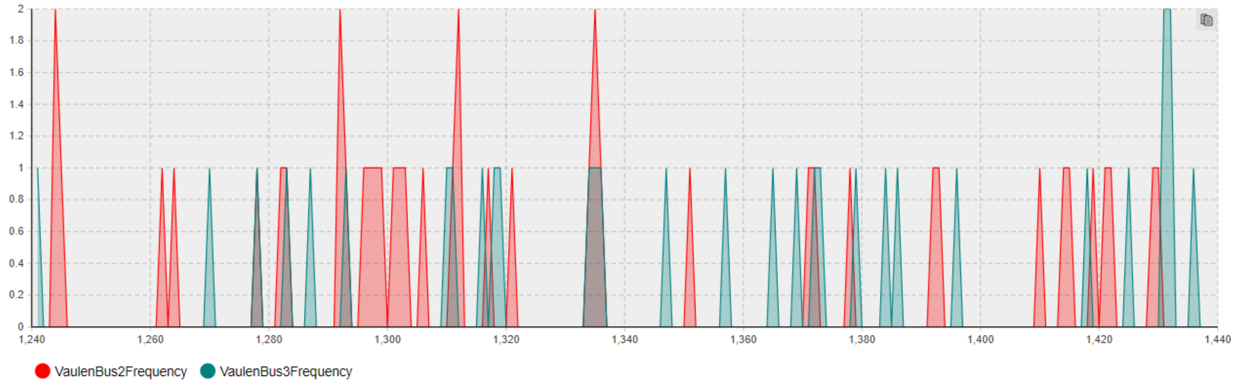

Figure 38. Scenario1-Bus frequency at Vaulen between minute 1240 and1440

The frequency of bus2 and bus3 is presented in a red and blue-green color, respectively, in Figure 37 and Figure 38. The two figures show that a single bus appears at Vaulen most of the time. Often there is also times where the buses run in the same place at the same time. Figure 38 illustrates the last 200 minutes of bus frequency, which is presented in Figure 37. The graph time window is reduced from 1440 minutes to 200 minutes to provide a simple representation.

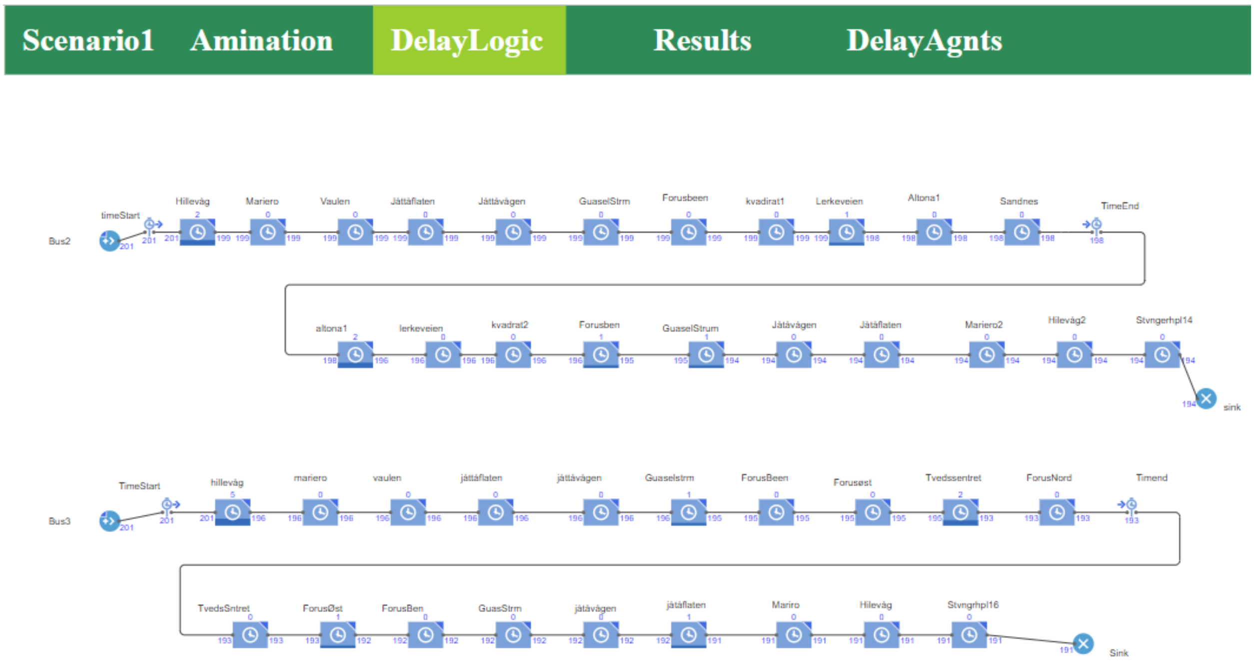

Figure 39. Scenario1-Bus distribution along the route.

The number of buses that generate from the source and their distribution on the route is indicated in Figure 39. It is assumed that buses are released from the stavangerhlp10, with an arrival rate of eight buses per hour. With this assumption, 400 buses will be generated and operated on a round trip for both route2 and route3. The figure shows, in particular, an equal number of buses are produced by bus2 and bus3 sources. The author also extracted and processed bus frequency data in Excel, and presented as charts in Appendix B for clarification. The conditioned data, together with Figure 37, shows that three buses appeared fifteen times, and two buses appeared seventy-six times.

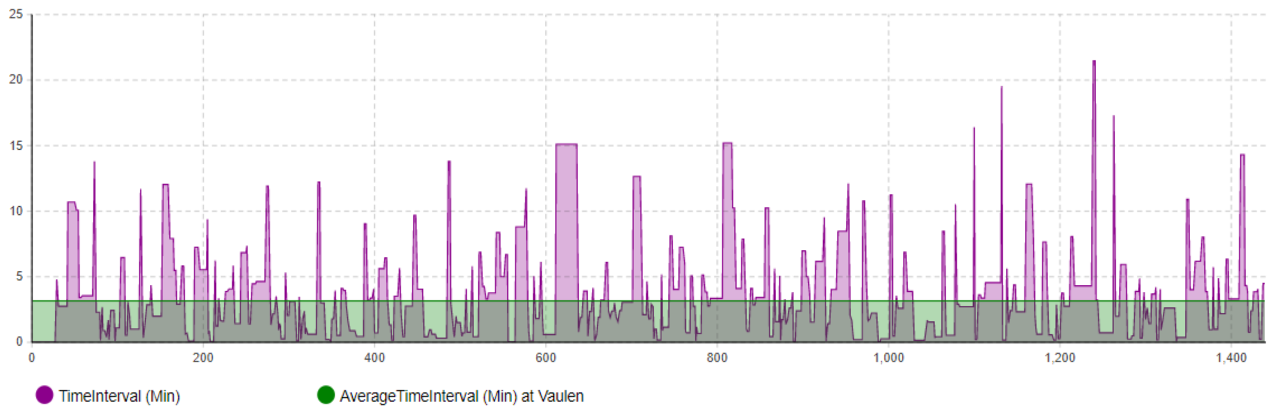

Figure 40. Scenario1-Time Interval Between buses at Vaulen

Figure 40 indicates the arrival time difference between two buses at Vaulen. The author conditioned the data extracted from Figure 40 to identify the minimum, average, and maximum bus arrival time interval. Figure 40 and the data processed indicate that the time between two buses ranges from one to twenty-five minutes, which means that the bus flow is not either punctual or regular. However, Figure 40 and the conditioned data presented as charts in Appendix B indicates that the average arrival time interval lies between 3-4 minutes, to be specific 3.156.

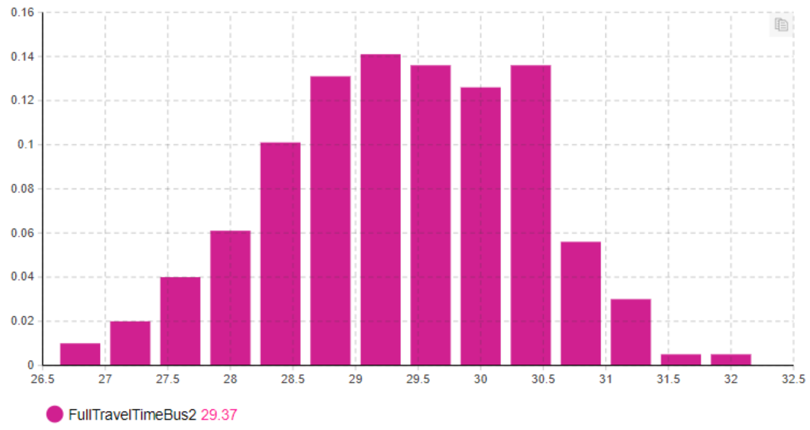

Figure 41. Scenario1- Bus2 Travel time.

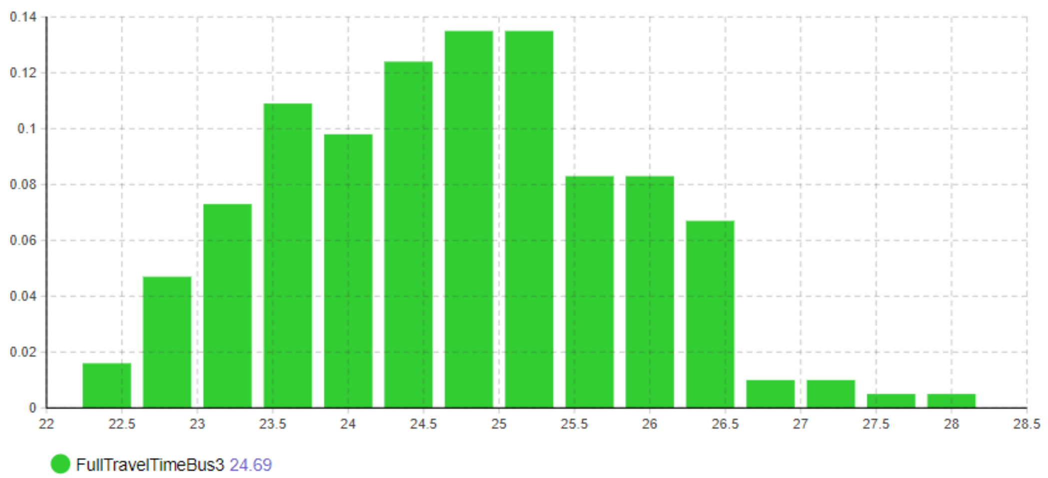

Figure 42. Scenario1-Bus3 Travel Time

Figure 41 and Figure 42 indicate the journey time of Bus 2 and Bus 3. Travel time is the amount of time a bus takes to arrive at the last bus stop of the two routes (Sandness or ForusNord) from the starting bus stop Stavangerhpl10. As shown in Figure 41, the bus2 drive time from Stavangerhpl10 to Sandness is 29.37 minutes. Correspondingly, Figure 42, indicates that bus3 spent 24.69 minutes on the road to drive from Stavangerhpl10 to ForusNord.

10.3. Scenario-2 Results

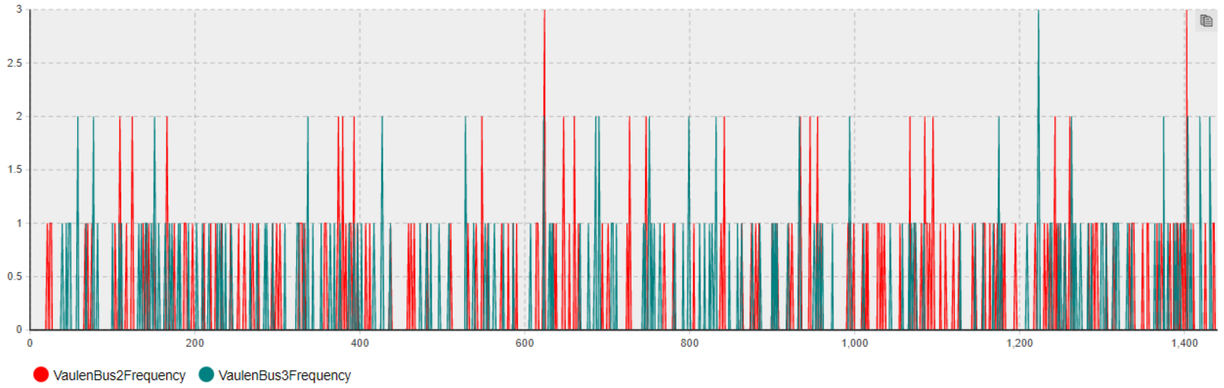

Figure 43. Scenario2 -Bus frequency at Vaulen.

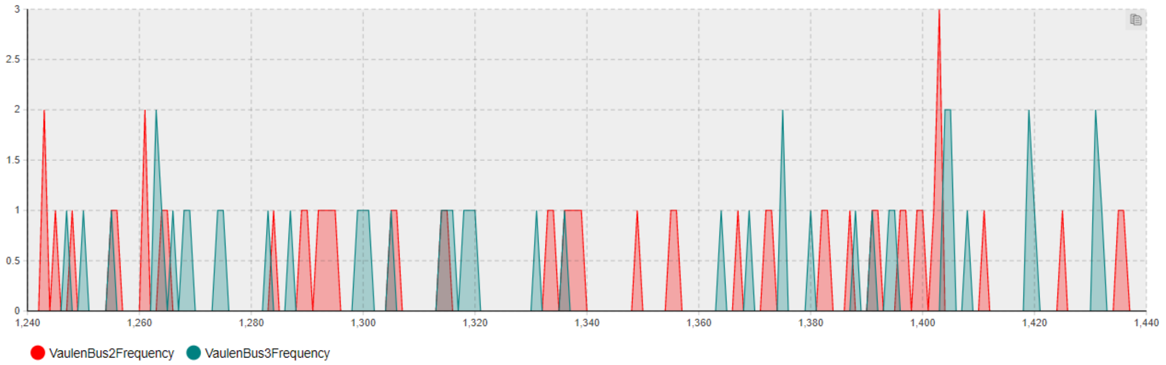

Figure 44. Scenario2 -Bus frequency at Vaulen between minute 1240 and1440.

The frequency and number of each bus that appears at Vaulen is illustrated in Figure 43 and Figure 44. Bus2 and bus3's arrival frequency is presented in red and a blue-green color, respectively. The two figures show that a single bus appears at Vaulen most of the time. Yet there are times where bus bunching occurs. Figure 44 illustrates the last 200 minutes of bus frequency. The graph time window is reduced from 1440 minutes to 200 minutes to provide a simple representation.

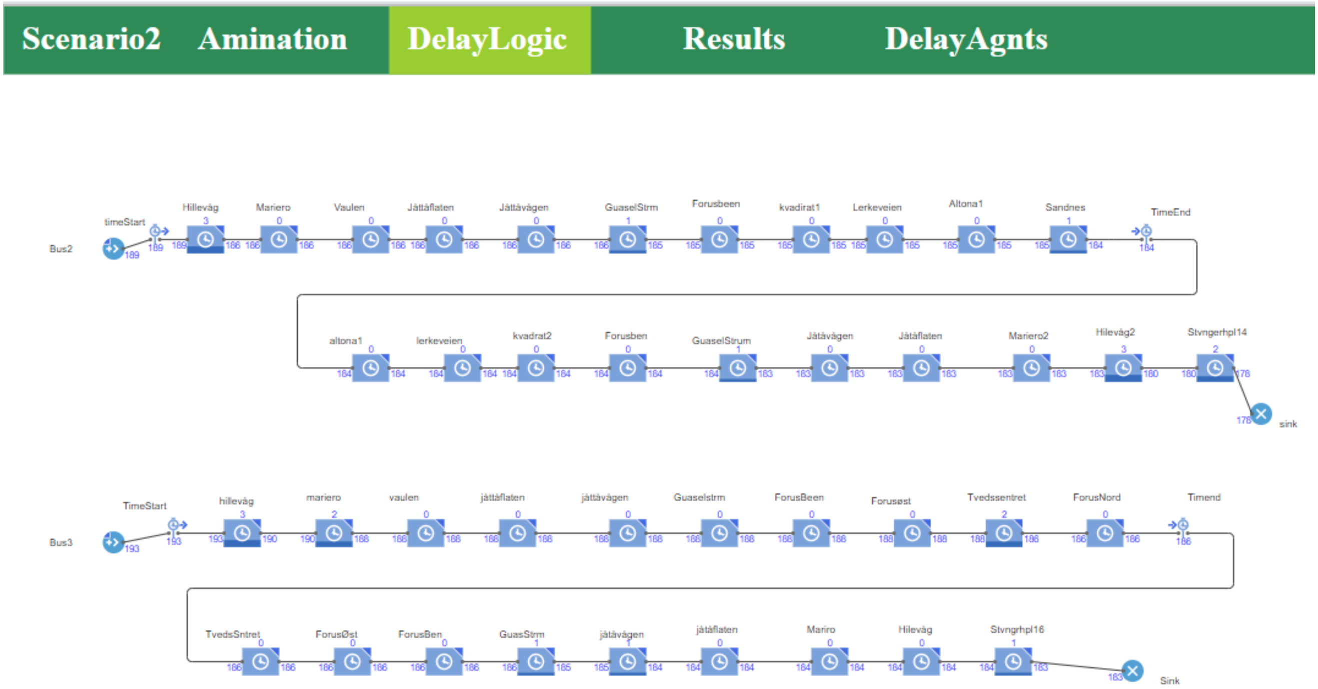

Figure 45. Scenario2-Bus distribution along the route.

Figure 45 demonstrates the number of buses generated from the sources, and their distribution along the two routes is shown. It is assumed that buses are released from the stavangerhlp10, with an arrival rate of eight buses per hour. With this assumption, 189 bus2, 193 bus3, and 384 buses in total will be generated and operated on a round trip for both route2 and route3. The author also extracted, processed bus frequency data in Excel and presented as charts in Appendix C for clarification. The conditioned data, together with Figure 43, shows that four buses appeared twice, three buses bunched eight times, and two buses clumped seventy times at Vaulen.

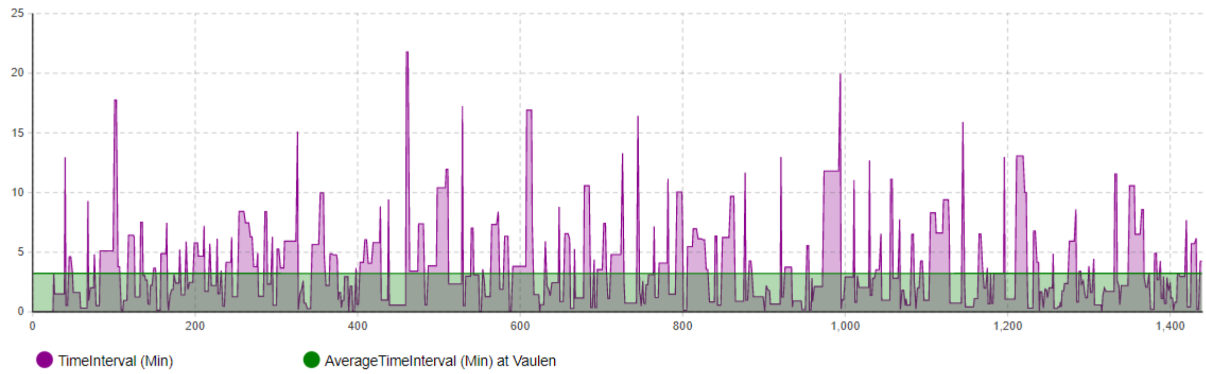

Figure 46. Scenario2-Time Interval Between buses at Vaulen

Figure 46 indicates the arrival time difference between two buses at Vaulen. The author uses the conditioned data that are extracted from Figure 43 to identify the maximum, average, and minimum bus arrival time interval. Figure 43 and the data processed indicate that the time between two buses ranges from one to twenty-one minutes, which means that the bus flow is not either punctual or regular. However, the processed data indicates that the average arrival time interval lies between 3-4 minutes which is illustrated in a green color in Figure 46, to be specific 3.223.

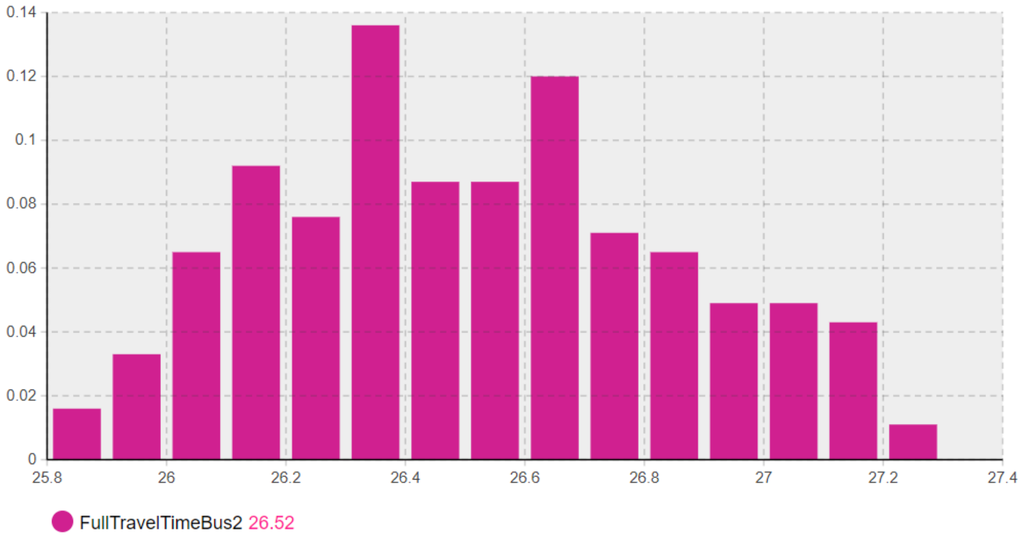

Figure 47. Scenario2- Bus2 Travel time.

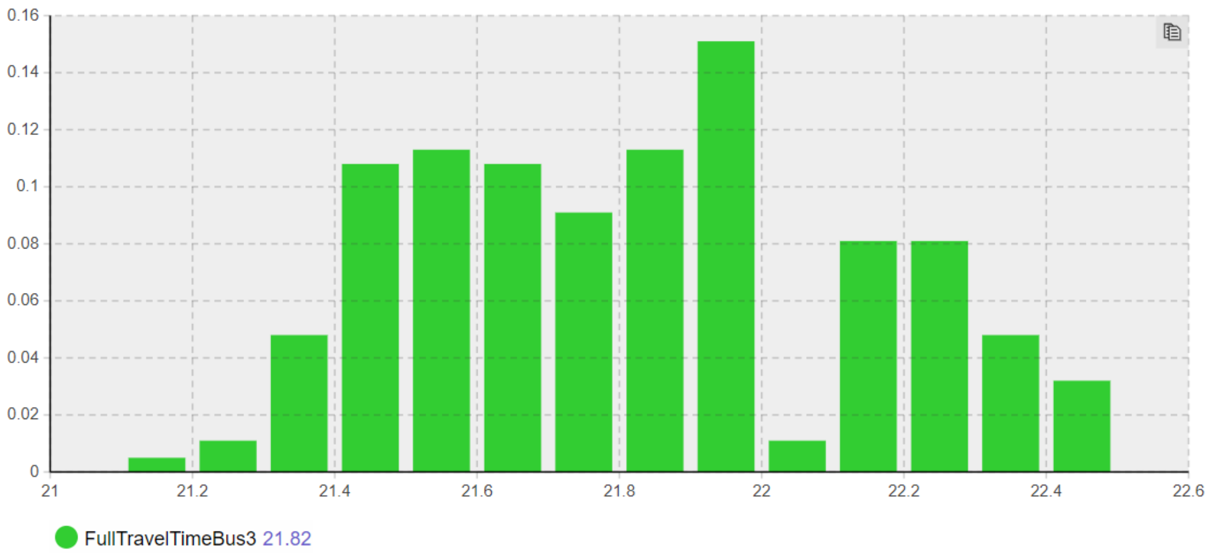

Figure 48. Scenario2- Bus3 Travel time.

The time spent by bus2 and bus3 to drive from Stavangerhpl10 to Sandnes or ForusNord is illustrated in Figure 47 and Figure 48. As illustrated in the two figures, bus2 drives 26.52 minutes to travel from Stavangerhpl10 to Sandness. Likewise, bus3 takes 21.82 minutes to drive from Stavangerhpl10 to ForusNord.

10.4. Scenario-3 Results

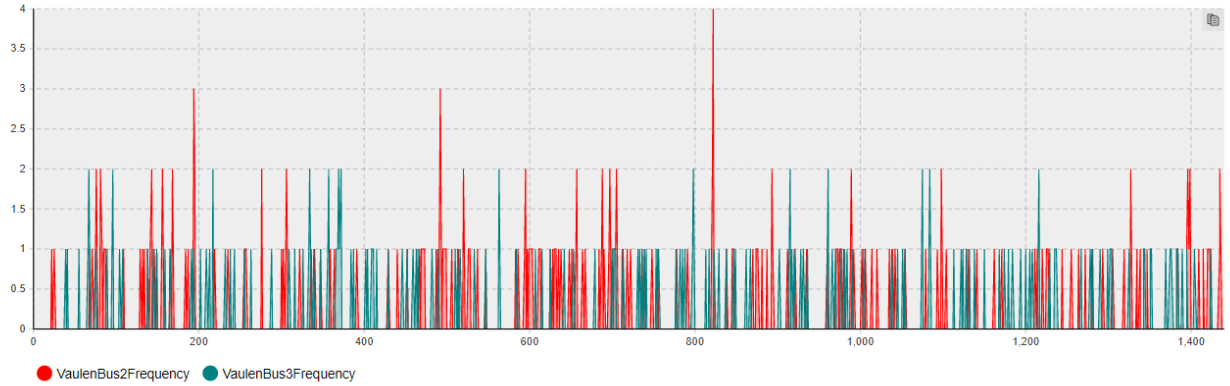

Figure 49. Scenario3 -Bus frequency at Vaulen.

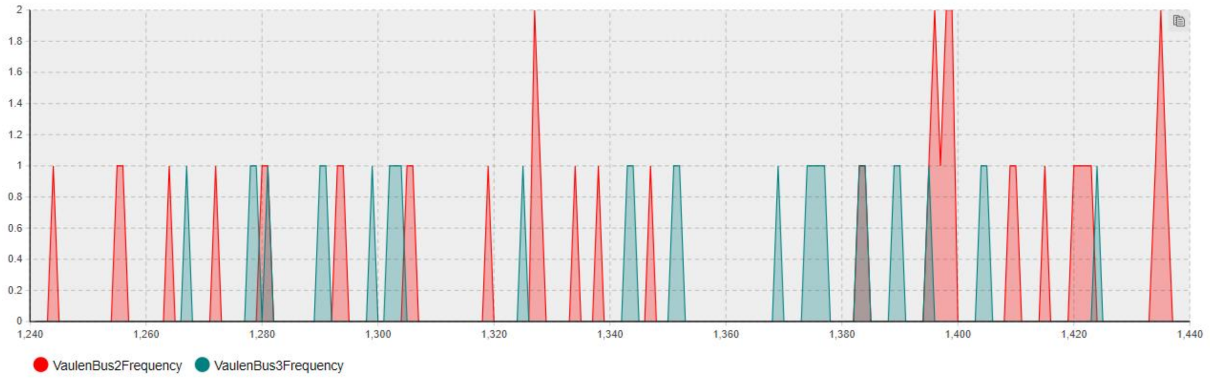

Figure 50. Scenario3 -Bus frequency at Vaulen between minute 1240 and1440.

Figure 49 and Figure 50 illustrates the frequency and number of buses 2 and 3 at Vaulen. The frequency of arrival of bus2 and bus3 is shown respectively in red and blue-green colors. Both figures indicate that a single bus appears at Vaulen most of the time. Nonetheless, there are occasions when bus bunching occurs. Figure 50 illustrates the last 200 minutes of bus frequency. The graph time window of the graph is reduced from 1440 minutes to 200 minutes to provide a simple representation.

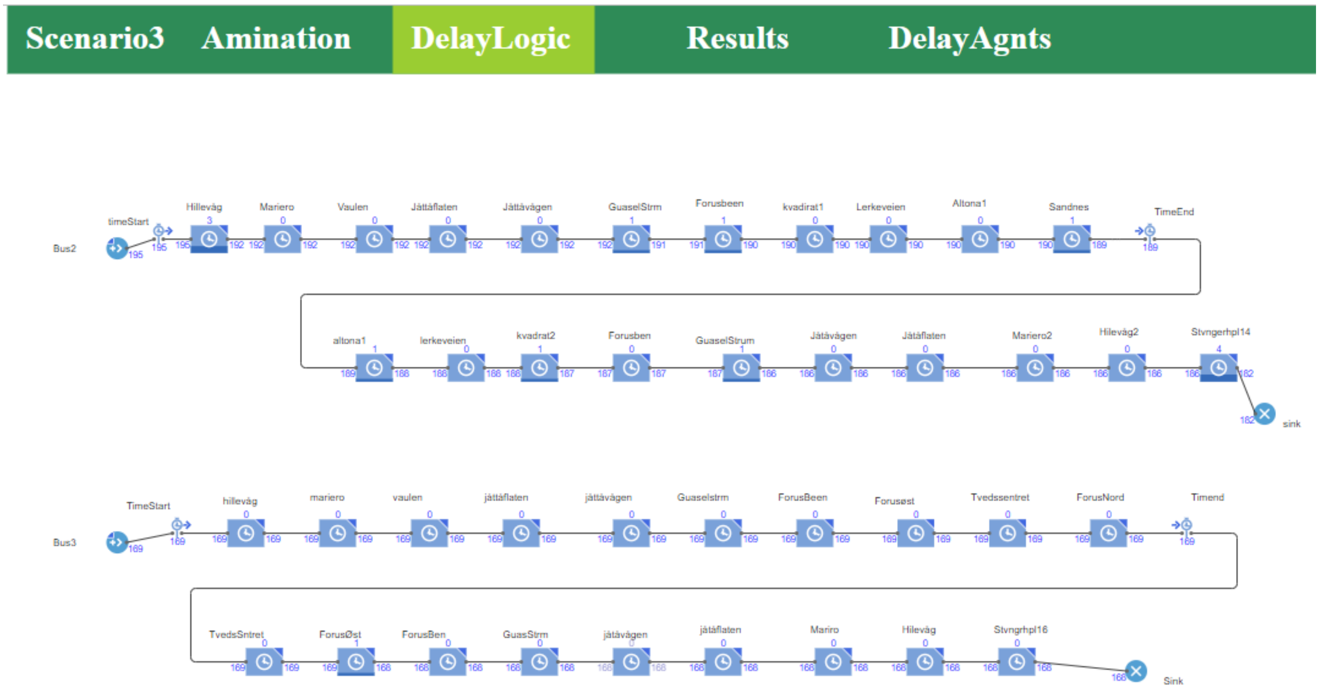

Figure 51. Scenario3-Bus distribution along the route.

Figure 51 illustrates the number of buses generated from the sources, and their distribution along the two routes is shown. Buses are assumed to be released from stavangerhlp10, with an arrival rate of eight buses per hour. With this assumption, a total of 195 buses2, and 169 buses3 will be generated and operated on a round trip for both route2 and route3. The author has also collected, processed bus frequency data in Excel and presented in Appendix D for clarification. The conditioned data, together with Figure 49, shows that four buses appeared twice, three buses bundled three times, and two buses clumped seventy-five times at Vaulen.

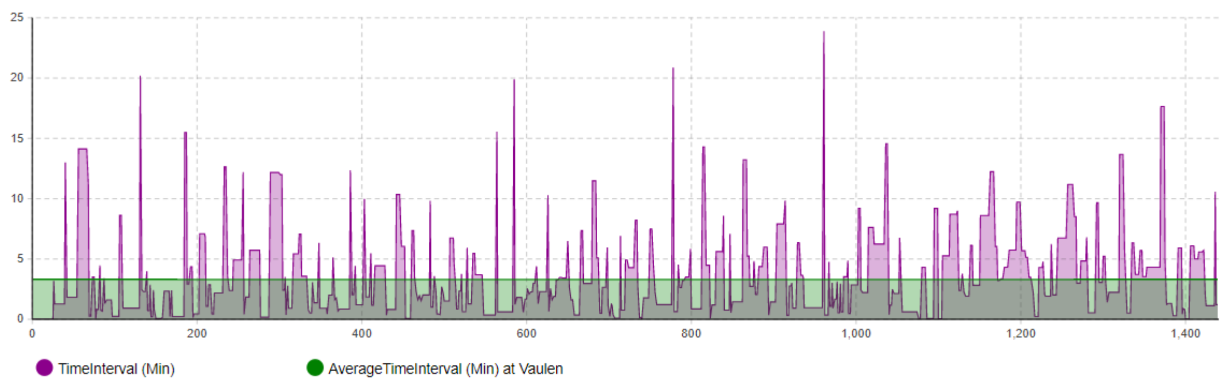

Figure 52. Scenario3-Time Interval Between buses at Vaulen

Figure 44 indicates the difference in time of arrival between two buses at Vaulen. The author uses the conditioned data collected from Figure 41 to describe the maximum, average, and minimum time of arrival of the bus. The data analyzed, and Figure 41 indicate that the arrival time between two buses varies from one to twenty-four minutes, which means that the bus flow is not either punctual or regular. Nevertheless, the processed data shows that the average time of bus arrival is about 3-4 minutes, shown in green color in Figure 44, to be specific 3.304.

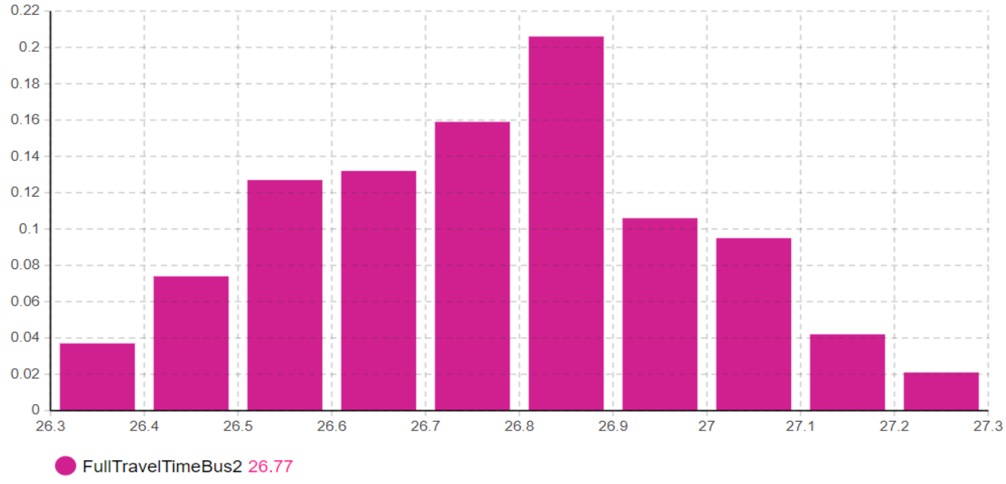

Figure 53. Scenario3- Bus2 Travel time.

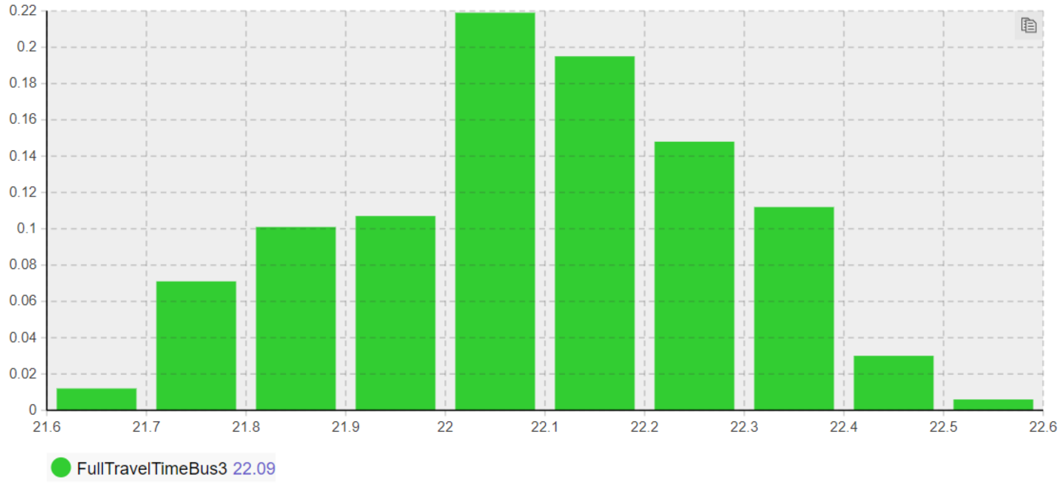

Figure 54. Scenario3- Bus3 Travel time.

The time spent on the route from Stavangerhpl1p to Sandnes and from Stavangerhpl10 to ForusNord by bus2 and bus3 is illustrated in Figure 53 and as shown in Figure 53, the driving time of bus2 is 26.77 minutes. Correspondingly, Figure 54, shows that bus3 spent 22.09 minutes on the route to make a single trip.

10.5. Summary

The presented reference case and scenarios simulation models are built under consideration of a bus rate of eight per hour, and a default bus speed of 50Km/Hr. A comparison assessment is made to discuss the difference in bus frequency, average travel time, and the occurrence count of bunching that arises by the conditions implemented to each model. The comparison is shown in Table 16 ,

Table 17 and Figure 55.

Table 16. Comparison on between Scenarios in terms of bus Frequency, Bunching and Travel time

Simulation Model	**Bus frequency at Vaulen**			**Average Travel time (Min)**		**Bunched Buses and their occurrence count**		
	Min	Avg	Max	**Bus2**	**Bus3**	2 Buses	3 Buses	4 Buses
Reference case	0	3.277	22	25.29	20.6	75	5	2
Scenario 1	0	3.156	25	29.37	24.69	76	15	-
Scenario 2	0	3.223	21	26.52	21.82	70	8	2
Scenario 3	0	3.304	24	26.77	22.09	75	3	2

Table 17. Comparison on punctuality and bus punching between Scenarios

Simulation Model	**Punctuality (%)**	**Bus Bunching (%)**
Reference case/Scenario 0	70	31
Scenario 1	70	35
Scenario 2	70	32
Scenario 3	56	42

The above table shows that if the operation of parts of Korridor1 changes from a dedicated lane to non-priority, the average travel time of the buses will be increased. The comparison between the reference case and scenario3 gives a good visualization of the effect of the introduction of a delay factor in the system. A delay that happens in the two roundabouts at Hillevåg can disrupt the whole system by affecting both bus punctuality, travel time and create bus bunching.

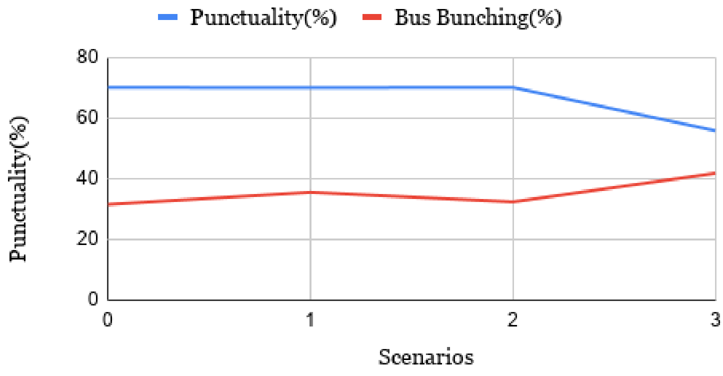

Figure 55. Punctuality (%) and Bus Bunching (%) Vs. Scenarios

Furthermore, the author also makes an assessment and provides an insight into the relationship between the bus rate, punctuality, and bunching. Table 17 and Figure 56 illustrates how the number of buses per hour that released in the system relates to the punctuality and bus bunching.

Table 18. The relationship between Bus rate, Punctuality and Bus bunching.

Rate (Bus/Hr.)	Punctuality (%)	Bus Bunching (%)
6	61	30
8	70	31
10	76	32
12	83	42

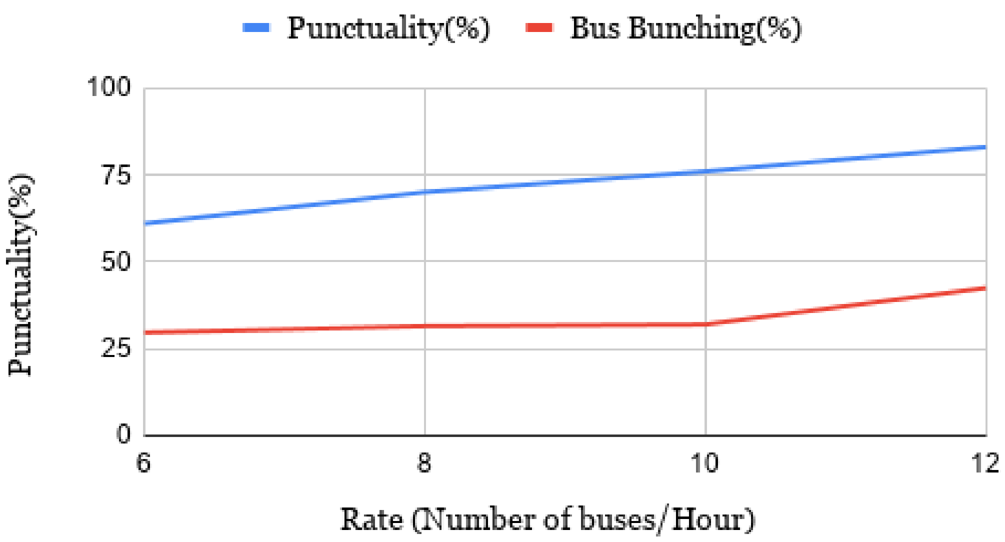

Figure 56. Punctuality (%), Bunching (%) vs, Bus rate (Number of bus/Hour)

11. Conclusion

In this paper, a combination of a discrete event, system dynamic, and agent-based simulation model for a high-frequency bus line is developed for the mobility provider company, Kolumbus. The objective of the study was to answer two questions. The first aim was to determine what the effect will be on punctuality when part of korridor1 is changed from having priority at crossings, traffic light, and roundabouts to no priority. Besides, the study was also aimed to learn the number of buses that are required to achieve the planned 3-4 minute bus frequency if korridor 1 is a BRT system. Bus frequency and travel time are used as performance measurements to measure punctuality.

A case study and simulation model was made for a route that stretches from Stavanger to Sandness, and Stavanger to ForusNord. Route2 and Route3 contain a total of 73 bus stops, and 26 shared stops. In addition to the reference case model, which constitutes a complete bus priority system, three scenarios were simulated by introducing a delay factor into parts of the shared lane. Scenario 2 and 3 simulated the condition of two roundabouts with no priority. From the assessment made, insight is obtained for bus punctuality and bunching.

A rate of eight buses per hour and a four-minute time interval between two consecutive buses are taken for the punctuality check. Comparing the simulation models, if the interval time is less than four minutes, the system is assumed to be punctual On average, the bus frequency lies between three-four minutes in all scenarios. However, the degree of punctuality and the occurrence of bus bunching is varied between the scenarios.

For the full bus priority network, the result shows 70% punctuality with 31% bunching. By introducing two roundabouts in part of the route, the punctuality reduced to 56% and 42% of bus bunching. If buses have no priority at roundabouts, the punctuality decreased by about 14%. Meanwhile, bus bunching is increased by about 11%, showing that the two roundabouts can be a bottleneck for the whole system. In addition, the simulation result shows about 18% and 20% increase in travel time of bus2 and bus3, respectively, if the first segment of korridor1 is operated in mixed traffic.

Furthermore, varying the bus rate affects bus punctuality. With an increase in bus rate, both punctuality and bunching are increasing proportionally. Increasing the rate from eight to twelve improves punctuality by 13% with 11% increase in bus bunching. In contrary, with only decreasing the bus rate from eight to six, punctuality degrades by about 11% with a slight improvement in bus bunching. In general, a delay caused by operating the buses in a non-priority route affects the frequency, and travel time and increasing the number of operating buses improved punctuality.

In conclusion, the thesis provides insight into the possible effect of the changes made on parts of the BRT system in terms of the relationship between delay time, punctuality, travel time, and the number of buses. It can also help decision-making for the planning and operation optimization of the bus transportation system.

Further work may focus on extending this AnyLogic simulation model to include the rush hour effect, passenger distribution, and bus capacity. The model can also be further developed to allow scenarios to run continuously instead of running a single scenario at a time. It will enable the users to check, visualize, and gather results in a shorter time. Furthermore, this work can be utilized as an input to a solution to avoid bus bunching based on real-time communication using the internet of things.

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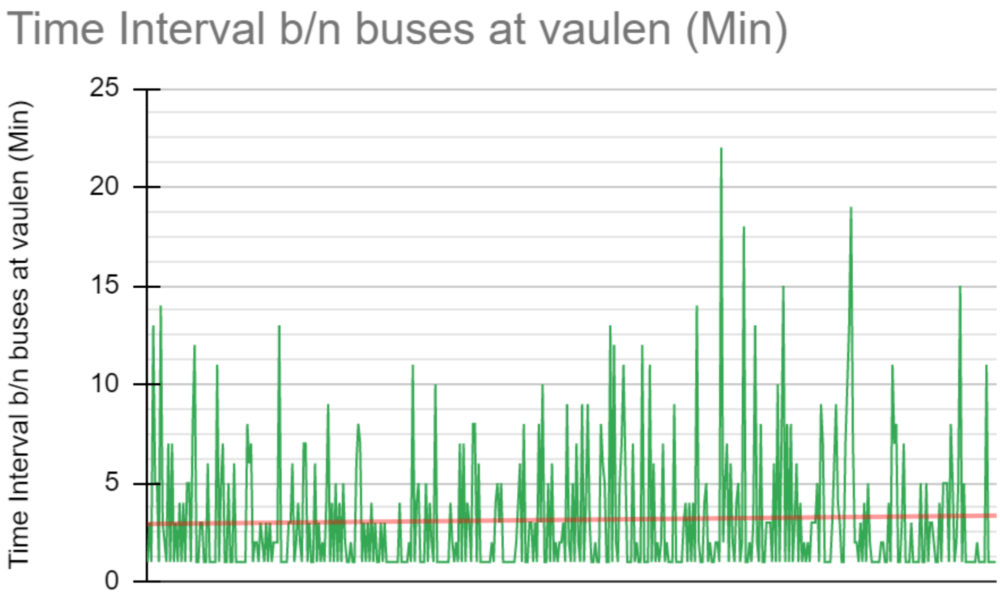
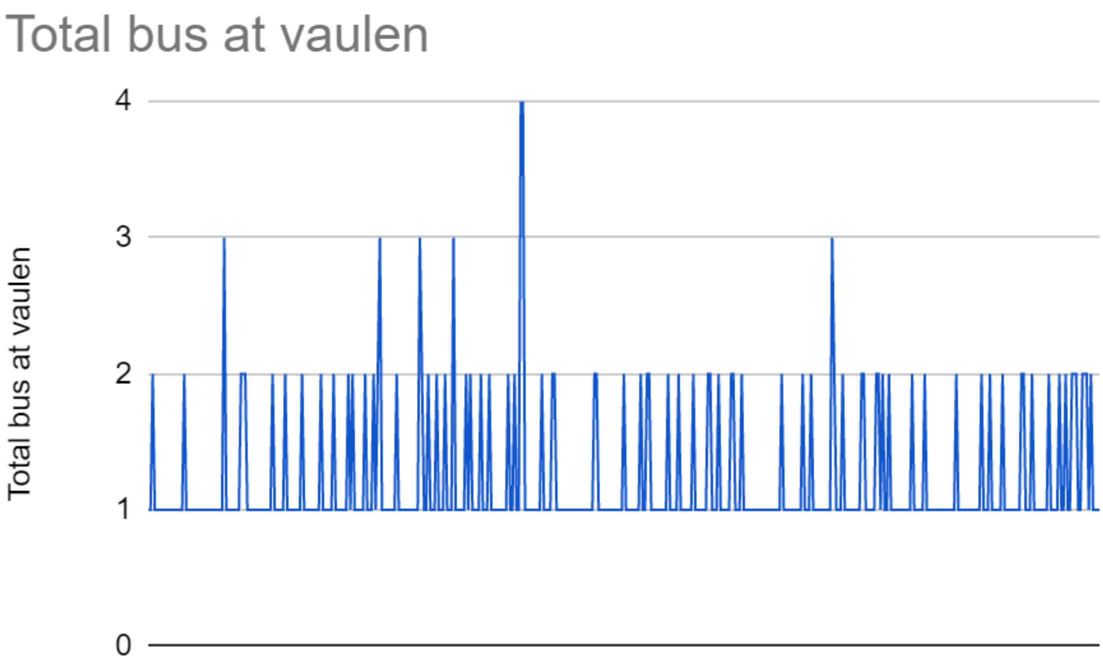
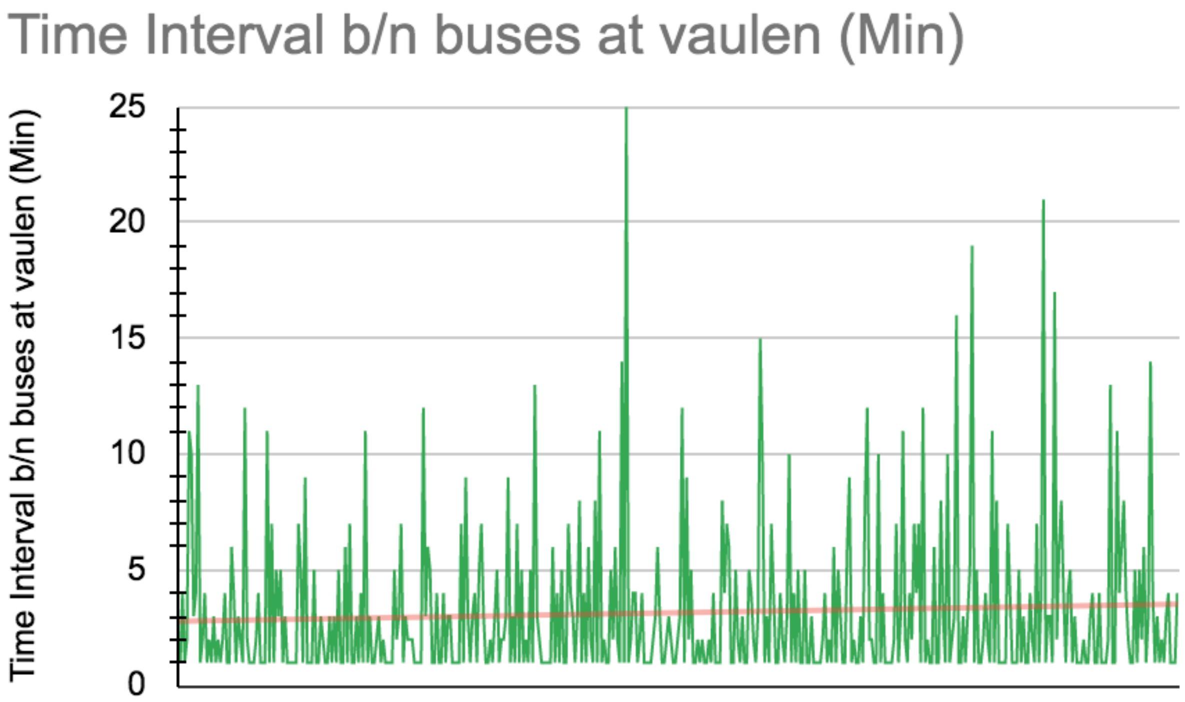
Appendices

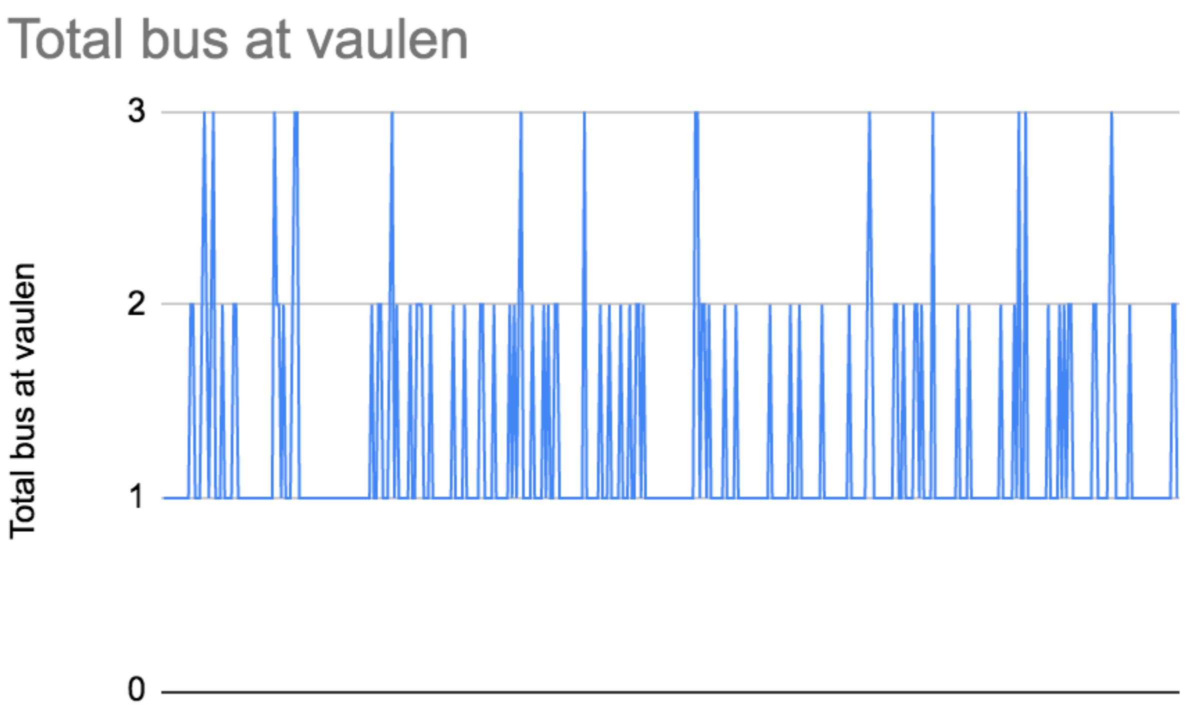
Appendix A. Reference case bus frequency and total number of buses at Vaulen



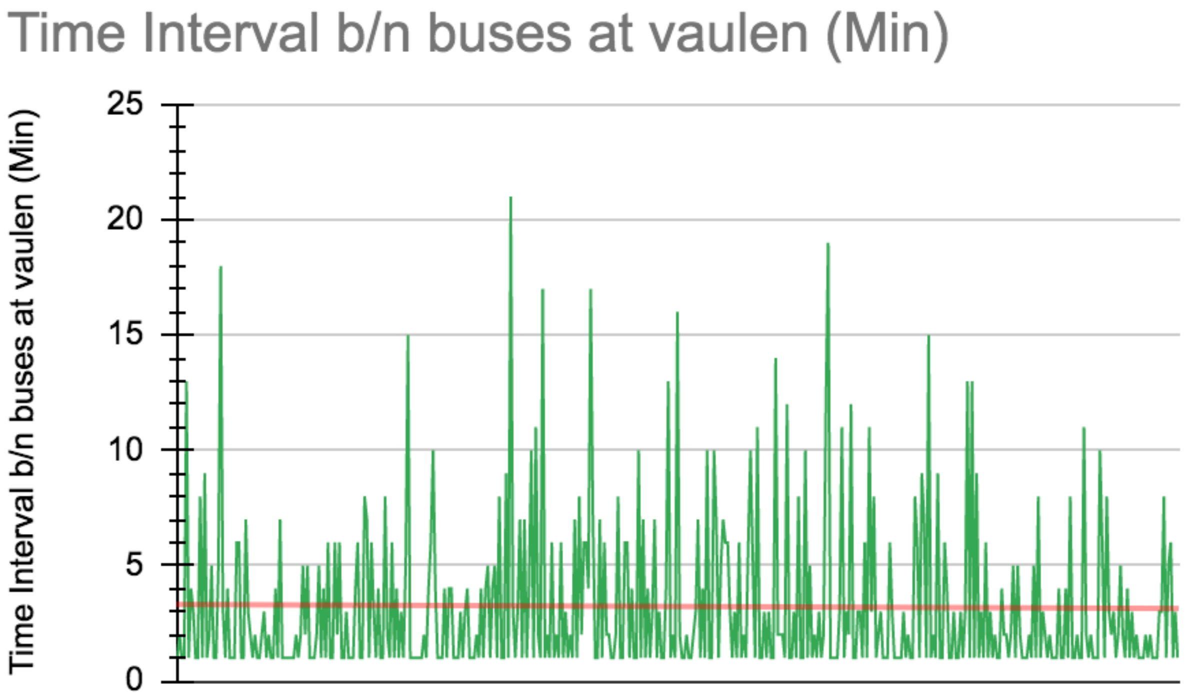


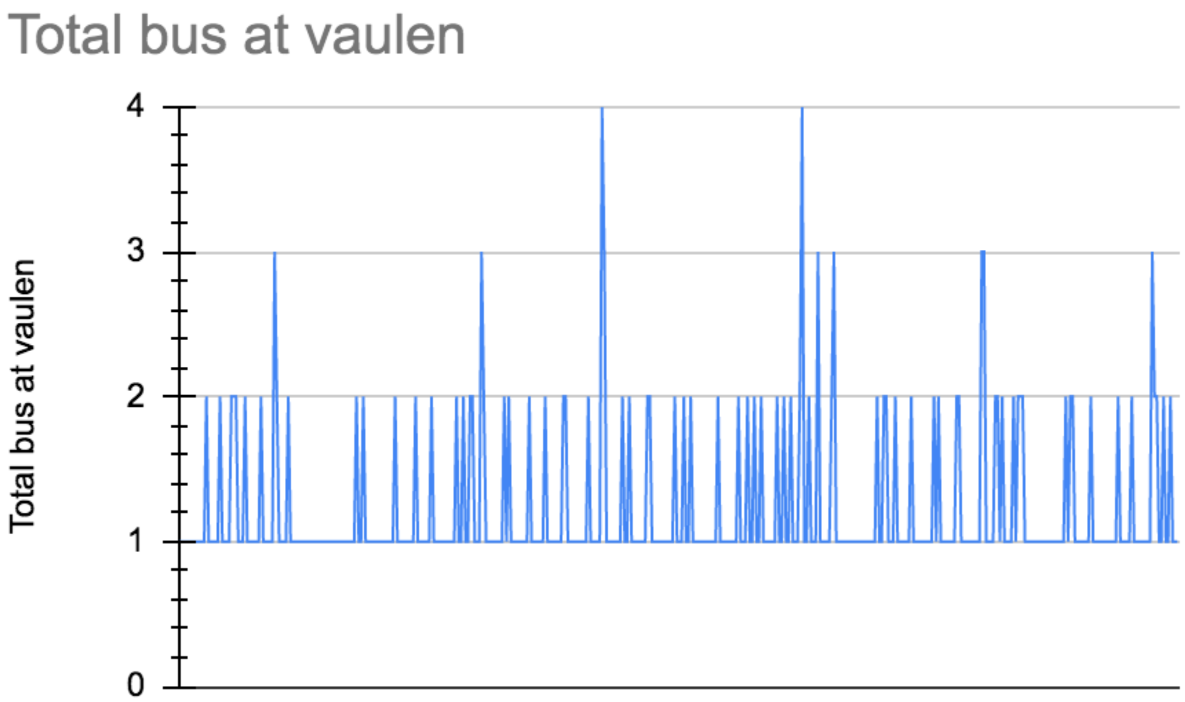
Appendix B. Scenario-1 bus frequency and total number of buses at Vaulen





Appendix C. Scenario-2 bus frequency and total number of buses at Vaulen





Appendix D. Scenario-3 bus frequency and total number of buses at Vaulen