Ålesund

A Dutch Perspective on a Future-Proof City

CEGM3000: Multidisciplinary Project
Bouwe-Jan, Christiaan, Isabelle, Rona and Thijs

Delft University of Technology

TUDelft NTNU Ålesund kommune SØRSIDA RE-VALUE

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Student Name	Student Number	Track
Bouwe-Jan ten Donkelaar	5078172	Resource and Waste Engineering
Christiaan Boon	5172047	Structural Engineering
Isabelle van Heijzen	5347289	Structural Engineering
Rona Jak	5024234	Traffic and Transport Engineering
Thijs Krijgsman van Spangenberg	5596963	Traffic and Transport Engineering

Supervisors TU Delft:	Dr. V.L. (Victor) Knoop, Prof. dr. H.M. (Henk) Jonkers, Dr. ir. Y. (Yuguang) Yang
Supervisor Ålesund Kommune:	Ir. A. (Andreas) Amundsen
Supervisor NTNU i Ålesund:	Dr. ir. T.S. (Torodd) Nord
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Preface

Before you lies the report *Ålesund, A Dutch Perspective on a Future-Proof City*. It has been written as part of the Master's programme of Civil and Environmental Engineering at the TU Delft in a Multidisciplinary Project from September until November 2025. The project brings together knowledge from different specialisations to provide a clear and practical advisory perspective for the local municipality.

We wanted to step out of our comfort zone and take the opportunity to experience another culture and work setting abroad. After a few online meetings and preparatory documentation, we got the green light and were allowed to go to Norway. It has brought us many benefits, from learning to communicate professionally in an international setting, to gaining more experience in research in an unknown language, but overall, it has brought us together closer as a team.

However, we could not have done it without the wonderful support of the many people who helped us during the process. First and foremost, we would like to acknowledge Andreas Amundsen from the Ålesund Kommune, who was available throughout the entire quarter for general questions and consistently offered his guidance and support. Together with his always enthusiastic and kind-hearted colleague, Lin Marie Norberg Jacobsen, we felt very welcome in the city from day one, and they introduced us to everyone. We would also like to express our gratitude to Torodd Skjerve Nord (NTNU) for his weekly availability, detailed feedback, and the broad and valuable knowledge he shared with us. We would also like to thank our supervisors from TU Delft, Victor Knoop, Henk Jonkers, and Yuguang Yang. Their guidance throughout the entire process has helped bring our deliverables to a high standard. We are also very thankful to everyone who is not explicitly mentioned, but who assisted us during our time abroad.

Bouwe-Jan, Christiaan, Isabelle, Rona and Thijs
Ålesund, Norway, November 2025

Summary

The municipality of Ålesund has large ambitions to make the city more sustainable, more vibrant and ultimately future-proof. However, it faces several problems in doing so. First of all, the population is increasing, while there are limited possibilities for growth. The increasing population will put extra pressure on the road infrastructure network, which is already congested every day. The city has an extensive public transport network, but this is barely used. In addition, the population is ageing. Young people leave the city, while the share of older residents increases. A balanced population in terms of age is desired, so efforts have to be made to let the city remain attractive for all generations. This could be done by realising a vibrant new city district, which the municipality aims to do in Sørsida. This area is now mainly unused, with unoccupied or temporarily used buildings. The Sørsida project first entailed demolishing these buildings, and constructing new ones after. However, since sustainability is becoming increasingly more important, reuse of existing buildings is now also considered. An example is the Devold building close to the cruise quay. Another problem is the nearing end of life of the Steinvåg bridge between Hessa and Aspøya. This bridge has to be replaced within the coming 12 years, but no plans are in place yet. It forms the only connection between Hessa and the rest of the city, forming an essential link in the road network.

The municipality has set out three separate cases to investigate:

- Design a new connection between Hessa and Aspøya as a replacement for the Steinvåg bridge.
- Assessing the environmental impact of demolishing the Devold building and constructing something new compared to reusing it.
- Investigate the transport network to determine if further growth of car usage is possible and to analyse if public transport can help reduce the congestion problems.

The cases are separate projects, but the long-term effects of them will influence each other and the vision of the city. Therefore, they are linked to each other in order to get more insight in their long-term effects, as well as they ways in which they influence each other. This will give also give a better insight in the opportunities of the cases when considering it as a single, large project.

The public transport network of Ålesund (operated by *FRAM*) was analysed using General Transit Feed Specification (GTFS) data in two configurations: buses only and buses plus already existing ferries. The system is generously dimensioned relative to current demand: no link reaches saturation and average bus occupancy is 32%. Coverage is city-wide, with passenger flows concentrated on the main west–east corridor between the city centre (*Kollektivknutepunkt*) and *Moa trafikkterminal*; key hubs show high betweenness centrality. The network is robust and well-structured. However, since ridership is low, there are other factors than the network itself that prevents people from using public transport. Further research to these factors is recommended.

A traffic model of the city and its direct surroundings is also constructed. This model is built for the evening peak and includes the car, bus, cycling and walking as travel modes. Congestion occurs on the main east-west connection during the evening peak. No further increase in car traffic is possible on the current infrastructure network. Increasing the bus frequency on all lines by 50% has a negligible effect on overall ridership, so it is not worth it.

A multi-criteria decision analysis is performed to deduce the optimal location of a new connection between Hessa and Aspøya, as replacement of the Steinvåg bridge. Criteria are for example costs and emissions, but also travel time between Hessa and the city centre and compatibility with the existing infrastructure. The travel times for different location alternatives are determined with the previously mentioned traffic model. The optimal location turns out to be at the location of the current bridge, but the orientation of the bridge is slightly altered.

The newly designed bridge is a tied-arch bridge, which is comparable to the design of the Steinvåg bridge. This design was mainly chosen to appeal to the local population, as the current bridge is a landmark in the city centre. Designing a different type of bridge would likely lead to resistance from the local population. In addition, it is common practice to replace bridges with a bridge of similar shape in Norway. The bridge will have one lane per direction, with a cycling lane and side walk on either side. Since Hessa might see developments like new housing or jobs in the future, due to an increase in population, the bridge needs to accommodate future traffic flows. Even if 5,000 inhabitants and 5,000 new job opportunities are realised on Hessa, the bridge will not be the bottleneck in the traffic system when designed with one lane per direction. The preliminary design is based on both a DIANA FEA model and hand calculations. This is done based on the Norwegian Standard of the Eurocode and the National bridge guidelines.

The chloride content of the Steinvåg bridge is analysed to investigate appropriate end of life scenarios for its construction elements. Data on the chloride content of the bridge in 2007 and 2017 was provided by the county of Møre og Romsdal. This data was used to estimate the chloride content in 2037, which is close to the end of the service life of the bridge. A publication of Statens vegvesen was used to establish which chloride contents were acceptable and which were not. Comparing the estimated chloride contents to the limit values shows that the concrete is too contaminated to be reused for structural purposes. Therefore, it is advised to separate the steel from the concrete, so that the steel can be recycled into new products and the concrete can be used as landfill.

Multiple life cycle assessments are performed in parallel for the Devold building. The first is based on both the Norwegian standard NS 3720 and the second on European standards EN 15978 and EN 15804. The results of both assessments show that reusing the Devold building has a lower environmental impact than demolishing the building and constructing a new one. They both show that reusing the Devold building has a lower environmental impact than demolishing the building and constructing a new one. This is mainly due to the high environmental impact of producing and installing new construction elements, encompassed by modules A1-A5 in the assessment. A comparison between the results of the Norwegian and European methodologies shows that the Norwegian one is less effective at creating a complete image of the environmental impact. Therefore, it is recommended to opt for the European methodology.

The municipality is investigating the future use of the Devold building. One of the options is to turn it into a concert hall. This is in line with the municipality's vision of making Sørsida a new vibrant city district. However, a concert will have a large impact on the already busy transport network. When a concert starts during the evening peak, the maximum amount of visitors is 500. A total grid lock will occur with higher visitor numbers due to people arriving by car. If a concert starts just after the evening peak, 1,000 people can be attracted by it without heavy congestion occurring.

Lastly, a comparison has been made between projects in Norway and the Netherlands. Some important differences were found between the two engineering cultures. In Norway, projects are usually more flexible and can therefore be completed faster. In contrast, the Dutch approach often takes more time, as it focuses more on long-term planning and preparation. Both approaches have corresponding advantages and limitations.

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Introduction

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This chapter outlines the scope of the project and presents the general background information necessary to understand its context. It highlights the relevance of the various disciplines involved and clarifies how they interconnect throughout the work. Finally, it identifies the central problem that serves as the guiding thread for the remainder of the report.

1.1. Delft University of Technology

This project was carried out by five master's students from the Delft University of Technology, all in their second year of study. The team consists of students from three different specialisations within the Faculty of Civil Engineering and Geosciences: two from Traffic and Transport Engineering (master Civil Engineering), two from Structural Engineering (master Civil Engineering), and one from Resource and Waste Engineering (master Environmental Engineering).

The Multidisciplinary Project (MDP) is an MSc elective module in which students from different disciplines work together to solve a real-world problem for an external client. The goal of the MDP is to combine the technical, environmental, and societal dimensions of civil engineering into an integrated solution strategy. Students are encouraged to set up their own project and to conduct it abroad, thereby gaining experience in international collaboration and professional practice.

In this case, the project was initiated in cooperation with Ålesund Kommune, focusing on the future development of the city's transport, structural, and environmental systems. Working from different technical perspectives, the team analysed the existing situation, developed scenario-based approaches, and formulated recommendations to support Ålesund's ambition to become a more sustainable and resilient city.

1.2. Project Description and Area

1.2.1. City Context and Demographics

Ålesund is the largest city between Bergen and Trondheim on the west coast of Norway, located in the Sunnmøre fjords in the Møre og Romsdal county. The city has experienced steady population growth in recent decades and continues to function as a regional hub for commerce, education, and several services (Ålesund Kommune, 2025b). Its demographic profile is characterised by 46,310 inhabitants in the city (Stokkan et al., 2025) (59,305 inhabitants in the municipality), with a population distribution that reflects both a significant working-age group and an increasing share of elderly residents (Statistisk Sentralbyrå, 2025c), see Figure 1.1. The presence of a university campus (NTNU i Ålesund) and several secondary schools also attracts a younger demographic, which supports the demand for housing, transport, and cultural activities.
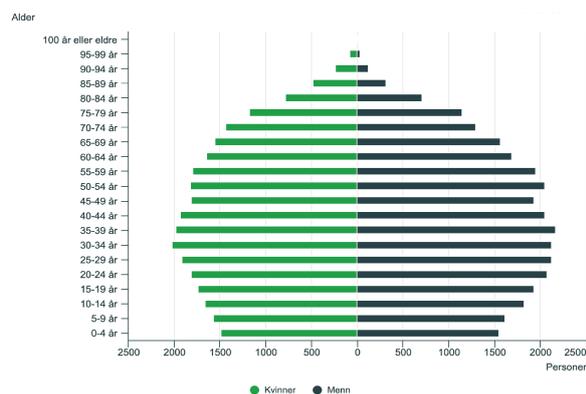
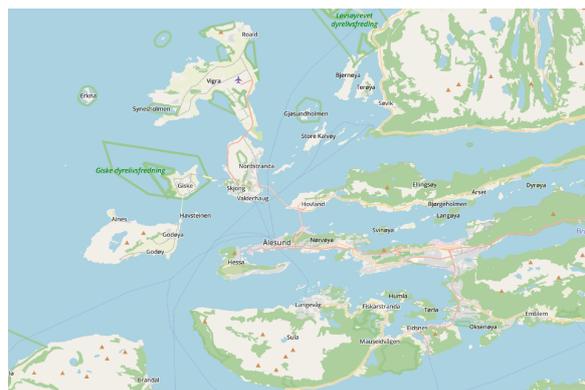**Figure 1.1:** Ages in Ålesund (Statistisk Sentralbyrå, 2025c).

Figure 1.2: Surroundings of the city of Ålesund (OpenStreetMap contributors, 2025).

Ålesund's economy is historically rooted in fisheries and the maritime sector, but today it also relies on tourism, education, and knowledge-intensive services. The city remains Norway's largest fishing port and an important cruise destination, underlining its dual role as both a production hub and a gateway for visitors. Besides, a significant share of the existing building stock and public infrastructure is ageing and no longer aligned with contemporary functional or environmental standards. At the same time, population growth and changing demographic needs have led to a growing shortage of suitable housing, particularly in central areas. As a result, the city faces increasing pressure to renew outdated facilities while simultaneously expanding its capacity to accommodate future residents and services (ITU, 2020).

Despite the expected population growth (from 59,305 inhabitants today to 59,627 in 2030 and 62,151 in 2050 (Statistisk Sentralbyrå, 2025c)), Ålesund faces a demographic challenge. Many young residents move to larger cities for study or employment opportunities, while the share of elderly inhabitants continues to increase. This shift in the population structure places pressure on the city to remain attractive and accessible for all generations.

In response, Ålesund Kommune has set the ambition to make the city more sustainable, accessible, and ultimately future-proof. These goals focus on maintaining reliable connections between the islands, increasing public transport use, and reducing congestion and emissions. At the same time, the municipality aims to create a more vibrant urban atmosphere by encouraging active mobility and the reuse of existing buildings (Re-Value, 2025).

1.2.2. Urban Vision and Development Plans

Ålesund Kommune adopted the Sørsida plan in 2015, a strategic framework for redeveloping the southern waterfront. The plan envisions approximately 130,000 m² of new mixed-use space, including housing, offices, cultural venues, and educational facilities (Ålesund Kommune, 2025b). Sørsida Utvikling AS, established in 2019, oversees this transformation with the goal of making Sørsida a flagship example of sustainable urban development, balancing ecological, economic, and social objectives. The municipality is also part of the Re-Value project, a European initiative that promotes innovative and people-centered planning methods for waterfront regeneration. Through this collaboration, Ålesund aims to test new tools for stakeholder engagement, sustainable mobility, and climate adaptation, ensuring that Sørsida becomes a resilient and inclusive urban district (Re-Value, 2023).

1.2.3. Current Challenges and Opportunities

The ongoing projects show that Ålesund Kommune envisions several changes for the city. It would like to become more sustainable in different aspects, to offer efficient accessibility throughout the city, and to realise urban development that supports cultural and social life, all while dealing with an increasing population.

Ålesund faces several critical challenges in translating this vision into practice:

- Transport and car dependency: The city's strong reliance on private cars conflicts with the am-

bition of sustainable urban mobility. Ålesund aims for zero growth in car traffic use (Bypakke Ålesund, 2024a), making a modal shift towards public transport, walking, and cycling essential, though it requires systemic investments and behavioural change.

- Ageing infrastructure: The Steinvåg bridge between Aspøya and Hessa is at the end of its expected service life, highlighting the need for a replacement design that balances durability, capacity, and sustainability.

- Sustainability and circular construction: Large-scale demolition and redevelopment raise questions about material waste. Integrating reuse and circular economy principles is essential to reduce environmental impact.

- Ageing population: As mentioned before, young people leave the city, which leads to an ageing population.

1.3. Problem statement

The main problem is that the city of Ålesund is not yet future-proof, which becomes clear from the challenges mentioned in the previous section. Therefore, the municipality has asked to investigate three separate cases, which will help them with policy planning for the future.

- Design a new connection between Hessa and Aspøya as a replacement for the Steinvåg bridge.
- Assessing the environmental impact of demolishing the Devold building and constructing something new compared to reusing it.
- Investigate the transport network to determine if further growth of car usage is possible and to analyse if public transport can help reduce the congestion problems.

Even though these cases are separate projects in different domains, the outcome of each design will to some extent influence the city as a whole and its overall vision. Efforts have been made to identify these effects in order to provide more insight into the long-term impacts and opportunities of the projects.

Traffic intensity is, for example, directly related to the design of a new connection as replacement for the Steinvåg bridge, especially when determining the required number of lanes and width. Also, the location of the bridge determines travel time to the city centre and beyond for the inhabitants of Hessa. Since houses need to be build in order to facilitate the population growth, Hessa might see an increased population as well in the future. This has to be taken into consideration when designing a new connection. Next, the Devold building is located in the Sørsida area, where the municipality aims to develop a vibrant new city district. Such a district could increase pressure on the traffic network because of the additional travel demand to and from the area. The Devold building could be used to create an attractive place that encourages young people to stay in the city, helping to reduce population ageing. Lastly, the construction elements of the Steinvåg bridge can be recycled and repurposed at the end of the service life of the bridge, which is in line with the sustainability goals of the municipality.

Therefore, the three cases given by the municipality are closely related to one another and to the overall future vision of the city. Working on the future of Ålesund is therefore a multi-disciplinary project, where collaboration between disciplines is of utmost importance.

Although Sørsida is the spatial starting point of the municipality's future vision, the wider region is considered in this project to understand how the city functions as an interconnected system.

1.4. Objectives

In order to tackle the three cases given by the municipality, thorough analyses are conducted of the traffic system, environmental impact of different scenarios for the Devold building and new design of the Steinvåg bridge. These analyses are included in Appendix A, B and C respectively.

However, since it has become clear that the cases are closely related to each other and the general future vision of the municipality, 5 additional objectives are formulated that combine the different aspects of the project. These objectives will help show the municipality how the different cases influence each other, which will give them the knowledge to take well-considered decisions for planning decisions that affect the long term development of the city.

The main objectives in which different fields of expertise intersect are formulated in the following objectives for this multi-disciplinary project:

1. Location choice of new main connection between Hessa and Aspøya;
2. Population and jobs growth on Hessa;
3. Realisation of cultural centre;
4. End of Life of the Steinvåg bridge;
5. General future planning.

The fifth objective is not focussed on a specific location, building, or network in Ålesund, but sheds light on the conflicts between ambitious long-term goals and short-term projects.

The three separate detailed analyses form the basis of these objectives. The constructed models and attained results of the analyses are used to adequately tackle these objectives.

1.5. Stakeholder Analysis

As the project involves major spatial and infrastructural changes in Ålesund's city centre, several public, private, and societal actors play an important role in shaping its outcomes. A stakeholder analysis was carried out to identify the most relevant organisations, their interests, and their level of power. These stakeholders were positioned in a power-interest diagram (see Figure 1.3) to visualise their relative importance in the decision-making process.
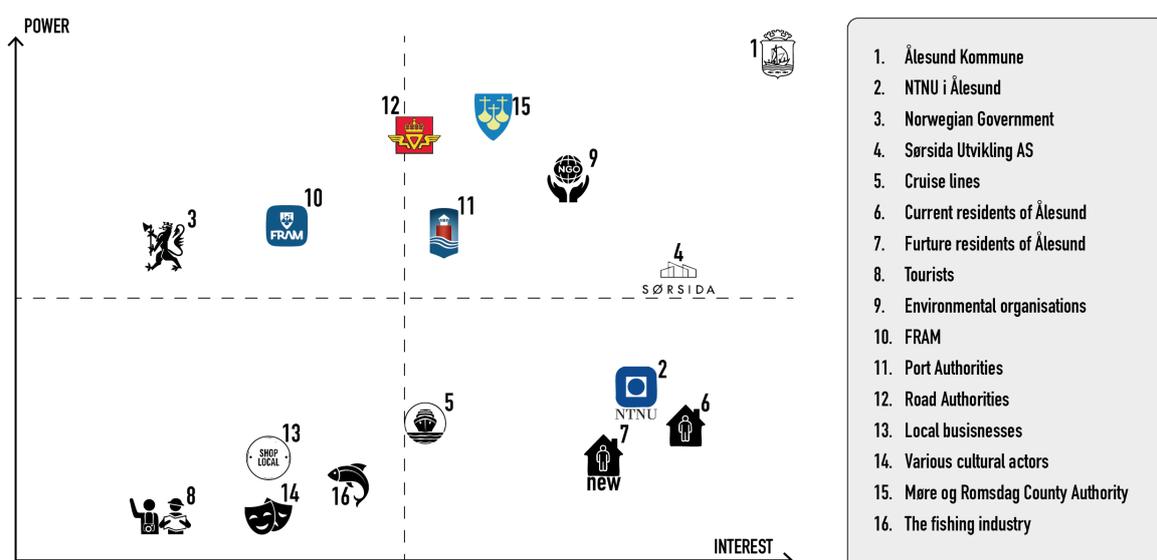
Figure 1.3: Power-Interest diagram.

The most powerful and interested stakeholders are Ålesund Kommune, Sørsida Utvikling AS, Møre og Romsdal County Authority, the road authorities, the port authorities, and environmental organisations.

Ålesund Kommune is the main client and leading authority for this project, as it holds responsibility for all developments within the municipality. The municipality's best interest is to make Ålesund more sustainable, accessible, and future-proof. Sørsida Utvikling AS is part of Ålesund Kommune and coordinates both the strategic planning and day-to-day management of the area. Its primary objective is to turn Sørsida into an example of sustainable urban development combining economic growth, environmental responsibility, and new housing opportunities. Møre og Romsdal County Authority and the Road Authority (Statens vegvesen) hold formal decision-making power regarding infrastructure and road safety. The Port Authorities (Ålesundregionens Havnevesen) influence the relocation and future use of harbour areas, while environmental organisations safeguard compliance with sustainability and emission targets.

A detailed description of all stakeholders and their position in the power-interest framework is provided in Appendix F.

1.6. Reading Guide

Chapter 1 introduces the background and context of the project. It describes the city of Ålesund, its demographic and urban development characteristics, and the key challenges that motivated this research. The stakeholder analysis identifies the main actors involved and their interests and is elaborated in more detail in Appendix F.

Chapter 2 explains the methodologies applied for the objectives. Results are given in Chapter 3. Finally, Chapter 4 contains a discussion and Chapter 5 gives conclusions and recommendations.

Appendix A contains a detailed description of the analyses related to the transport network. The Life Cycle Assessment of the Devold building is included in Appendix B. Appendix C contains the structural analysis of a new bridge as a replacement for the Steinvåg bridge.

Appendix D gives the additional information for the Norwegian load model, Appendix E provides a preliminary estimation of the amount of vehicles passing the Steinvåg bridge. The final appendix, Appendix G, contains the lines of code used for the traffic and structural analyses.

2

Methodology

The analyses are based on three cases provided by the municipality, each drawing upon knowledge and methods previously developed at TU Delft. These cases serve as the foundation for the future scenarios explored in this project. Each scenario offers an opportunity to explore a different field of application and to integrate multiple perspectives, enabling a broader and more integrated vision to make Ålesund future-proof.

For the Steinvåg bridge, a preliminary design proposal is developed by selecting a suitable location, identifying the governing loads and establishing the basic geometry. These will be identified based on the client's requirements and the norms that apply to the region. These are mainly the Norwegian annex to the Eurocode and the Håndbok N400 from Statens vegvesen. With these dimensions and loads, the bridge can be designed. The internal and external forces are calculated with a fininite element model in the DIANA FEA software and verified with hand calculations. Based on these forces the dimensions of the bridge can be iterated. Besides the design of the bridge, the construction process will also be described, such that a complete and feasible design of the bridge is made. The full explanation can be found in Appendix C.

A traffic model of Ålesund is developed in the software OmniTRANS. This model computes traffic flows through the city and its direct surroundings for four different transport modes during the evening peak (between 15h and 17h). The car, bus, walking and cycling are the considered modes. The model is constructed using the logic of the 4-phase model. The city is divided into 25 zones. The production and attraction (number of people departing/arriving) of all zones is computed using the number of inhabitants, number of job opportunities, sport area and culture area in each zone. These data are taken from Statistisk Sentralbyrå (SSB). Next, it is computed how many people travel between each pair of zones for each transport mode. The travel time is used as an indicator to do so. Higher travel times are less attractive, so less people travel between a pair of zones with a certain transport mode for higher travel times. Finally, the computed travel movements are assigned to the network, using the All-or-Nothing assignment (AON), the Deterministic User Equilibrium (DUE) and the Zenith algorithm for the bike/walk, car and bus mode respectively. Finally, the model is calibrated using observed traffic counts of Statens Vegvesen. The full methodology of the OmniTRANS model is included in Section A.2.

The Ålesund bus network is analysed to evaluate how effectively its structure facilitates passenger travel and to understand the patterns of its current use. Using General Transit Feed Specification (GTFS) data from *Entur*, the network was built for a typical weekday and adjusted to reflect the actual operations. The network was then represented as graphs to capture both the physical routes and the transfer connections between lines. Based on this representation, several indicators were calculated to assess the network's connectivity, efficiency, and resilience. A demand model was developed to estimate how passengers move through the system, and these flows were assigned to the routes based on travel time, waiting time, and number of transfers. This results in link-level passenger loads and saturation values, providing insight into which parts of the network are most and least used. Together, these analyses provide a clear picture of how well the current network performs and how its structure

influences passenger behaviour. The detailed methodology underlying this analysis is presented in Section A.3.

The environmental impact of the Devold building in the case of demolition and new construction, as well as reuse, is evaluated using the Life Cycle Assessment (LCA) methodology. The process involves creating a bill of materials for each scenario, identifying relevant Environmental Product Declarations (EPDs), and quantifying the environmental impacts. These results are then used for comparison between scenarios and to identify environmental impact hotspots. To ensure transparency and consistency, two parallel LCAs are performed. The first is based on the Norwegian standard NS 3720 and includes only greenhouse gas (GHG) emissions. This first assessment makes it possible to compare the results of this study with other Norwegian projects. The second is based on the European standards EN 15978 and EN 15804 and includes all impact categories and modules as far as possible. This second assessment is used as a sensitivity analysis to test whether the conclusions of the GHG-only LCA remain valid when additional impact categories are considered. A more detailed description of the LCA methodology is presented in Section B.3.

2.1. Location choice of new main connection between Hessa and Aspøya

When designing a replacement for a key infrastructure element, the most straightforward solution is often to rebuild in the same location with a similar design. However, in a complex network like Ålesund, relocating the connection could potentially improve the network performance, for example by reducing the travel times between Hessa and the city centre (Aspøya). Therefore, several alternative locations have been identified, each with its own advantages and disadvantages. Different locations of the new connection might lead to different traffic intensities during peak hours, so each option must be able to accommodate the expected traffic load. In addition, every alternative location must be assessed in terms of structural feasibility to ensure that it can physically support the intended function. The alternatives are implemented in the OmniTRANS model to evaluate their impact on traffic intensity and travel times between Hessa and the city centre.

A multi-criteria decision analysis (MCDA) is applied to identify the optimal location of the new connection between Hessa and Aspøya. The criteria in the MCDA are the following:

- Costs;
- Travel time between Hessa and Aspøya;
- Compatibility to existing infrastructure;
- Conflict with surroundings;
- Environmental Impact;
- Hindrance for ships during construction;
- Connection to Hessa during construction.

Each alternative was assigned a score between 1 and 10 for each criterion, and each criterion was given a specific weight reflecting its relative importance. A score of 1 is the worst, and 10 is the best. The overall performance of each alternative was then calculated as the weighted sum of its criterion scores, with the highest total score indicating the preferred option.

The criterion scores were derived from a combination of literature review, expert's opinion, and results from the OmniTRANS traffic model.

2.2. Population and jobs growth on Hessa

The new design for the Steinvåg bridge will have to accommodate any future increase in traffic during the design life of the new bridge. The new bridge will be the only connection between Hessa and Aspøya. This means that all the traffic between the two islands has to use the bridge. Therefore, the objective is to determine the required number of lanes per direction, and to determine to what extent population and employment could grow without the bridge becoming a bottleneck in the traffic network.

First, the current intensity during the evening peak on the Steinvåg bridge will be estimated. Unfortunately, the traffic registration point at Steinvåg bridge (that measures the intensity) is out of service. Due to the scope of this project, it is not possible to determine the exact intensity with the OmniTRANS model beforehand. That is why an intensity is first estimated.

There are two approaches for estimating the traffic intensity: (1) using the amount of inhabitants and employees, and (2) extrapolating traffic counts on the old bridge. These strategies require assumptions, so the result has to be checked afterwards with the OmniTRANS model.

Method 1 relies heavily on assumptions. Intensities towards Hessa depend in this estimation only on the amount of inhabitants returning home after a work day. Assumptions are made regarding the number of employed inhabitants of Hessa, the fraction of inhabitants working outside of Hessa, and the fraction of people travelling during the evening peak. The intensity towards Aspøya is assumed to only depend on the number of employees working on Hessa but not living on Hessa. Finally, the current modal split is used to determine the fraction of people using the car.

Method 2 uses measurements from Statens vegvesen of the intensity at Steinvåg bridge in the past (when the measurement point was still active), extrapolated using the growth of intensity at another nearby measuring point.

The two methods are compared, and a single intensity in both directions is determined. Håndbok 159 of Statens vegvesen is used to determine the required number of lanes in each direction for the estimated current intensity on the Steinvåg bridge.

To evaluate whether the determined number of lanes remains sufficient under significantly higher population levels and more job opportunities on Hessa, the maximum feasible number of new inhabitants and new job opportunities will be derived through trial-and-error testing in the OmniTRANS traffic model, once it has been developed. The methodology for developing the OmniTRANS model is included in Subsection A.2.2. Extra population and extra job opportunities are added to the model separately, and simultaneously, to see the effects of only adding inhabitants or jobs, and the effect of adding both at the same time. Additional population is expected to lead mainly to higher traffic volumes towards Hessa, and additional jobs mainly to higher traffic volumes towards Aspøya. The population and number of jobs on Hessa will be increased and the model will be rerun. This process repeats itself until the capacity on the bridge is reached.

2.3. Realisation of cultural centre

The analysis of the Devold building currently assumes that its future use will remain similar to its current function as a skatehall and event space. However, alternative uses are also worth considering. The most demanding option appears to be a concert hall, as it would require additional structural assessments and renovations to meet current standards, while also impacting the surrounding transport network.

The network analysis will be redone for a major attraction at the Devold building to investigate the impact of additional travel demand. The new Brosund bridge (parallel to the current Hellebrua) is assumed to be constructed before the new concert hall is opened, since both are part of the Sørsida project. The results will indicate whether the infrastructure and building configuration are resilient enough to accommodate such a high level of intensity.

The network analysis is performed for different visitor numbers to the concert hall (extra attraction of travellers) at different moments in time. Since concerts usually take place after a work day, only attraction to the concert hall is considered, because going to the concert hall takes place during busier moments than leaving the concert hall. Two time frames are used: during the evening peak (15-17h) and just after the evening peak (17-19h). Moreover, scenarios with higher frequency of buses are tested to see the effects on the overall transport network. The frequency of bus line 1 is increased by 50% in these scenarios, which is the only line passing the concert hall. The same duration for the second period is used as the duration of the evening peak (2 hours) for a fair comparison between time frames. Note that the peak intensity caused by a concert will be higher than the model will show, since most people arrive in a short time frame shortly before the start of a concert. It is, however, not possible to determine this with the developed static evening peak traffic model.

The OmniTRANS traffic model is developed for the evening peak, so it has to be adapted for the time frame after the evening peak. Technical details about these model modifications are included in Subsection A.2.4.

The network is analysed on the following indicators for the different scenarios:

- Car intensity and IC (intensity-capacity) ratio at Nedre Strandgate near Hotel Waterfront towards the centrum;
- Car intensity and IC ratio at Ålesundsvegen near the TINE factory towards the centrum;
- Travel time to the concert hall from Hessa north (west of the concert hall) and NTNU (east of the concert hall) by car;
- Number of bus travellers to the area of the concert hall and the percentage of people going to the area using the bus.

The car intensity is the number of cars on a road section. The IC ratio indicates the ratio between the intensity and the capacity of a road section. The two selected locations are expected to be the busiest road sections, because they are closest to the concert hall.

2.4. End of Life of the Steinvåg bridge

Reuse of the Steinvåg bridge is not possible due to the presence of chloride and the corresponding risk of corrosion (I.A. Lervik, personal communication, September 2025). To evaluate other possible End of Life (EoL) strategies, an assessment of the bridge's elements and materials will be carried out.

The technical drawings provided by the county of Møre og Romsdal will be used to identify the dimensions of the main elements of the bridge. These drawings are supplemented with additional measurements and estimations of elements whose dimensions are not clearly specified. All materials of the bridge are assumed to consist of reinforced concrete. Using the dimensions, the volume of each element will be calculated to determine its contribution to the total volume of the structure.

Next, chloride content measurements from 2007 and 2017 from 15 different locations and four depths (0-10 mm, 10-20 mm, 20-40 mm, and 40-60 mm) will be analysed to assess the risk of chloride-induced corrosion of the reinforcement steel. The risk of corrosion is assessed according to a document by Statens vegvesen on Norwegian coastal structures.

Lastly, the increase in chloride content up to the end of the bridge's service life in 2037 will be projected using two scenarios. The first scenario assumes that the increase between 2017 and 2037 is similar to the increase observed between 2007 and 2017, and the second scenario assumes a more conservative increase of 50%. These projections are then used to investigate suitable EoL strategies, such as recycling.

2.5. General future planning

This scenario analyses the Norwegian planning system in comparison to the Dutch context. The analysis will focus on the Plan- og bygningsloven (PBL) (Lovdata, 1985) and the Nationale Omgevingsvisie (NOVI) (Rijkswaterstaat, 2020) as primary references. In Norway, municipalities have broad discretion over local planning, including zoning and master plans, which allows incremental, adaptive development that can respond to local conditions. This approach prioritises meeting current needs, with staged investment and the possibility to adjust plans over time, reflecting a shorter initial planning horizon. In contrast, the Dutch system is characterised by strong national guidance, integrated life-cycle considerations, and early-stage optimisation to manage scarce space and infrastructure efficiently. By analysing these contrasting approaches through the lens of the PBL and the NOVI, the study aims to identify how Ålesund can combine Norwegian flexibility with the long-term planning principles seen in the Dutch context.

To compare the two systems, the study first looks at Norway under the PBL and then the Netherlands under the NOVI. For each, it describes the main features, advantages, and disadvantages, and provides examples to illustrate how the systems work in practice. Finally, it points out similarities and differences and gives advice on what parts could be useful for Ålesund.

3

Results

A tied arch bridge is suggested as a replacement for the current Steinvåg bridge. The arch will span 90 meters and be 20 meters high. The width of the bridge is 15.5 meters, such that traffic can pass the bridge in both ways, as well as cyclists and pedestrians. All general design decisions can be seen in Figure 3.1, 3.2, 3.3, and 3.4.

Figure 3.1: New orientation for the bridge.

Figure 3.2: Inspiration bridge ("Ashton Arch Bridge", n.d.).
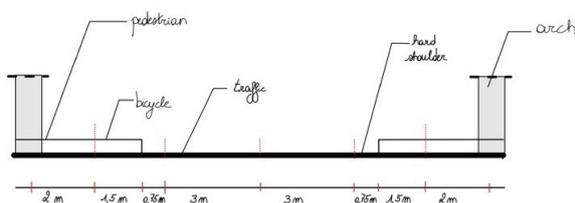
Figure 3.3: Side profile.

Figure 3.4: Logistical map.

The complete results and recommended steps can be found in Appendix C

The OmniTRANS evening peak traffic model shows that growth in car traffic is not possible in Ålesund. Most sections of the main east-west connection from the city centre to Moa (E136) are already

at, near or over their capacity in both directions, indicating that congestion occurs, as shown in Figure 3.5 in red. Intensity-capacity (IC) ratios on the main east-west connection are between 0.9 and 1.25. The intensities in the road network are asymmetric in the evening peak; travel demand out of the city is higher than into the city. Moreover, public transport, cycling and walking have low modal shares. Therefore, congestion and emissions could be reduced by realising a modal shift from the car towards these modes. However, the bus network is already good. Increasing the frequency of all buses by 50% does not lead to a significant higher bus ridership, which means that investing in more buses is not worth it. Other aspects of the public transport system could be improved, but are not included in the OmniTRANS model. Furthermore, the new road configuration in Sørsida including the new Brosund bridge will lead to lower intensity on Hellebrua and higher overall network robustness, but it does not solve the congestion problem on the E136 on Nørvøya and further east. Detailed results of the traffic model are included in Appendix A.
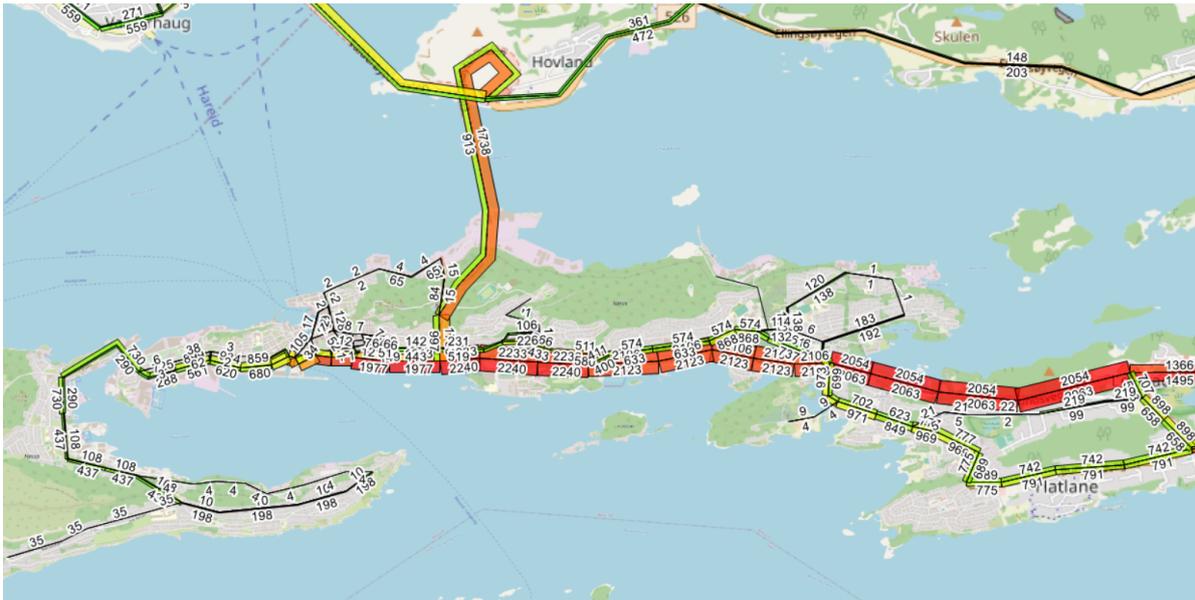
Figure 3.5: Current situation in car network during the evening peak.

The bus network performance analysis shows that the Ålesund bus network is generously dimensioned compared to current demand, with no signs of overcrowding on any line. Passenger flows are mainly concentrated along the main west–east corridor between the city centre and *Moa trafikkterminal*, while routes to the surrounding islands such as Ellingsøya and Vigra carry fewer passengers. The inclusion of ferry connections shortens both the longest and average travel paths, improving regional accessibility without changing the overall structure of the network. Ferries therefore act as fast, long-distance links that complement the bus services between islands. Overall, the network appears well-structured and robust, offering good coverage and sufficient capacity across the region. However, bus utilisation remains relatively low, suggesting that the current service supply exceeds actual passenger demand in most areas.

Both the LCA based on the Norwegian standard NS 3720 and the LCA based on the European standards EN 15978 and EN 15804 show that, over a reference study period of 60 years, reuse of the Devold building results in a lower environmental impact compared to demolition and new construction. The difference between the scenarios is smaller when using the Norwegian LCA methodology, which only considers greenhouse gas (GHG) emissions, compared to the broader European LCA methodology. Both assessments show that the highest environmental impact occurs during the production and transport of construction elements (modules A1-A4 in the demolition and new construction scenario, and module B4 in the reuse scenario due to element replacement). The results also show that the environmental impact of the reuse scenario improves when the need for repairs and replacements is reduced or delayed. Overall, both LCAs show that reuse is more environmentally favourable, especially

when element replacements are minimized and the service life of the current elements is extended as much as possible. The detailed results, as well as their interpretation, are presented in Appendix B.

3.1. Location choice of new main connection between Hessa and Aspøya

This section outlines the outcomes for selecting the optimal location of the new connection between Hessa and Aspøya. It first introduces the four proposed alternatives, after which the outcomes of the multi-criteria decision analysis are discussed.

3.1.1. Location Alternatives

Four potential locations for a new connection between Hessa and Aspøya are considered and evaluated in this section. Figure 3.6 shows the location of the alternatives. Option 1 and 2 involve bridge structures, option 3 can be realised either as a bridge or a tunnel, and option 4 represents a tunnel alternative. Given the expertise of the structural engineers in this project, only bridges are possible to design in this project, but a tunnel might also be an interesting alternative. Therefore, tunnels are considered in the location analysis.
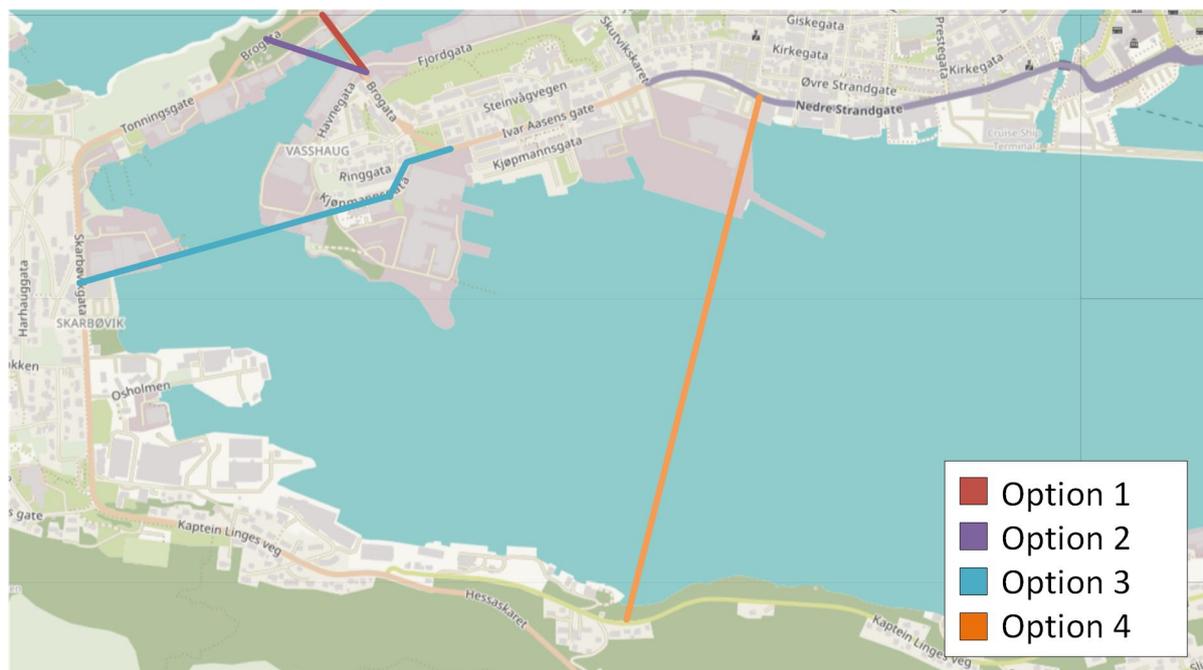
Figure 3.6: Potential new connection locations, edited from (OpenStreetMap contributors, 2025).

Redesign of current bridge (Red)

The first option is a new bridge at the same location and retaining the current infrastructure of the connection between the islands. The connection between the islands over the current bridge works fine, which is why a bridge at the same location is a viable option. It has a total span of around 80 meters.

The main advantage of this alternative is the cost. The redesign entails that no changes are to be made to the surrounding roads and buildings in the area. The first downside of this alternative is that the two islands will be disconnected for a longer period since the existing bridge has to be demolished before the new bridge can be built. Secondly, the existing support infrastructures might also need to be rebuilt to be up to standard. The biggest downside of this alternative is the restriction on the dimensions of the bridge. One of the reasons for the new bridge is to make room for pedestrians and cyclists. In this location alternative, it is quite complicated to make room for these road users without impacting the surroundings. In order to increase the width of the bridge, buildings will have to be demolished, which will result in low support from the local residents.

New bridge-design at current location (Purple)
The second location alternative consists of a bridge that has the same starting point as the existing bridge but crosses the water in a different orientation. It thus ends at a different location than the current bridge does. This makes the bridge a bit longer, with a total span of approximately 130 meters.

The first advantage of this alternative is the possibility of increasing the bridge's width. With the new path of the bridge, fewer or no buildings would have to be demolished or relocated (depending on the design) to accommodate the increased width of the bridge. This will hopefully increase the residents' support for the new bridge. The second advantage is that parts of this bridge can be constructed whilst the current one is still operational, resulting in a shorter disconnection between the islands. There will still be a disruption since the two bridges start at the same location on Aspøya. Since the bridge will follow a new path, it will cross new buildings on land. It is important that there is good communication with the owners of these buildings, since the new bridge might cause some disturbances both during construction and after completion.

New bridge- or tunnel-design at docks (Blue)
This location alternative features a whole new location around 500 meters south of the current location. The location is chosen based on the current road infrastructure of Ålesund. The idea is to extend the E136, which is shown in Figure 3.6. Road infrastructure is already present, but would need to be modified to accommodate the increased traffic on the route towards the bridge. On Hessa, the bridge would end on the Skarbøvikgata.

At this new location, both a bridge and a tunnel can be constructed, however, the minimum span is 250 meters, which will increase the dimensions of the bridge drastically. The new structure will cross two harbour structures, which can act as a foundation for the bridge or tunnel. The advantage of building a bridge compared to a tunnel is the cost, since the construction of a bridge is cheaper. The tunnel has the advantage that vertical clearance is not an issue, which is a constraint when building a bridge, since there is no height difference on both sides of the waterway.

The biggest advantage of the new location of the bridge is that there is no disconnection between the islands during construction, since the existing bridge can remain open. The new location also makes it easier to make the bridge wider to accommodate all road users. A downside is the cost, both when building a bridge and a tunnel. This is due to the adjustments to the existing road structure that need to be made and the proportions of the structure. The bridge at this location would have a larger span than at the current location, making it more expensive. As mentioned before, the construction of a tunnel is also costly. Just as with the previous alternative, good communication with the surrounding residents is of great importance. When a tunnel will be built an alternative needs to be suggested for pedestrians and cyclists.

New tunnel to the south (Orange)
Currently, there might be plans plans to divert part of the traffic through a tunnel at the southern part of the city of Ålesund (Ålesund Kommune, 2025a), to lower the traffic intensity of the Hellebrua and the rest of the old city centre. This location alternative uses these plans as a starting point for the location of a new tunnel. This tunnel could be split, or a tunnel at this location could be built, regardless of the existing plans.

This plan has little to no clash with the existing infrastructure, making it a viable option. The cost, however, will be very high due to the scale of the tunnel (over one kilometre), which makes this alternative less desirable. Tunnelling might be hard through this part of the bay, since the depth profile varies rapidly over the distance, and it is again not suitable for pedestrians and cyclists

3.1.2. Multi-Criteria Location Analysis
The different locations will be compared to each other by certain criteria. These criteria will receive appropriate weights based on their importance to the final decision. The criteria used are stated below and ranked for each location alternative. In Table 3.2, the weight and score for each criterion and alternative are presented. This comparison will result in the most desired alternative for the location of the new connection.

Cost

The first and foremost criterion in any project is the cost it will incur, both construction and maintenance costs. Bridges are overall cheaper than tunnels due to the simpler design and fewer risks (U.S. Department of Transportation, 2023). This means that the red alternative will be the cheapest, followed by purple. This is due to the larger span of the purple alternative compared to the red one. Blue will be even more expensive since the span is almost five times as long and the tunnel at this location is even more expensive. The orange option is the costliest due to its length.

Travel time between Hessa and city centre

The new connection could reduce travel time between Hessa and the city centre, which is beneficial for the residents of the island. It makes living there more attractive and also opens possibilities for new businesses. The two main residential areas at Hessa are in the north and south. Uncongested travel times between these two areas on Hessa and the city centre are presented in Table 3.1. The red and purple alternatives result in the same travel time and are mainly beneficial for residents of the northern neighbourhood. The blue alternative results in the lowest overall travel time. The orange alternative is beneficial for the southern neighbourhood, but leads to a travel time increase for the northern neighbourhood compared to the current situation. Differences between the red, purple and blue alternatives are small, but the orange alternative leads to a significantly high travel time for residents of Hessa north.

Table 3.1: Free flow travel time between Hessa and city centre for different location alternatives.

Alternative	tt **Hessa north** $\rightarrow$ **city centre [min]**	tt **Hessa south** $\rightarrow$ **city centre [min]**
Red	6.06	4.14
Purple	6.06	4.14
Blue	5.52	3.60
Orange	8.28	4.26

Compatibility with existing infrastructure

The connection with the current infrastructure is another important criterion to take into consideration, as the new connection should not negatively impact the currently present infrastructure. The red and purple designs will align perfectly with the current situation. Moreover, a new location of the bridge might require upgrades of the road infrastructure on Hessa. This is not the case for the red, purple, and blue alternative, since the main traffic flows use the same road as in the current situation. Figure 3.7 shows the OmniTRANS model output for the red and purple alternative. All routes near and at Hessa have IC ratios below 0.6 (shown in green/yellow), indicating that no congestion occurs. The same holds for the blue alternative, presented in Figure 3.8. For the orange location, Kaptein Linges veg needs to be repurposed from a local to a distributor road, because it will serve as access road to Hessa. This road has an IC ratio around 0.8 (shown in orange) in Figure 3.9, indicating moderate forms of congestion.
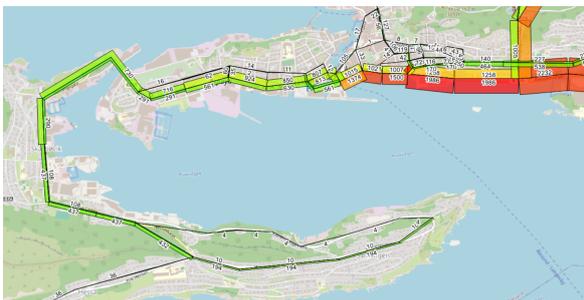
Figure 3.7: Intensities and IC ratios on road network for location alternative red and purple.
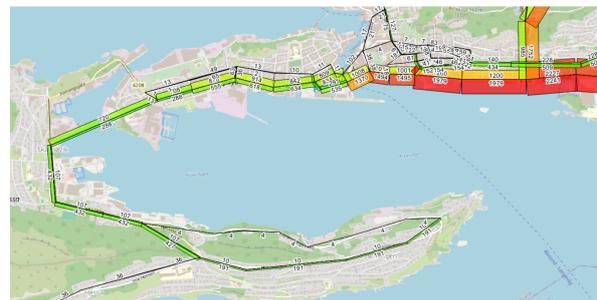
Figure 3.8: Intensities and IC ratios on road network for location alternative blue.
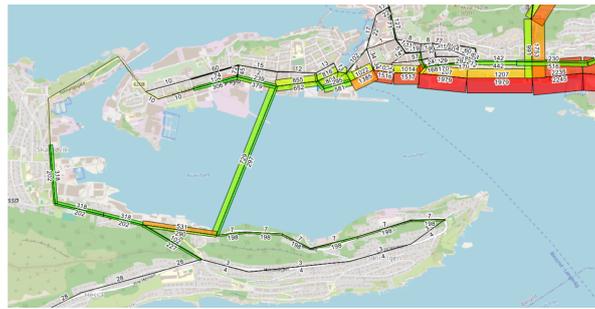
Figure 3.9: Intensities and IC ratios on road network for location alternative orange.

Conflict with surroundings

This criterion analyses the impact the new construction will have on the current buildings and the surrounding area of each location alternative. The current alignment of the road does not offer much space for widening of the road. The red scenario will require demolishing several buildings and will have a significant impact on the surroundings. The purple alternative will allow more space and an easier option to widen the road for pedestrians and cyclists. The blue and the orange variants start and end in port areas, where there are not many structures that might influence the construction of the new connection. The correct alignment with the current connecting roads might result in conflict with some houses.

Environmental impact

The emissions are hard to calculate beforehand, therefore this section will only provide an estimation. The short bridge, the red option, will have the least direct emissions. The secondary emissions caused by the destruction also have to be considered, and these are comparable in pollution to the purple design. The construction of a tunnel will require more building materials, a higher construction time and heavier machinery, which will result in higher emissions.

Hindrance for ships during construction

The large marine traffic does not use the waterway under the Steinvåg bridge, but the route is used by the local fishermen and other recreational boats. The construction of a bridge in the red and purple scenario has an impact on this traffic route. The other two plans depend on the construction method of the tunnel. If it is a drilled tunnel, the hindrance will be minimal, while a tunnel with submerged elements will result in an entire closure of the waterway, which causes heavy disruption in the waterway.

Connection during construction

The different location alternatives have varying effects on the connection between the islands. The red alternative will require a full destruction and rebuild of the current bridge. This will cause a long disconnection between the two and result in a heavily undesired situation. A better scenario is the purple situation, where this time is significantly reduced, since the new structure can be built alongside the current bridge and only requires a short time of disruption. The two other designs will cause negligible disruption since these constructions can be built entirely besides the current scenario, and Hessa will be connected at all times.

3.1.3. MCDA Decision Matrix

Table 3.2 shows the decision matrix of the multi-criteria location analysis. A high score is positive in the analysis, although it might seem counterintuitive for some criteria, like emissions.

From the MCDA, the purple alternative appears to be the best option for the connection between the islands. The difference in score between purple and blue is, however, small. Therefore, more research to the criteria has to be done and other criteria might need to be included as well. Given the limited time of this project, it is chosen to move forward with the purple alternative. The design of the bridge is further explained in Appendix C.

Table 3.2: MCDA Decision Matrix.

Location alternative	Cost	Travel time	Compatibility with existing infrastructure	Conflict with surroundings	Environmental impact	Hindrance for ships during construction	Connection during construction	Total Score
Weights	*0.25*	*0.10*	*0.10*	*0.15*	*0.10*	*0.05*	*0.25*	*1.00*
Red	9	7	9	3	8	6	2	5.90
Purple	8	7	9	5	8	8	5	6.80
Blue	5	9	7	6	5	4	9	6.70
Orange	3	4	5	7	3	2	9	5.35

3.2. Population and jobs growth on Hessa

The estimated current traffic intensity on the Steinvåg bridge is 607 vehicles towards Hessa and 723 towards Aspøya during the evening peak (15:00–17:00). The detailed calculations underlying these values are provided in Appendix E. Based on these intensities, a single lane per direction is sufficient, as the capacity of a two-lane road under ideal conditions is approximately 2,800 veh/hour for both directions combined. The current demand is therefore well below capacity.

The estimated intensities are compared to the model intensities in OmniTRANS. The current population on Hessa is 3,852 and the current number of job opportunities is 791. This leads to 730 cars driving to Hessa over the Steinvåg bridge and 303 cars driving to Aspøya during the evening peak (15-17h). The intensity was over-estimated in both directions. However, the capacity of the bridge was also over-estimated, and is only 1,600 veh/2h per direction. Still, one lane per direction is sufficient, for the coming years, and there are currently free flow conditions in both directions.

When only the population at Hessa increases by 5,000 (equally divided over zone 1 and 2 in the traffic model) to 8,852 people, the intensity on the Steinvåg bridge towards Hessa during the evening peak becomes 1,559 passenger cars. The capacity is almost reached, and congestion occurs in this situation. However, the bridge itself would not be the bottleneck in the traffic network. The intensity in the other direction, towards Aspøya, increases to 369 cars.

When only the number of job opportunities on Hessa increases by 5,000 to 5,791, the intensity on the Steinvåg bridge towards Aspøya increases to 1,531 cars during the evening peak. The intensity towards Hessa increases to 600 vehicles.

When both the number of inhabitants and the number of job opportunities increase by 5,000, the intensity on the bridge towards Hessa becomes 1,292 vehicles and the intensity towards Aspøya 1,548 vehicles during the evening peak. Interestingly, in this scenario the intensity on the bridge is lower than when only adding inhabitants or only job opportunities to Hessa. This is caused by a higher number of trips on Hessa itself. When both inhabitants and jobs are added to the island, more new inhabitants can work on Hessa, so they do not have to leave the island.

Table 3.3: Intensities during evening peak on Steinvåg bridge in different development scenarios at Hessa.

Scenario	Intensity towards Hessa	Intensity towards Aspøya
Current situation	730	303
Only adding 5,000 inhabitants to Hessa	1,559	369
Only adding 5,000 job opportunities to Hessa	600	1,531
Adding 5,000 inhabitants and 5,000 job opportunities to Hessa	1,292	1,548

Figure 3.10 shows the intensities and intensity-capacity (IC) ratios on the car network in the scenario with 5,000 additional inhabitants and 5,000 additional jobs on Hessa. The numbers show the intensity

on a road section and the colours indicate the traffic state, where red means congestion and green free flow conditions.

The bridge is able to handle the mentioned increase in population and jobs on Hessa. It will not be the bottleneck of the network, although capacity is almost reached. Some delays occur in this situation near the bridge, but it is not necessary to construct a four-lane bridge (two lanes in both directions) for this population and job opportunity growth.

The infrastructure network on Hessa would have to be improved to facilitate the additional traffic. The roads at the southern part of Hessa experience congestion. The E136 (Nedre Strandgate) on Aspøya also needs improvements to facilitate this traffic growth. At some road sections, intensity exceeds the capacity of the road, so there are major delays.
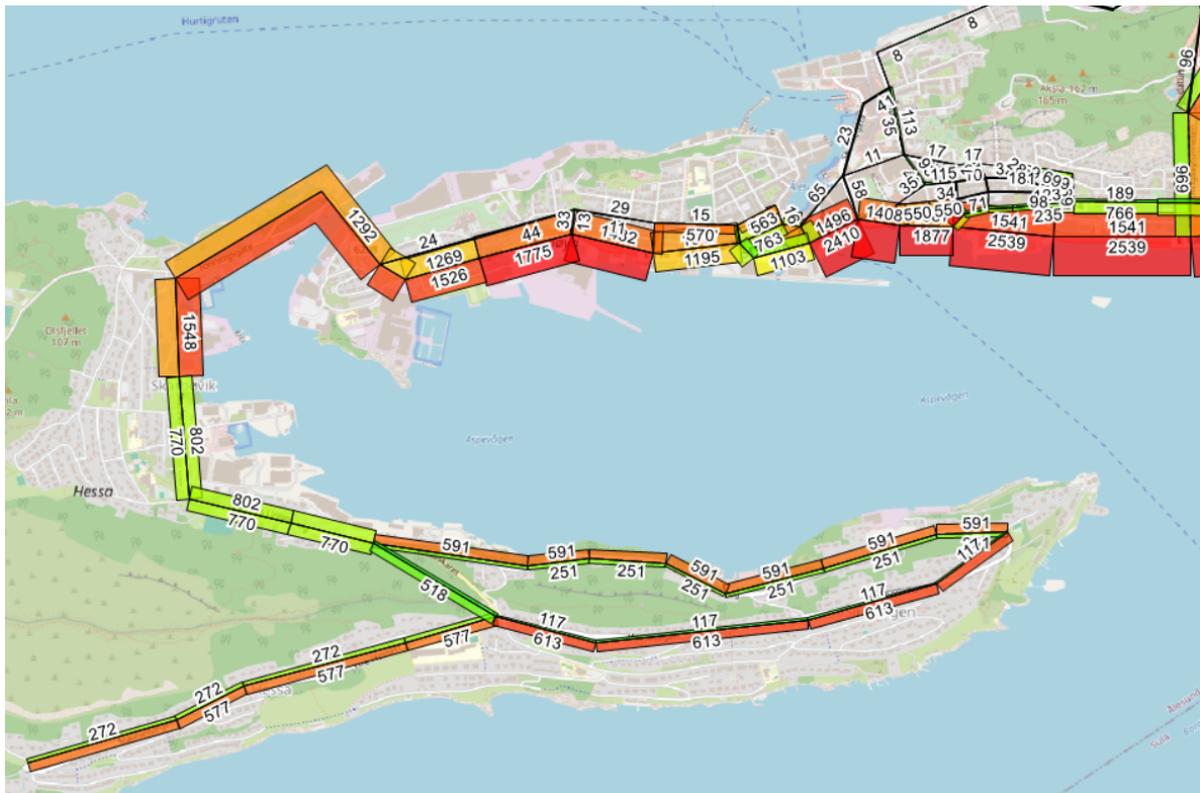
Figure 3.10: Intensities on network in case of 5,000 additional inhabitants and 5,000 additional jobs on Hessa.

In conclusion, the population and number of job opportunities at Hessa can both increase by 5,000 in combination with the proposed bridge design with one lane in each direction. However, infrastructure on Hessa and Aspøya does need to be improved to facilitate the growth in traffic demand due to the increase in inhabitants and employees on Hessa.

3.3. Realisation of cultural centre

Table 3.4 gives the performance indicators of the transport network for different scenarios regarding the concert hall, which is located in zone 4 in the traffic model.

As can be seen in Table 3.4, the road from Hessa towards the concert hall (and city centre) is not congested in any case. Most of the people attracted to the concert hall live east of Hellebrua, so they do not use Nedre Strandgate to get there. Travel times between Hessa and the concert hall are constant in all scenarios as well.

Interestingly, intensity at Nedre Strandgate is lower in all concert hall scenarios than in the base scenario (no concert hall, evening peak). The differences are low; the intensity for the scenario with 2,000 visitors and increased bus frequency during the evening peak is 30 vehicles lower than in the base scenario.

Table 3.4: Network performance for different scenarios related to the concert hall.

Scenario	$I_{\text{NS}\rightarrow\text{C}}\ (IC)$[1] [veh/2h],[-]	$I_{\text{AV}\rightarrow\text{C}}\ (IC)$[2] [veh/2h],[-]	$tt_{\text{Hessa}\rightarrow\text{CH}}$[3] [min]	$tt_{\text{NTNU}\rightarrow\text{CH}}$[4] [min]	Bus users to CH (percentage)[5] [passengers],[%]
No concert hall, evening peak	638 (0.40)	1,255 (0.78)	3.40	4.93	51 (11.1%)
During evening peak					
500 visitors	625 (0.39)	1,464 (0.92)	3.40	5.49	106 (11.0%)
” + increased bus frequency	620 (0.39)	1,473 (0.92)	3.40	5.12	108 (11.3%)
1,000 visitors	616 (0.39)	1,667 (1.04)	3.40	5.62	161 (11.1%)
” + increased bus frequency	612 (0.38)	1,664 (1.04)	3.40	5.49	163 (11.2%)
2,000 visitors	602 (0.38)	1,974 (1.23)	3.40	6.19	269 (10.9%)
” + increased bus frequency	598 (0.37)	1,956 (1.22)	3.40	6.14	274 (11.2%)
After evening peak					
500 visitors	301 (0.19)	848 (0.53)	3.40	4.47	78 (10.9%)
” + increased bus frequency	299 (0.19)	845 (0.53)	3.39	4.47	79 (11.1%)
1,000 visitors	294 (0.18)	1,107 (0.69)	3.40	4.55	131 (10.8%)
” + increased bus frequency	292 (0.18)	1,103 (0.69)	3.39	4.54	134 (11.0%)
2,000 visitors	282 (0.18)	1,637 (1.02)	3.40	4.95	237 (10.7%)
” + increased bus frequency	280 (0.18)	1,632 (1.02)	3.39	4.95	242 (10.9%)

[1] Intensity at Nedre Strandgate (near Hotel Waterfront) towards the centrum [veh/2h], IC ratio is dimensionless.
[2] Intensity at Ålesundsvegen (near TINE factory) towards the centrum [veh/2h], IC ratio is dimensionless.
[3] Travel time by car from Hessa north towards concert hall in minutes.
[4] Travel time by car from NTNU towards concert hall in minutes.
[5] Total bus ridership towards concert hall area (Aspøya east) [number of passengers], percentage of total attraction [%].

The differences are caused by an adapted origin-destination matrix, because the gravity model (see Subsection A.2.2) is rerun with the additional attraction due to the concert hall.

Ålesundsvegen is congested in all scenarios during the evening peak. Many people use this road to get to the concert hall. The scenario with 500 visitors during the evening peak has an IC ratio of 0.92, meaning that congestion occurs, but capacity of the road is not reached yet. The concert hall cannot attract 1,000 or even 2,000 visitors during the evening peak. The IC ratios are above 1.0, meaning that the capacity is reached and heavy congestion occurs. Spillbacks occur, leading to a grid lock in the network. The travel time from the NTNU to the concert hall increase from 4.93 minutes to 5.49 and 5.62 minutes when the concert hall attracts 500 or 1,000 people respectively, without increased bus frequencies. If the concert hall attracts 2,000 people, the travel time increases to 6.19 minutes.

Logically, travel times by car are lower when bus frequencies are increased, since more people chose the bus. However, the differences in travel times are small because the amount of people choosing the bus instead of the car is also low.

If a concert starts after the evening peak, more people can be attracted by it without leading to congestion. No congestion occurs if the hall attracts 1,000 people (max. IC ratio of 0.69). This is caused by the lower amount of commuters on the road. A concert that attracts 2,000 people also leads to congestion between 17h and 19h.

The last column of Table 3.4 shows the number of concertgoers that uses the bus and the percentage. Increasing the frequency of bus line 1 by 50% only leads to a slight increase in public transport usage: 5 additional people use the bus in the case of 2,000 concertgoers, both with concerts during and after the evening peak. Intensities on the car network decrease with an increasing bus frequency, but this decrease is negligible. It is, therefore, not worth it to increase the frequency. However, an important aspect in mode choice for concertgoers is not included in the model: alcohol consumption. It could be that people do not use the car to go a concert because they want to be able to drink. Still, a 50% increase of frequency of bus line 1 is unlikely to lead to many additional bus users.

Another aspect in choosing the travel mode that is not included in the model is parking availability. 364 cars are expected to go to the concert hall if it starts during the evening peak (500 visitors). If a concert starts after the evening peak (1,000) visitors, 739 cars are expected. If no parking is available, people

might be inclined to use other modes instead of the car. This is a policy decision the municipality has to make, and further investigation in decision making processes of concertgoers is required to support this policy decision. It should be noted that the number of cars could be lower, because a higher percentage of people use carpooling to go to a concert than for regular commuter traffic, where the model is constructed for.

3.4. End of Life of the Steinvåg bridge

To investigate appropriate EoL scenarios for the Steinvåg bridge, an overview of the dimensions and material composition of its elements has been created. The overview is based on technical drawings supplied by the county of Møre og Romsdal and is supplemented with additional measurements and estimations of elements whose dimensions were not clearly specified (Heien & Selbrug, 1951). Table 3.5 shows the different elements and their estimated volumes and volume percentages.

Table 3.5: The elements of the Steinvåg bridge and their respective volumes and volume percentages.

Element	Volume [m³]	Volume percentage [%]
Arches	252	15.0
Columns	46	2.7
Crossbeams	8	0.5
Deck	982	58.5
Foundation	345	20.5
Tension rods	3	0.2
Walls	43	2.6

Table 3.5 divides the Steinvåg bridge into several elements, namely the deck, foundation, arches, columns (with varying heights and cross-sections), walls, crossbeams, and tension rods, listed here from largest to smallest in volume. All elements are assumed to consist of reinforced concrete, as the internal properties cannot be derived from the technical drawings or other available documentation.

As stated in Section 2.4, the reuse of the Steinvåg bridge is not possible due to the high chloride content in the concrete. The allowable chloride content in reinforced concrete is typically specified in European or national standards, However, no separate Norwegian standard specifying the allowable chloride contents in reinforced concrete was found. Therefore, a publication by Statens Vegvesen (the Norwegian Public Roads Administration), *Betongkonstruksjoners Livsløp*, was used as a reference (Helland, S. and Maage, M. and Fluge, F., 2003). This document contains a table showing chloride contents and the corresponding risk of corrosion of the reinforcement steel for Norwegian coastal structures, such as the Steinvåg bridge. Table 3.6 summarizes these values.

Table 3.6: Chloride contents of concrete and corresponding risk of corrosion.

CI^- % of concrete (assumed 440 kg cement/m³)	Risk of corrosion
> 0.36	Certain
0.18 - 0.36	Probable
0.07 - 0.18	Possible
< 0.07	Negligible

Since no updated national values were found, it is assumed that these values remain applicable today. They also closely correspond with the European limits for chloride content in reinforced concrete specified in EN 206, which are 0.4% for most structures and 0.2% for structures exposed to harsher climates, such as the coastal climate in Ålesund (Silva et al., 2015). This alignment supports the applicability of the Statens vegvesen ranges for chloride content of reinforced concrete and the corresponding risk of corrosion in this study.

The county has provided results from tests measuring the chloride content in the reinforced concrete elements of the Steinvåg bridge at various locations. These tests were carried out by Statens vegvesen in 2007 and 2017 and are used to estimate the chloride content in 2037, which is the end of the bridge's service life. The tests include results for various reinforced concrete elements of the bridge, such as the arches, columns, deck, and walls, and show chloride content measurements from 15 different

locations. For each location, measurements were taken at four depths: 0-10 mm, 10-20 mm, 20-40 mm, and 40-60 mm.

Due to confidentiality, the measurements of the chloride content cannot be included in this report. Nevertheless, the available data has been analysed to assess the risk of corrosion of various elements of the bridge.

The results of the tests carried out in 2007 indicate that, for most of the locations, the risk of corrosion was within the negligible range. Overall, 71.7% of the measurements fell within this range, 18.3% fell within the possible range, and 10.0% fell within the probable range. None of the tests were within the certain range.

The results of the tests carried out in 2017 show a different distribution. Here, 46.8% of the measurements were within the negligible range, 38.3% fell within the possible range, 8.5% fell within the probable range, and 6.4% fell within the certain range.

The change in chloride content since 2017, as well as the projected change until 2037, is uncertain. With the available data, it is not possible to identify a trend in the rate of change in chloride content for the different elements, as the exact locations of the measurements are not known. However, it can be assumed that elements closer to the water will experience a faster increase in chloride content due to their higher exposure to chloride in the water.

A comparison between the results of 2007 and 2017 shows a shift from mainly chloride contents with a negligible risk of corrosion to a larger share of chloride contents with a possible or probable risk of corrosion. This indicates a gradual decrease in the quality of the concrete. The average increase in chloride content between 2007 and 2017 (after excluding outliers) was approximately 161.7%.

Assuming a similar change in chloride content between 2017 and 2037, 25.5% of the measurements are expected to be within the negligible range, 38.3% within the possible range, 14.9% within the probable range, and 21.3% within the certain range. Assuming a more conservative increase in chloride content of 50%, 29.8% of the measurements are expected to be within the negligible range, 40.4% within the possible range, 19.1% within the probable range, and 10.6% within the certain range.

Table 3.7 shows the distribution of the risk of chloride-induced corrosion for the different measurement locations in 2007 and 2017, as well as the two possible future scenarios.

Table 3.7: Distribution of the risk of chloride-induced corrosion for the different measurement locations of the Steinvåg bridge.

Risk of corrosion	2007	2017	2037 (similar increase)	2037 (conservative increase)
Certain	0.0%	6.4%	21.3%	10.6%
Probable	10.0%	8.5%	14.9%	19.1%
Possible	18.3%	38.3%	38.3%	40.4%
Negligible	71.7%	46.8%	25.5%	29.8%

Overall, the results indicate an ongoing increase in chloride-induced corrosion risk across various elements of the Steinvåg bridge.

3.5. General future planning

Situation Norway

Norway has a large land area relative to its population, which means there is generally more space available for development. Many areas have low population density, and natural landscapes often remain largely untouched, offering opportunities to balance development with nature. Under the PBL, municipalities have significant authority over local planning, including zoning, master plans, and approvals for construction projects. This allows them to adapt plans to local conditions, consider environmental features, and respond to changing needs over time. Compared with the Dutch system, Norwegian regulations are less strict, giving more freedom in design, technical requirements, and implementation.

This system has several advantages. The flexibility of local decision-making allows municipalities to make incremental changes, adapting to new social, environmental, or economic circumstances. Plans can be adjusted to the specific needs of each community at a certain moment in time. In addition,

staged investment makes it easier to manage costs over time, as projects can be developed gradually instead of requiring large upfront spending.

At the same time, there are some disadvantages. Because municipalities act independently, long-term goals may not be coordinated across regions. Different standards and priorities can create inconsistencies in infrastructure or services. Planning often focuses on immediate needs, which can lead to higher costs or redesigns in the future. Finally, without early large-scale planning, opportunities for efficiency or multifunctional land use may be missed.

Situation Netherlands

The Netherlands has a much smaller land area and a higher population density than Norway, which makes efficient use of space a central concern. The NOVI provides strong national guidance and requires municipalities to align local plans with broader strategic objectives. Dutch planning integrates long-term considerations, such as life-cycle costs, multifunctional land use, and infrastructure durability, early in the process. This system is more prescriptive than the Norwegian PBL, ensuring that developments are coordinated across regions and meet national policy goals.

This system has several advantages. Early-stage planning helps optimise land use, reduces conflicts between different projects, and ensures that infrastructure and housing are durable and sustainable. National and regional coordination makes it easier to implement large-scale projects consistently and reduces the risk of redundant investment. By integrating long-term considerations from the start, municipalities can plan for growth, climate adaptation, and future expansion in a more systematic way.

At the same time, there are some disadvantages. Because national rules are strict, municipalities have less room to adapt plans to new or unexpected local needs. Decision-making can be slower because amendments often require approval from higher authorities. In some cases, local priorities may be overshadowed by national objectives, which can reduce responsiveness to immediate community demands.

Observations and Cases

A recent example in Ålesund is the development of the new bus terminal, which was planned and built as a street terminal rather than the bus station near Terminalen that was in use before. The project was prepared in about one year (Bypakke Ålesund, 2024b) and construction took just over another year (Møre og Romsdal Fylkeskommune, 2022), which shows that projects can be delivered quickly when needed. The terminal has made transfers more visible and convenient. However, because the surrounding infrastructure is still changing, it is uncertain how well the terminal will connect to the future network, especially with the crossing of the Korsegata and Keiser Willems gata. Some buses already need to wait or stop in less suitable locations, which shows that short-term solutions can later create planning challenges if the wider system is not yet decided.

Another example is the Steinvåg bridge, which is reaching the end of its service life. There are no real plans for its replacement yet, but research and early planning will need to begin on time to prevent major traffic disruption. Previous projects in the municipality have shown that large interventions can be completed successfully within short time frames. However, without early coordination, there is a risk of choosing a solution that works in the short term but reduces future options. Exploring alternative scenarios (see Section 3.1) could help identify whether a different location or design might bring more long-term value for the area.

The south side of the city presents several challenges for future planning. Various parts of the quay construction in Sørsida are not under ownership of the municipality, but are instead the responsibility of the port authorities. In general, governance and communication within the municipality, especially to municipal companies such as the port authority, parking company and property company, is challenging (A. Amundsen, personal communication, September 2025). The municipality is planning on constructing new housing and other cultural facilities on top of the quay construction in the seafront area of Sørsida (known as Kulturhavna within the Re-Value project). This makes them dependent on the future plans of the port authorities, which are not always in line with the politically approved plan for the area. The harbour is also affected by frequent cruise ship arrivals, which block views and generate large flows of pedestrians. At present, there is no concrete plan to address these issues, leaving uncer-

tainty for future development. In addition, parts of the quay construction appear to be in bad condition and are in need of renovation (Norconsult, 2023). Although this is not the municipality's responsibility, the uncertainty surrounding the condition of the quay construction makes it difficult for them to develop concrete ideas for the future development of the area.

An important observation is that LCAs are, in both countries, often performed only after a project is completed, but integrating it during the design phase allows planners to take results into account early and adjust decisions. While the Dutch approach includes more factors than CO_2, the Norwegian approach is simpler, but leads to less detailed outcomes. The Dutch method potentially influences key decisions more strongly based on these extra insights. Both countries have major steps to take regarding early anticipation to environmental impact.

A few Dutch cases are included below to show how similar planning challenges are handled in practice in The Netherlands. They illustrate how long-term preparation can be helpful, but also how high early investment and fixed designs can sometimes create new problems.

A clear example of long-term planning in the Netherlands is the train station in Delft that was built in 2014 (Treinenweb, 2015). During construction, two railway tunnels were built, even though only one was needed at the time. The second tunnel was planned as a future capacity expansion. This approach required a much higher investment at the start, but it was less expensive than executing the project twice. However, because the demand for the second came later, it could not be used immediately, and extra maintenance had to be carried out before it could become operational (Bicycle Dutch, 2018). This shows both the strength and the risk of long-term planning: the future is well prepared for, but high upfront costs can also lead to long waiting periods before benefits are realised.

Another example is the tram connection between Delft and the university campus. The idea behind the route was to improve sustainable mobility and offer a direct link between the central station and the university area. It was initially planned to operate in 2014, however the project faced several miscalculations and design issues, which meant that the parts of the line had to be rebuilt twice (Vermond, 2024). This caused disruptions to other projects in the network and created a chain effect in planning. In this case, long-term planning was not based on all relevant factors, showing that a high upfront investment does not always lead to lower total costs in the end.

A third example is the new study facility Flux at TU Delft. This building was designed as a short-term, modular solution to provide more study spaces and exam halls while the campus undergoes redevelopment (Van der Wal, 2023). It can be dismantled or moved easily, and does not interfere with the university's long-term spatial strategy. Unlike the earlier examples, this project shows how Dutch planning can also be flexible when needed. In addition, the building was developed as a showcase project. It is emission-neutral, which fits long-term sustainability goals while still being temporary. It also includes several innovations, such as a connection to the district heating network, the reuse of furniture from previous projects, and refurbished floorboards from the 2012 London Olympics (Neptunus, 2023).

4

Discussion

Location choice of new main connection between Hessa and Aspøya

The multi-criteria analysis showed that the purple alternative is the best option for the new connection between Hessa and Aspøya. This option is at the same location as the current Steinvåg bridge, but the orientation of the bridge is slightly altered. However, the blue alternative has almost the same score in the multi-criteria analysis. Therefore, it is worth investigating this location alternative further.

The four location alternatives are scored on the seven alternatives. The alternatives are given a score between 1 and 10, but the actual value is not computed for all criteria. Actual costs and emissions are, for example, not calculated for the criteria, but an estimation has been made of the relative costs and emissions instead for each alternative. It is not possible to express the criteria conflict with surroundings, hindrance for ships during construction, and connection during construction in numbers, so again relative scores are assigned. The OmniTRANS model is used to score the alternatives on the criteria of travel time and compatibility with existing infrastructure. This model also has limitations, which are addressed in Subsection A.2.5.

To conclude, the multi-criteria analysis gives a useful first overview of the suitability of the location options. Nevertheless, more detailed and quantitative research is required to select the optimal location.

Population and jobs growth on Hessa

At most 5,000 new inhabitants and 5,000 new jobs can be realised on Hessa without the new Steinvåg bridge becoming a bottleneck in the traffic system. These numbers are solely determined based on the transport network, without investigating if it is physically possible and socially acceptable to construct that many new houses, appartment buildings, offices and other structures. Hessa is a small island with a relatively low population. This many new buildings will likely change the culture and living environment on Hessa substantially, and it is the question whether this is desired and required for the expansion of the city. However, this investigation is only meant to find out if it is possible to accommodate so many new residents and employees on Hessa, from a traffic point of view.

The methodology consisted of adding new inhabitants and job opportunities on Hessa in the Omni-TRANS model, until the bridge reached its capacity. Therefore, all uncertainties regarding this research are caused by the uncertainties and assumptions in the OmniTRANS model. These are explained in Subsection A.2.2 and Subsection A.2.5.

Realisation of cultural centre

The OmniTRANS traffic model is used to compute how many visitors a new concert hall can attract at different moments during the day and for different frequencies for passing buses, without leading to a grid lock in the infrastructure network. In this project, a total of 6 scenarios are considered, but this

could be more to investigate the effects of small changes in number of visitors, start time of a concert and bus frequencies.

An important result of this research is that the start time of a concert has a considerable impact on the maximum number of visitors that can be attracted by it, without leading to heavy congestion in the transport network. By starting a concert after the evening peak, the maximum visitor number is 1,000 instead of 500.

The OmniTRANS model is developed for the evening peak, and includes commuting, regular sporting, and regular cultural activities as travel purposes. Going to a concert could be considered a regular cultural activity, but could also be a special type of activity, for which people consider other travel decisions than the model includes.

In addition, the model considers a 2-hour period. Travel demand is assumed to be constant during this period, and the same holds for the resulting intensities on the network. For a concert, most people arrive shortly before the start. People do not arrive equally spread over a 2-hour period before the concert. Therefore, the peak intensities on the network are higher than the model predicts.

End of Life of Steinvåg bridge

The analyses of the chloride content of the elements of the Steinvåg bridge Section 3.4 indicate that the expected increase in chloride will cause a shift from a mainly negligible risk of corrosion to a possible, probable, or even certain risk of corrosion. The following section will interpret the results and evaluate feasible EoL strategies for the bridge's materials.

The largest element of the bridge, the deck, is expected to have a chloride content with a probable or certain corrosion risk. This makes it difficult to reuse this element, as the high chloride content is likely already to have started affecting the reinforcement steel. If this is not yet the case, it will probably not be long before this process is set in motion. In addition, the uncertainty associated with chloride-induced corrosion would likely make it difficult to find a buyer willing to reuse the element, as buyers usually opt for newly constructed elements with negligible corrosion risk.

The second largest element of the bridge, the foundation, was not assessed by Statens vegvesen. However, as discussed Appendix B, it is common practice for foundation piles to remain in the ground when the service life of a structure has ended. Therefore, it is assumed that a similar EoL strategy applies to the foundation of the Steinvåg bridge. If the foundation is to be removed from the ground, then it is expected that the elements will have a relatively high chloride content, because of their proximity to the water. This makes it difficult to fully reuse these elements, similarly to the deck.

The third largest element of the bridge, the arches, is expected to have a chloride content with a possible corrosion risk. Although this is on the lower side of the corrosion risk, it is still difficult to reuse these elements, similarly to the deck and foundation. Selective removal of chloride-containing surface layers is not a viable option to make high-end reuse of the arches possible, as this will likely be too labour-intensive. Furthermore, since the chloride measurements were taken at only a couple of points along the arches, it is difficult to determine which areas would require selective removal.

Given the chloride content of the deck and the arches, recycling may be a more feasible EoL strategy than reuse. As identified Subsection B.6.1, a waste processing facility is located 14 km from the Devold building, which places it 14.8 km from the Steinvåg bridge. Here, the elements could be crushed to produce recycled aggregates while simultaneously separating the reinforcement steel from the concrete. The recovered steel could then be recycled at the nearby facility that specializes in steel recycling. As the aggregates remain contaminated with chloride after crushing, they should either be treated to reduce the chloride content or landfilled under controlled conditions to prevent leaching of chlorides into the soil or groundwater.

The other smaller elements of the Steinvåg bridge, such as the columns and walls, are expected to have a chloride content with a possible corrosion risk. Just like the arches, removal of chloride-containing surface layers is not a viable option for similar reasons. Furthermore, the columns and walls make up only a small portion of the overall structure. It would likely be inefficient to selectively demolish and process these elements separately from a logistics point of view. It is therefore more practical to

process these elements together with the larger elements.

A major uncertainty comes from estimating the dimensions of elements for which no measurements were given. For example, the thickness of the deck is unknown. Any difference in the deck thickness would change the total amount of reinforced concrete used in the analysis. And since the deck is responsible for ~60% of the total volume, this might have a significant impact. However, this does not affect the assessment of the Steinvåg bridge, because the elements are still unsuitable for reuse and are better suited for future use as landfill, for example.

Another important observation were some unexplainable changes in the data between 2007 and 2017. In some locations, the chloride levels went down, which is not possible naturally without human interference. It is possible that maintenance or other processes caused this phenomenon. Since there was no extra information to explain these points, these locations were not included in the analysis.

Since the current chloride levels were estimated, there is no guarantee that the calculated values are accurate. Extrapolation without knowing the possible error in the data is not very reliable, so any conclusions drawn from the data can only be interpreted qualitatively, not quantitatively.

General future planning

Before comparing the systems, it is important to note that overall planning procedures and methods in Ålesund are quite similar to those in the Netherlands. The differences highlighted here are mainly small observations about local culture and ways of working, rather than fundamental structural differences.

The Norwegian and Dutch examples show two different ways of planning. The Norwegian PBL model works well for quick decisions and local flexibility, but long-term coordination is sometimes limited. This can lead to solutions that work now, but are harder to adjust later. The Dutch NOVI model plans far ahead and prepares for future growth, but this often requires high investment early on and leaves less room for change once plans are fixed.

For Ålesund, the Norwegian approach is visible in the rapid delivery of the bus terminal and the uncertainty regarding the harbour area in Sørsida. These show that the city can move fast, but also that long-term choices are not always secured. It was noted that in both cultures, life-cycle analysis is usually done only after construction, but it will give early insights and should be included during the design stage. The Dutch examples show the opposite risk: preparing too much in advance can create inertia or maintenance costs if the timing changes.

Both approaches have their advantages and drawbacks, and the best choice always depends on the specific boundary conditions of the project. Some situations benefit from Norwegian-style flexibility, while others are better served by Dutch-style long-term planning and tools such as life-cycle analysis or early scenario testing.

5

Conclusion and Recommendations

5.1. Conclusion

The optimal location for a new connection between Hessa and Aspøya is at the current location of the Steinvåg bridge. The orientation of the bridge is altered, making it possible to construct the new bridge while the old bridge is still open, preventing a long disconnection between Hessa and the city.

The design of the new bridge includes one lane per direction. The current intensity on the bridge during the evening peak is well below the capacity of a one lane per direction road. Even with a population increase on Hessa from 3,852 to 8,852 (+5,000) residents and an increase in employment from 791 to 5,791 (+5,000), the bridge is not going to be a bottleneck in the traffic network. These developments on Hessa might be needed in the future to accommodate potential population, as the population of Ålesund is increasing. In conclusion, a bridge design with one lane per direction is a suitable solution for the long term, considering possible development plans on Hessa.

From the separate analysis regarding the bridge, it has been found that a tied-arch bridge is a feasible option, all information considered. The proposed design consists of a superstructure with a span of 90 meters and two approach bridges connecting the two islands. The width of the design is 15.5 meters, which should be enough to allow for future intensities as well as different modalities.

The Steinvåg Bridge has high levels of chloride in the concrete. Measurements taken at different places and depths show that the chloride levels vary. When this data is projected to the year 2037, it shows that there is too much uncertainty about how the chlorides and other elements will spread. Because of this, demolition contractors cannot safely reuse some parts of the structure.

The life cycle assessments for the different future scenarios of the Devold building show that reusing the building is more environmentally sustainable than demolishing it and building a new one. The environmental impact, expressed in NOK per m² GFA over a reference study period of 60 years, of the former is approximately NOK 437.33 when using the Norwegian methodology and NOK 891.53 when using the European methodology. The impact of the latter is NOK 621.80 when using the Norwegian methodology and NOK 2,542.58 when using the European methodology. In addition, the European methodology is better at creating a complete overview of the environmental impact compared to the Norwegian methodology. Therefore, the European methodology is preferred.

One of the options of reusing the Devold building is to open a concert hall in it. This is in line with the vision of the municipality of creating a vibrant new city district in Sørsida. Such a concert hall could host at most 500 people if an event starts during the evening peak. If more people are attracted by it, congestion reaches levels that are too high, and a grid lock will occur. Concerts that start after the evening peak can host 1,000 people without leading to too high congestion levels. Increasing bus frequencies on lines to the concert hall does not lead to a significantly higher modal share of public transport. It would not solve congestion problems and is therefore not advised.

This is related to the already high quality of the bus network, which provides large coverage across

the region. It offers frequent connections along the main west-east corridor linking the city centre and Moa. The connection to the islands is less frequent but serves the demand from and to these locations. The network is capable of accommodating future population and job growth without the need for major structural changes. However, the relatively low utilisation levels indicate that the service is over-dimensioned for the current demand, showing that the challenge for Ålesund lies not in the network design, but in encouraging more people to use public transportation. The good performance of the bus network is a beginning in achieving the sustainability goals, and will support a modal shift towards bus usage in the future.

The traffic model also showed that increasing all bus frequencies does not lead to significantly more people in the bus. Congestion now occurs during the evening peaks, with highest levels of congestion at the E136 between the city centre and Lerstad. An increase in car traffic is not possible, since it would lead to a total blockade of the roads in the city.

Finally, the Norwegian approach of civil engineering projects is characterised by fast-moving projects that can be quickly realised. However, long term coordination between different stakeholders is some-times limited, which might lead to problems in the future. In contrary, Dutch projects are often planned far ahead, but this leads to less flexibility in changes during a project. Both methods have their advantages and disadvantages, and could learn from each other. Also, in both countries, life cycle assessments are often performed after a project is completed, while it is better to implement it in the design phase.

5.2. Recommendations

The new connection between Hessa and Aspøya should have one lane per direction, with a cycle lane and a side walk on either side. The best option is to build a bridge rather than a tunnel, specifically a tied-arch bridge. However, it is recommended to further investigate the optimal location of the new connection between Hessa and Aspøya. A quantitative analysis of the considered criteria is required, as is potentially the inclusion of other criteria. In addition, new tests of the chloride content in the Steinvåg bridge are required to obtain the current state of different parts of the bridge, to determine which end of life scenarios are feasible. Furthermore, it has to be investigated whether the computed maximum number of new inhabitants and jobs on Hessa is physically possible on the limited area and whether it is socially desirable.

The Devold building should be reused instead of demolished, based on the environmental impact of both options. The Devold building can be used as a concert hall in the future. A maximum amount of visitors of 1,000 is recommended if concerts start after the evening peak, and 500 if they start during the evening peak.

Moreover, research to other aspects of the public transport system is required to determine which policy measures increase its modal share. Increasing the frequency of local buses is not recommended, because it has been found that this will not increase bus ridership.

Finally, it is recommended to take inspiration of some of the aspects of the Dutch method of planning in civil engineering projects. Increasing long term planning and improving coordination between stakeholders from different fields of expertise can further enhance project efficiency in Norway. Also, the inclusion of life cycle assessments during the design phase of projects is recommended.

References

AB Strängbetong. (2025, April). *ENVIRONMENTAL PRODUCT DECLARATION: Svängda betongtrappor*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13226549-1744130090/EPDer/Byggevarer/Betongvarer/NEPD-9646-9251_Sv--ngda-trappor.pdf

Adventures.com. (n.d.). *Alesund City*. https://adventures.com/norway/attractions/cities-towns/alesund/

Ålesund Kommune. (2025a, January 6). *Brosundtunnelen i Ålesund*. https://alesund.kommune.no/politikk-og-samfunnsutvikling/slik-utviklar-vi-alesund/prosjekt-veg-gang-og-sykkelveg/brosundtunnelen-i-alesund.48458.aspx#faqsporsmal-3060

Ålesund Kommune. (2025b, June). *Byutvikling på sørsida i Ålesund sentrum*. https://alesund.kommune.no/politikk-og-samfunnsutvikling/slik-utviklar-vi-alesund/prosjekt-by-og-stadutvikling/byutvikling-pa-sorsida-i-alesund-sentrum.17426.aspx

Ålesund Kommune. (n.d.). *Sørsida*. https://sorsida.no/s%C3%B8rsida#

Ålesundregionens Havnevesen. (n.d.). *Ålesund havn*. https://alesund.havn.no/

Amundsen, A., Blindheim, G. V., & Vilje, T.-L. (2024). Detailed Roadmap for the Waterfront Pilot in Ålesund. *Re-Value Deliverable D2.1*.

Årskog, V., & Fossdal, S. (2004, January). *LIFE-CYCLE ASSESSMENT OF REPAIR AND MAINTENANCE SYSTEMS FOR CONCRETE STRUCTURES*. Norwegian University of Science and Technology. https://www.researchgate.net/publication/237288224_LIFE-CYCLE_ASSESSMENT_OF_REPAIR_AND_MAINTENANCE_SYSTEMS_FOR_CONCRETE_STRUCTURES

Ashton Arch Bridge. (n.d.). https://issuu.com/thegreenagenda/docs/the_green_agenda_april_2022/s/15509391

Attvin. (n.d.). *Bingsa, Ålesund*. https://attvin.no/miljostasjonar/bingsa

Bergmesteren Raudsand AS. (n.d.). *Miljø for fremtiden*. http://bergmesteren.no/

BEWI ASA, Insulation and Construction. (2024, June). *ENVIRONMENTAL PRODUCT DECLARATION: Greenline EPS Norway, Fredrikstad*. The Norwegian EPD Foundation. https://bewi.com/wp-content/uploads/2023/12/EPD-Greenline-EPS-Norge-Fredrikstad.pdf

Bicycle Dutch. (2018, December 3). *The Delft bicycle parking facility revisited*. https://bicycledutch.wordpress.com/2018/11/20/the-delft-bicycle-parking-facility-revisited

Bjørn, A., Owsianiak, M., Molin, C., & Hauschild, M. (2017). LCA History. *Life Cycle Assessment*, 17–30. https://doi.org/10.1007/978-3-319-56475-3_3

Bovy, P., Bliemer, M., & Van Nes, R. (2006). *Lecture notes CT4801 - Transportation Modelling*. TU Delft. https://acrobat.adobe.com/id/urn:aaid:sc:EU:afba4eee-06f5-49ee-92f3-a519a42e81f9?viewer%21megaVerb=group-discover

Brødrene Aa. (2024). *Passenger models*. https://www.braa.no/passenger

Bypakke Ålesund. (2024a). *Handlingsprogram 2024-2027*. https://www.bypakkealesund.no/_f/p32/ia840a0a2-570c-4278-8858-8ffa109e3016/bypakke-alesund-handlingsprogram-2024-2027-med-vedlegg.pdf

Bypakke Ålesund. (2024b, January 17). *Kollektivknutepunkt Keiser Wilhelms gate*. https://mrfylke.no/tenester/veg-og-kollektiv/fylkesveg/vegprosjekt/oversikt-over-alle-fylkesvegprosjekt/kollektivknutepunkt-keiser-wilhelms-gate.10344.aspx#faqsporsmal-558

Bypakke Ålesund. (2025a, October 21). *Breivika-Lerstad*. https://www.bypakkealesund.no/prosjekt/veg/breivika-lerstad/

Bypakke Ålesund. (2025b). *Homepage*. https://www.bypakkealesund.no/

Bypakke Ålesund. (2025c, February 4). *Kollektivknutepunkt i Ålesund sentrum*. https://www.bypakkealesund.no/prosjekt/kollektiv/kollektivknutepunkt-i-alesund-sentrum/

Bypakke Ålesund. (2025d, February 4). *Sørsida og Brosundet*. https://www.bypakkealesund.no/prosjekt/veg/sorsida-og-brosundet/

Bypakke Ålesund. (2025e, June 5). *Sykkeltiltak, Tonningsgate-Brogata*. https://www.bypakkealesund.no/prosjekt/sykkel/tonningsgate-brogata/

Cats, O. (2024). Transport Modelling & Analysis Lecture 3: Trip distribution. https://brightspace.tudelft.nl/d2l/le/content/680516/viewContent/3826977/View

Cats, O., Massobrio, R., & Ruijter, A. (2025, February). *CIEM6230 Public Transport and Railway Systems (2024/25 Q4): Provided code*. https://gitlab.tudelft.nl/pt-networks/repo

Cedar Lake Ventures. (n.d.). *Climate and Average Weather Year Round in Ålesund*. https://weatherspark.com/y/54943/Average-Weather-in-%C3%85lesund-Norway-Year-Round

Centrum Pæle A/S. (2025a, August). *ENVIRONMENTAL PRODUCT DECLARATION: 1 meter steel reinforced fundation Pile in B3 45 x 45 type 20, with 20 rebar*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13232682-1754593239/EPDer/Byggevarer/Betongvarer/NEPD-10192-10192_2_1-meter-steel-reinforced-fundation-Pile-in-B3-45-x-45-type-20--with-20-rebar.pdf

Centrum Pæle A/S. (2025b, September). *ENVIRONMENTAL PRODUCT DECLARATION: 1 meter steel reinforced fundation Pile in G3 45 x 45 type 16, with 16 rebar*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13236537-1759231447/EPDer/Byggevarer/Betongvarer/NEPD-10325-10325_2_1-meter-steel-reinforced-fundation-Pile-in-G3-45-x-45-type-16--with-16-rebar.pdf

Centrum Pæle A/S. (2025c, September). *ENVIRONMENTAL PRODUCT DECLARATION: 1 meter steel reinforced fundation Pile in G3 45 x 45 type 20, with 20 rebar*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13236541-1759231427/EPDer/Byggevarer/Betongvarer/NEPD-10326-10326_2_1-meter-steel-reinforced-fundation-Pile-in-G3-45-x-45-type-20--with-20-rebar.pdf

Circular Ecology. (2023, March). *EN15804 Modules Explained*. https://circularecology.com/en15804-modules-explained.html

Editor Engineeringtoolbox. (2025, February 5). *Earth Pressure Acting on Basement Walls*. https://www.engineeringtoolbox.com/basement-wall-earth-pressure-d_558.html

Entur Developer. (2025). *Stops- and timetable data*. https://developer.entur.org/stops-and-timetable-data

EPD-Norge. (n.d.). *Om EPD-Norge*. https://www.epd-global.com/om-oss/

EurocodeApplied. (n.d.). *Table of concrete design properties*. https://eurocodeapplied.com/design/en1992/concrete-design-properties

European Committee for Standardization. (2004a). *EN 1992-1-1: Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings*. https://www.phd.eng.br/wp-content/uploads/2015/12/en.1992.1.1.2004.pdf

European Committee for Standardization. (2004b). *EN 1997-1: Eurocode 7: Geotechnical design - Part 1: General rules*. https://www.ngm2016.com/uploads/2/1/7/9/21790806/eurocode_7_-_geotechnical_designen.1997.1.2004.pdf

European Environment Agency. (2025, September 23). *Total waste generation*. https://www.eea.europa.eu/en/europe-environment-2025/countries/norway/waste-generation

Finnveden, G., Hauschild, M., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, *91*(1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

FRAM. (2025a). *Express boat*. https://frammr.no/journey/timetables-and-line-maps/express-boat/

FRAM. (2025b). *Timetables for Ålesund, Giske and Sula*. https://frammr.no/journey/timetables-and-line-maps/bus/#faqsporsmal-291

FRAM. (n.d.). *Om FRAM*. https://frammr.no/about-fram/fram/

Goudappel. (n.d.). *Traffic modelling software OmniTRANS Expert*. https://www.goudappel.nl/en/expertise/data-and-it-solutions/traffic-modelling-software-OmniTRANS-Expert

Gundersen, H. (2017). *Støvprøvar/kloridprøvar i betong – 15-0299 Steinvågbrua* (tech. rep.). Statens Vegvesen.

Heien, S., & Selbrug, R. (1951, June). Steinvågsund bru: Oversiktstegning.

Helland, S. and Maage, M. and Fluge, F. (2003, January). *Betingkonstruksjoner livsløp: Et utviklingsprosjekt i samarbeid mellom offentlige byggherrer, industri og forskningsinstitutter*. Statens vegvesen, Vegdirektoratet. https://vegvesen.brage.unit.no/vegvesen-xmlui/bitstream/handle/11250/192616/Betongkonstruksjoners%20livsl%C3%B8p%2019.pdf?sequence=1&isAllowed=y

Helle-Tautra, C., & Strand, K. (2020, December). *Byanalyse Ålesund og Ålesundregionen*. Statens Vegvesen. https://alesund.kommune.no/_f/p1/i2ff1396e-61eb-402e-aa4c-b5e56fdc8715/21-0084-byanalyse-alesund_web.pdf

Hop On AS. (2025). *Route Map: Ålesund Hop-On Hop-Off Bus Tour*. https://www.hop-on-hop-off-bus-tours.com/fileupload/tour/1022_Alesund_RouteMap.pdf

Humanity in Action. (2019, August). *The Bijlmer: a Dutch Approach to Multiculturalism*. https://humanityinaction.org/knowledge_detail/the-bijlmer-a-dutch-approach-to-multiculturalism/?lang=nl

International Organization for Standardization. (2006, June). *ISO 14025:2006(en)*. https://www.iso.org/obp/ui/#iso:std:iso:14025:ed-1:v1:en

ITU. (2020, June). *Factsheet Ålesund*. https://www.itu.int/en/ITU-T/ssc/united/Documents/U4SSC%20Publications/Factsheets/Factsheet_Alesund_Norway.pdf

Ji, S., Wang, Q., & Salisbury, M. (2009). Composition and tectonic evolution of the Chinese continental crust constrained by Poisson's ratio. *Tectonophysics*, *463*, 15–30. https://doi.org/10.1016/j.tecto.2008.09.007

Kartverket. (2025). *Norgeskart*. https://www.norgeskart.no/#!?project=seeiendom&layers=1001,1011&zoom=16&lat=6958109.42&lon=43323.13&sok=vadset

Kerr, N. B. (2024, December). *Floor Insulation Thickness: Regulations & Recommendations*. https://www.greenmatch.co.uk/insulation/floor/thickness

Killi, M. (1999). *Summary: Recommended values of time for passenger transport*. Transportøkonomisk institutt - TØI. https://www.toi.no/getfile.php/133367-1142432960/Publikasjoner/T%C3%98I%20rapporter/1999/459-1999/sum-459-99.pdf

K.S. Knudsen. (1961, June). *Bygningsanmeldelse*. Ålesunds Bygningsråd.

Latimer, J. (2023). *LCA Stages: The Four Stages of Life Cycle Assessment*. https://www.vaayu.tech/insights/lca-stages

Lindab A/S. (2022, May). *ENVIRONMENTAL PRODUCT DECLARATION: Sectional Doors LDI Steel LDS Steel LDP*. The Norwegian EPD Foundation. https://itsolution.lindab.com/lindabwebproductsdoc/assets/production/MzI1NWEwZGUtOTczMS00ZGRlLWI1Y2UtNjVjNmE3OWExOTI5/5249838523216688513/EPD_LindabDoors.pdf

Lister Ferdigbetong AS. (2025, April). *ENVIRONMENTAL PRODUCT DECLARATION: B45 MF40*. The Norwegian EPD Foundation. https://digi.epd-norge.no/epder/byggevarer/ferdig-betong/b45-mf40

Lovdata. (1985, June 14). *Plan- og bygningslov*. https://lovdata.no/dokument/NLO/lov/1985-06-14-77

Martin, W. A., & McGuckin, N. A. (1998). *Travel Estimation Techniques for Urban Planning* (NCHRP Report 365). Transportation Research Board, National Research Council. Washington, D.C. https://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_365.pdf

MobilityData. (2025). *General Transit Feed Specification*. https://gtfs.org/documentation/overview/

Møre og Romsdal Fylkeskommune. (2022). *Kollektivknutepunkt Keiser Wilhelms gate*. https://mrfylke.no/tenester/veg-og-kollektiv/fylkesveg/vegprosjekt/oversikt-over-alle-fylkesvegprosjekt/kollektivknutepunkt-keiser-wilhelms-gate.10344.aspx

Møre og Romsdal fylkeskommune. (n.d.). *About Møre og Romsdal County Council*. https://mrfylke.no/om-oss/english/

Mtoi, E. T., & Moses, R. (2014). Calibration and Evaluation of Link Congestion Functions: Applying Intrinsic Sensitivity of Link Speed as a Practical Consideration to Heterogeneous Facility Types within Urban Network. *Journal of Transportation Technologies*, *04*(02), 141–149. https://doi.org/10.4236/jtts.2014.42014

Nationale Milieudatabase. (n.d.). *Rekenen met set A1 en set A2*. https://milieudatabase.nl/nl/milieudata-lca/milieu-impact-categorieen/rekenen-met-set-a1-en-set-a2/

Neptunus. (2023, July 27). *Modular Education Building TU Delft | Education Structures*. https://www.neptunus.co.uk/neptunus-starts-building-modular-education-building-for-tu-delft

Nikel, D. (2025, January). *Norway bans tourist buses from iconic Fjellstua Viewpoint*. https://www.forbes.com/sites/davidnikel/2025/01/30/norway-bans-tourist-buses-from-iconic-fjellstua-viewpoint/

NJ Transit. (2025, October 2). *Portal North Bridge Progress: December 2022 – June 2025*. https://www.youtube.com/watch?v=8198s2Hh2rI

Norconsult. (2023, October 4). *Befaringsnotat og konstruktiv vurdering av devoldbygget, inklusive tilhørende kaikonstruksjon*.

Norges Geologiske Undersokelse. (n.d.). *Mountain base - national bedrock database*. https://geo.ngu.no/kart/berggrunn_mobil/

Norges Idrettsforbund. (2024, October). *Nøkkeltall for norsk idrett 2023*. https://www.idrettsforbundet.no/nyheter/2024/nokkeltall-for-norsk-idrett-2023/

Norkstaal. (n.d.). *Reinforcement steel*. https://www.norskstaal.no/products/reinforcement-steel

Norwegian Ministry of Climate and Environment. (2022, July). *Norway's Climate Action Plan for 2021–2030*. https://www.regjeringen.no/contentassets/a78ecf5ad2344fa5ae4a394412ef8975/en-gb/pdfs/stm202020210013000engpdfs.pdf

Nowtricity. (n.d.). *Current emissions in Norway*. https://www.nowtricity.com/country/norway/

NRK. (2025, March 11). *Dårleg kapasitet på Steinvågbroa*. https://www.nrk.no/mr/darleg-kapasitet-pa-steinvagbroa-1.17334306

NTNU. (2025). *Student i Ålesund*. https://www.ntnu.no/student/alesund

Nybetong AB. (2024a, October). *ENVIRONMENTAL PRODUCT DECLARATION: Massiv vägg*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13169706-1741639674/EPDer/Byggevarer/Betongvarer/NEPD-7782-7162_Massivvagg%281%29.pdf

Nybetong AB. (2024b, October). *Environmental Product Declaration: Pelare och Balk*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13169695-1741639663/EPDer/Byggevarer/Betongvarer/NEPD-7781-7161_Pelare---Balk%281%29.pdf

Olav Thon Gruppen. (n.d.). *AMFI Moa*. https://thon.no/kjopesenter/amfi-moa/

OpenStreetMap contributors. (2025). https://www.openstreetmap.org

Opinion AS. (2025, March 18). *Nøkkeltallsrapport 2024, Nasjonal reisevaneundersøkelse*. https://www.vegvesen.no/globalassets/fag/fokusomrader/nasjonal-transportplan-ntp/reisevaner/2024/nokkeltallsrapport-rvu-2024-pdf-190324.pdf?v=494e5c

Raleigh Heating Home Services. (n.d.). *Is a Heat Pump More Effective at Cooling or Heating?* https://www.raleighheatingandair.com/blog/is-a-heat-pump-more-effective-at-cooling-or-heating/

Regjeringen.no. (2025, June 26). *Norway submits its new NDC under the Paris Agreement*. https://www.regjeringen.no/en/aktuelt/norge-har-meldt-inn-sitt-nye-klimamal-til-fn/id3112346/

Resch, E., Wiik, M., Tellnes, L., Andresen, I., Selvig, E., & Stoknes, S. (2022). FutureBuilt Zero - A simplified dynamic LCA method with requirements for low carbon emissions from buildings.

Re-Value. (2023, April 23). *Nyheter*. https://sorsida.no/nyheter/re-value

Re-Value. (2025). *Ålesund*. https://re-value-cities.eu/cities/alesund

Re-Value. (n.d.). *Vision*. https://re-value-cities.eu/about

Rijkswaterstaat. (2020, September). *Nationale omgevingsvisie: Duurzaam perspectief voor onze leefomgeving*. https://open.overheid.nl/overheid/openbaarmakingen/api/v0/attachment/ronl-59b3033c-0826-4624-ba7f-41aec10b6d7a

Saint-Gobain. (2022, June). *ENVIRONMENTAL PRODUCT DECLARATION: weber REP 45 Concrete patch repair (weber REP 45 Paikkauslaasti KOVA)*. The Norwegian EPD Foundation. https://www.epd-global.com/epder/byggevarer/teknisk-kjemiske-byggevareprodukter/weber-rep-45-concrete-patch-repair-weber-rep-45-paikkauslaasti-kova

Silva, R., Brito, J., Neves, R., & Dhir, R. (2015). Prediction of Chloride Ion Penetration of Recycled Aggregate Concrete. *Materials Research*, *18*, 427–440. https://doi.org/10.1590/1516-1439.000214

Skar Elements Hudiksvall AB. (2024, March). *ENVIRONMENTAL PRODUCT DECLARATION: Massiv vägg V*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13171009-1741641548/EPDer/Byggevarer/Betongvarer/NEPD-6311-5571_Massivvagg-V.pdf

Skonto Prefab. (2022a, November). *ENVIRONMENTAL PRODUCT DECLARATION: Reinforced concrete filigree (floor) slabs*. The Norwegian EPD Foundation. https://www.epd-global.com/epder/byggevarer/betongvarer/reinforced-concrete-filigree-floor-slabs

Skonto Prefab. (2022b, November). *ENVIRONMENTAL PRODUCT DECLARATION: Reinforced concrete stair flights and landings*. The Norwegian EPD Foundation. https://www.epd-global.com/epder/byggevarer/betongvarer/reinforced-concrete-stair-flights-and-landings

Standards Norway. (2010). *NS-EN 1991-2:2003+NA:2010 Eurocode 1 – Actions on Structures – Part 2: Traffic Loads on Bridges*.

Standards Norway. (2012, February). *NS-EN 15978:2011*. https://online.standard.no/en/ns-en-15978-2011

Standards Norway. (2016). *NS-EN 1990:2002+A1:2005+NA:2016 Eurocode – Basis of Structural Design*. Standards Norway.

Standards Norway. (2018). *NS-EN 1991-1-3:2003+A1:2015+NA:2018 Eurocode 1 – Actions on Structures – Part 1-3: Snow Loads*. Standards Norway.

Standards Norway. (2023, March). *NS-EN 15804:2012+A2:2019+AC:2021*. https://online.standard.no/en/ns-en-15804-2012a2-2019ac-2021

Standards Norway. (2024, November). *Greenhouse gas calculations for buildings – NS 3720*. https://standard.no/fagomrader/energi-og-klima-i-bygg/bygningsenergi/klimagassberegninger/

Statens Vegvesen. (1990). *Kapasitet på vegstrekninger* (Nr.159 i vegvesenets håndbokserie). https://kudos.dfo.no/documents/16577/files/16758.pdf

Statens Vegvesen. (2014, June). *Bruklassifisering: Håndbok r412*. https://vegvesen.brage.unit.no/vegvesen-xmlui/bitstream/handle/11250/2768075/hb-r412%20Bruklassifisering.pdf?sequence=1&isAllowed=y

Statens Vegvesen. (2025a, January 1). *N400:2025: N400 Bruprosjektering*. https://viewers.vegnorm.vegvesen.no/product/860016/nb#id-7c14e85e-fee3-4d09-a606-2620a4ce24c6

Statens Vegvesen. (2025b). *Trafikkdata*. https://trafikkdata.atlas.vegvesen.no/kart?zoom=11&lat=62.4761&lon=6.1618&trafficType=vehicle

Statens Vegvesen. (n.d.). *Tasks and responsibilities*. https://www.vegvesen.no/en/about-us/about-the-organisation/about-the-norwegian-public-roads-administration/our-service-to-society-tasks-and-responsibilities/tasks-and-responsibilities/

Statistik Sentralbryå. (n.d.). *Ssb kart*. https://kart.ssb.no/wayfinder/default?w=full&f=click-in-map&x=6.125686&y=62.471562&z=17.3

Statistisk Sentralbyrå. (2023). *Norsk kulturbarometer*. https://www.ssb.no/en/kultur-og-fritid/kultur/statistikk/norsk-kulturbarometer

Statistisk Sentralbyrå. (2024). *Labour force survey*. https://www.ssb.no/en/statbank/table/13999/tableViewLayout1/

Statistisk Sentralbyrå. (2025a, May 14). *06673: Kollektivtransport med buss. Byområde, etter region, statistikkvariabel og år*. https://www.ssb.no/statbank/table/06673/tableViewLayout1/

Statistisk Sentralbyrå. (2025b). *Befolkning*. https://www.ssb.no/befolkning/folketall/statistikk/befolkning

Statistisk Sentralbyrå. (2025c, October). *Kommunefakta Ålesund*. https://www.ssb.no/kommunefakta/alesund

Statistisk Sentralbyrå. (2025d). *Number of employments and earnings*. https://www.ssb.no/en/statbank/table/13126/tableViewLayout1/

Statistisk Sentralbyrå. (2025e). *SSB Kart – Wayfinder for Ålesund (koord: 6.192821, 62.476544; zoom 10.4)*. https://kart.ssb.no/wayfinder/default?x=6.192821&y=62.476544&z=10.4

Statistisk Sentralbyrå. (n.d.-a). *SSB Kart: Arealbruk (ssb-arealbruk wms)*. https://kart.ssb.no/wayfinder/default

Statistisk Sentralbyrå. (n.d.-b). *Statistikkbanken: Table 14412: Kjønn, alder og organiserte treningsaktivitetar blant barn og unge 2024.* https://www.ssb.no/statbank/table/14412/tableViewLayout1/

Statistisk Sentralbyrå. (n.d.-c). *Statistikkbanken: 13396: Hvor ofte man gjør treningsaktiviteter, etter treningsaktivitet, alder, hvor ofte man gjør aktivititen, statistikkvariabel, år og kjønn*. https://www.ssb.no/statbank/table/13396/tableViewLayout1/

Statkraft Varme AS. (n.d.). *Hjem*. https://www.statkraftvarme.no/

Stokkan, J., Thorsnæs, G., Haugen, M. O., de Amoriza, S. E., & Mæhlum, L. (2025, August). *Ålesund in the Great Norwegian Encyclopedia*. https://snl.no/%C3%85lesund

Tranemo Prefab AB. (2024, July). *Environmental Product Declaration: Pelare XC3-XF4, nivå 3*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13170259-1741640454/EPDer/Byggevarer/Betongvarer/NEPD-7054-6449_Pelare-XC3-XF4--niva-3.pdf

Tranemo Prefab AB. (2025, March). *Environmental Product Declaration: Massiv bjälklagsplatta/RD-platta nivå 3*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13225533-1743002014/EPDer/Byggevarer/Betongvarer/NEPD-9466-9110_Massiv-bj--lklagsplatta-RD-platta-niv---3.pdf

Träullit AB. (2024a, January). *ENVIRONMENTAL PRODUCT DECLARATION: Semullit Träullit Baux – Cement Grey wood wool cement panels and wall systems*. The Norwegian EPD Foundation. https://www.epd-global.com/epder/byggevarer/bygningsplater-skillevegg/semullit-traullit-baux-cement-grey-wood-wool-cement-panels-and-wall-systems

Träullit AB. (2024b, January). *ENVIRONMENTAL PRODUCT DECLARATION: Semullit/Träullit/Baux - Cement Grey/White Natural wood wool cement panels and wall systems A2 Fire class*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13174165-1741646754/EPDer/Byggevarer/Bygningsplater/NEPD-5711-4987_Semullit-Traullit-Baux-----Cement-GreyWhite-Natural-wood-wool-cement-panels-and-wall-A2-fire-class.pdf

Träullit AB. (2024c, January). *ENVIRONMENTAL PRODUCT DECLARATION: Semullit/Träullit/Baux - White Natural wood wool cement panels and wall systems*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13174143-1741646720/EPDer/Byggevarer/Bygningsplater/NEPD-5709-4987_Semullit-Traullit-Baux-----White-Natural-wood-wool-cement-panels-and-wall-systems.pdf

Treinenweb. (2015, February 19). *Station Delft in de vernieuwing*. https://www.treinenweb.nl/reviews/62/station-delft-in-de-vernieuwing

UBAB Ulricehamns Betong AB. (2024a, October). *Environmental Product Declaration: Pelare XC4+XF1*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13169574-1741639480/EPDer/Byggevarer/Betongvarer/NEPD-7907-7577_Pelare-XC4-XF1.pdf

UBAB Ulricehamns Betong AB. (2024b, September). *ENVIRONMENTAL PRODUCT DECLARATION: Trappa svängd XC1*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13169849-1741639867/EPDer/Byggevarer/Betongvarer/NEPD-7615-6997_Trappa-svangd-XC1.pdf

UBAB Ulricehamns Betong AB. (2025a, August). *ENVIRONMENTAL PRODUCT DECLARATION: Massiv vägg*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13234143-1756477372/EPDer/Byggevarer/Betongvarer/NEPD-12176-12212_Massiv-v--gg.pdf

UBAB Ulricehamns Betong AB. (2025b, September). *Environmental Product Declaration: Massivt bjälklag*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13235668-1758023403/EPDer/Byggevarer/Betongvarer/NEPD-12346-12403_Massivt-bj--lklag.pdf

UBAB Ulricehamns Betong AB. (2025c, September). *Environmental Product Declaration: Massivt förspänt bjälklag*. The Norwegian EPD Foundation. https://www.epd-global.com/getfile.php/13235322-1757589557/EPDer/Byggevarer/Betongvarer/NEPD-12277-12316_Massivt-f--rsp--nt-bj--lklag.pdf

Ultstein Betong Industri. (n.d.). *Betong, knuseverk og entreprenør*. https://www.ulsteinbetong.no/

U.S. Department of Transportation. (2023, October 25). *Tunnels*. https://www.fhwa.dot.gov/bridge/tunnel/

Van der Wal, R. (2023, January 19). *New temporary building behind EEMCS*. https://delta.tudelft.nl/en/article/new-temporary-building-behind-eemcs

Vandervaeren, C., Fufa, S., & Kallaos, J. (2022). Level(s) compared to European and Norwegian standards for life cycle assessment of buildings. *IOP Conference Series: Earth and Environmental Science*. https://doi.org/10.1088/1755-1315/1078/1/012056

Vartdal Gjenvinning AS. (n.d.). *En bedrift i miljøets tjeneste*. https://www.vgjenvinning.no/

Vermond, B. (2024, July 1). *Waiting for the tram*. https://delta.tudelft.nl/en/article/waiting-for-the-tram

Vy. (2025). *Travel to Ålesund by bus*. https://www.vybuss.com/destinations/alesund/

Yang, L., Niu, T., He, F., & Song, Z. (2023). Study on the compressive and tensile properties of gneiss outcrop of bozhong 196 gas field in china. *Energies*, *16*(9). https://doi.org/10.3390/en16093919

Yang, Y. (2025, June). CIEM5230_004. https://collegeramavideoportal.tudelft.nl/catalogue/ciem5230/presentation/4c2294689bac448a81116174e1475a7f1d?academicYear=2024-2025-ciem5230

Yeung, J. S., & Wong, Y. D. (2014). The effect of road tunnel environment on car following behaviour. *Elsevier*. https://doi.org/10.1016/j.aap.2014.03.014

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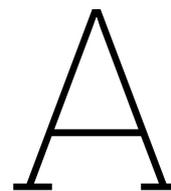
Analyses of the Transport Networks

This chapter focuses on traffic in Ålesund. Section A.1 is the introduction to the traffic and transport related work in the multidisciplinary project. Then, Section A.2 covers the development and application of a traffic model of Ålesund. Next, Section A.3 goes deeper into the current bus network of Ålesund. Finally, Section A.4 gives the overall conclusions of the analyses of the traffic system.

A.1. Introduction

This section first describes the current infrastructure of Ålesund, gives the problem statement, briefly mentions ongoing infrastructure projects in Ålesund and lists the goals of the transport project.

A.1.1. Current network

The city of Ålesund has one major road, the E136, connecting the islands from east to west to the mainland. Two bridges are crucial for connecting the islands: the Steinvågbrua between Hessa and Aspøya and the Hellebrua between Aspøya and Nørvøya. Moreover, the Ellingsøytunnel east of the city centre connects Ålesund to the island Ellingsøya, and is also on the route to the northern islands Vigra (airport), Valderøya, Giske and Godøya. There is also a ferry service for pedestrians and cyclists between the city centre and Valderøya. The mainland begins east of Aspøya, with the neighbourhoods Gåseid, Hatlane, Åse, Moa and Spjelkavik, stretching from west to east. The large island south of the city is Sula, which is accessible by car via the E39 and by foot or bike via the ferry from the city centre. Figure A.1 and A.2 show the overall network and the most important traffic-related locations in the city centre.

Figure A.1: Region of Ålesund.
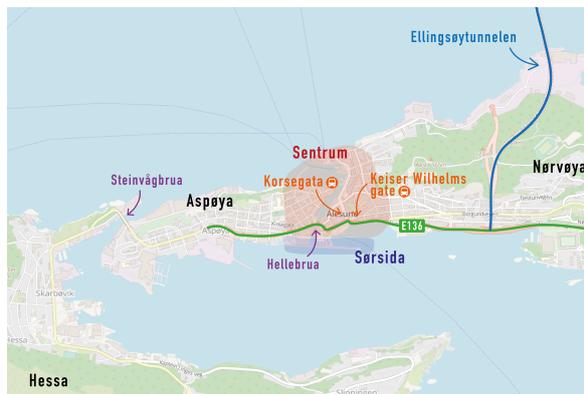
Figure A.2: Ålesund city centre.

There are several bus lines in Ålesund, shown in Figure A.3 and A.4. There is a new bus terminal at

Keiser Wilhelms gate in the city centre for city buses. Long-distance and airport buses depart from nearby Korsegata. At Moa, in the east of the city, there is a large bus terminal as well.
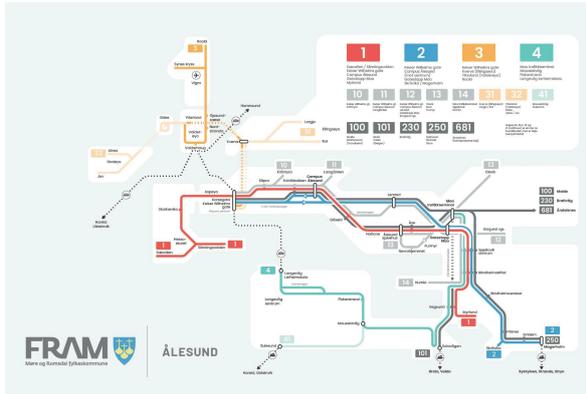
Figure A.3: Buses FRAM (FRAM, 2025b).

Figure A.4: Buses FRAM on map.

A.1.2. Problem statement

Congestion during peak hours occurs often in the city of Ålesund. Most of the inhabitants and employees of the city use the car as a travel mode, which causes traffic jams on the main roads. The current population of Ålesund Kommune is 59,305, the expected population in 2030 is 59,627, and in 2050 it is 62,151 (Statistisk Sentralbyrå, 2025c). This means that the travel demand in the city will increase. In order to make Ålesund future-proof, future traffic flows need to be modelled to determine if the infrastructure can offer this demand or if (policy) changes need to be implemented. Moreover, certain places in the city are being redeveloped to residential or working areas, which will likely increase the travel demand in the city.

In Norway, 47% of the trips are made as car driver, 23% by foot, 12% by public transport and 11% as passenger in a car (Opinion AS, 2025). In the region Ålesund, 71% of the trips are made as passenger car driver, 7% as car passengers, 6% by public transport, 14% by foot and 2% by bike (Helle-Tautra & Strand, 2020), as shown in Figure A.5.
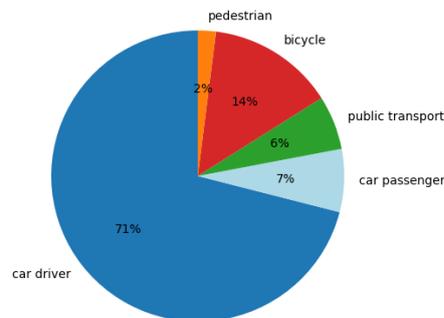
Figure A.5: Current modal split in Ålesund.

So, car traffic has a very high share in the modal split, in general and compared to the overall country statistics. In addition, on average only 32% of the bus seats was used in 2024 in Ålesund (Statistisk Sentralbyrå, 2025a). Apparently, the level-of-service of available bus services is not good enough for people to use the bus. In Ålesund, it would be beneficial to realise a modal shift from cars to public transport or active modes (walking, cycling) for some of the inhabitants. This would reduce the number of vehicles on the road, and thus reduce the congestion. There are also sustainable and health benefits related to this desired modal shift. Emissions decrease when less people use the car, and active modes (even only as access/egress mode for the bus) increase the health of people. Finally, running buses with a 32% occupation level is economically not viable, so it would also be financially beneficial to increase ridership in the buses.

To conclude, Ålesund is a car-oriented city, which leads to congestion during the peak hours. The infrastructure is likely unable to handle the expected increase in travel demand in the future. Moreover, the car is a non-sustainable travel mode. In addition, public transport usage is low, indicating an insufficient level-of-service of the public transport network. This should increase in order to realise a modal shift to the bus, which is desirable for reducing congestion and promoting sustainable travel.

A.1.3. Ongoing projects

There are already several ongoing infrastructure projects in Ålesund. Bypakke Ålesund is one of these projects. The project focuses on sustainable and efficient transport through the city in the coming 15 years, starting from 2022. Since the population will increase, and the network is already (near) its capacity, measures have to be taken. The project is a collaboration between Møre og Romsdal (the county), Ålesund Kommune (the municipality) and Statens Vegvesen (Norwegian Public Road Administration) (Bypakke Ålesund, 2025b). The goal of the project is to get more people to cycle, walk and use public transport in Ålesund, in order to reduce the share of car traffic in the city. Ålesund Kommune wants to realise a zero-growth of car traffic with the project (Bypakke Ålesund, 2024a).

The wider framework of Bypakke Ålesund is guided by three main objectives (Møre og Romsdal Fylkeskommune, 2022):

- Ensuring that the city has a reliable and efficient transport system across all modes of travel, capable of meeting the expected growth in demand.
- Contributing to the development of a future-oriented public transport service, adapted to changing mobility needs.
- Supporting attractive and sustainable urban development, in line with long-term city planning goals.

One of the subprojects of Bypakke Ålesund is "Sørsida og Brosundet". Statens Vegvesen is going to build a new main road through Sørsida, starting near the new bus terminal at Keiser Wilhelms gate and ending at the Waterfront Hotel (Nedre Strandgata). It involves a new bridge over Brosundet (Brosund bridge), which will decrease traffic load on Hellebrua. Moreover, Notenesgata will become a one-way street towards the west, also reducing the intensity on Hellebrua. The one lane reduction also makes it possible to build a new cycle path on Notenesgata (Bypakke Ålesund, 2025d). The new bridge will also increase network robustness, since the two parallel bridges are alternatives for each other in case one of them becomes obstructed due to for example an accident. Figure A.6 shows the new roads in the city centre.

Figure A.6: Future road plan in city centre (Bypakke Ålesund, 2025d).
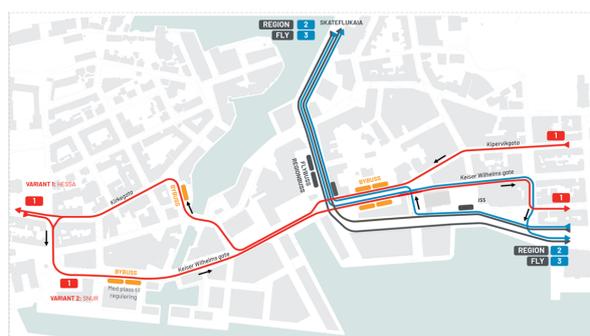
Figure A.7: Future bus plan in city centre (Bypakke Ålesund, 2025b).

Another subproject is the development of a new bus hub in the city centre. The Keiser Wilhelms gate and Korsegata bus stops, located close to each other, were developed into a central public transport hub (see Figure A.7).

The bus hub in Ålesund's city centre reflects the three main objectives of the Bypakke Ålesund project. Traditionally, buses waited for long periods at the central bus terminal, taking up valuable space (Møre og Romsdal Fylkeskommune, 2022). The former bus terminal has therefore been replaced by a street-

based hub that integrates bus operations more easily. The section of Keiser Wilhelms gate near the hub is now closed to through-traffic, though limited access remains for vehicles such as those entering the parking garage. Meanwhile, Korsegata was converted into a two-way street to accommodate both general traffic and bus operations (Bypakke Ålesund, 2025c).

Since the completion of the works in the fall of 2024, the organisation of services has been as follows (Bypakke Ålesund, 2025c):

- City buses depart from Keiser Wilhelms gate;
- Long-distance and airport buses depart from Korsegata.

In addition, the Post Office intersection (Keiser Wilhelms gate - Lorkenesgata) was adapted to allow Keiser Wilhelms gate to continue southwards via Sørsida and over the new (to be constructed) Brosund bridge. This connection will be realised in collaboration with the Norwegian Public Roads Administration as part of a later stage of the project (Bypakke Ålesund, 2025c).

There are also several subprojects of Bypakke Ålesund in the eastern parts of the city. For example, a new tunnel between Breivika and Lerstad will be built (Bypakke Ålesund, 2025a). However, in this multidisciplinary project the focus is on the city centre area.

There are also plans to construct a new tunnel underneath the city centre, connecting Aspøya and Nørvøya, reducing the car traffic in the city centre. It is, however, uncertain whether the project will be carried out and how it would be financed (Ålesund Kommune, 2025a). Therefore, it is chosen not to include it in this project.

A.1.4. Goals of transport and traffic project
There are two main goals of the transport-part of this project:

1. Develop a model that computes traffic flows through Ålesund in the current and future situations to determine the state of the network and to determine the effects of developments on land use, demography and bus frequencies on the network.

2. Analyse the current bus network to investigate if the low bus usage is caused by structural errors in the design of the network.

Traffic model
The first is to model traffic flows through the city for multiple transport modes. This results in an overview of the current intensities in the infrastructure network. Congested road sections will be identified, providing information on the current use of the network and determining if further growth of car traffic is possible with the current infrastructure.

Thereafter, scenarios with city developments are tested with the model to predict future traffic flows through the city, aiming to give insight into traffic flows through the city in different future scenarios. These future scenarios include the development of cultural hotspots in the Sørsida area, population increase at Hessa and different locations for a potential new connection between Hessa and the city centre. The new road configuration in the city centre (Figure A.6) is also incorporated into the future scenarios.

The traffic flow through the city is also an important factor for the bridges, for example for the new design of the Steinvågbridge. The traffic intensity, which follows from the traffic model, determines the required dimensions, mainly the width, of the bridge.

Bus network analysis
The second goal of the project is to analyse the current bus network in Ålesund.

Despite the construction of the new bus hub in the city centre, the fact that only 6% of trips (see Figure A.5) are currently made by bus suggests that the network still does not fully meet its potential. The low share of public transport use may indicate structural issues within the bus system, such as routing, connectivity, or service reliability that limit its attractiveness, even with the upgraded hub. A deeper analysis of the bus network's performance is therefore needed, in order to identify bottlenecks and opportunities for making public transport a more attractive alternative in Ålesund.

A.2. Traffic Model

This chapter covers the methodology, development and results of the overall traffic model of Ålesund.

A.2.1. Introduction to model

The model for traffic flows through Ålesund is constructed in OmniTRANS. This is a traffic modelling software developed by Dat.mobility (Goudappel) and commonly used in The Netherlands (Goudappel, n.d.). The software uses `Ruby` programming language.

In short, a simultaneous trip distribution and modal split model is incorporated in the 4-phase model, with as the final result the intensity on the infrastructure and ridership of public transport. The model is constructed for the evening peak hour. The evening peak hour lasts from 15:00 to 17:00, and is busier than the morning peak, as follows from the traffic counts in the city (Statens Vegvesen, 2025b). The focus of the model is on the city centre of Ålesund (the islands Aspøya and Norvøya). However, other areas are included, because they generate traffic demand in and through the centre.

The 4-phase model first determines the production and attraction per zone of the city. The city is divided into zones for determining the travel demand through the city. A total of 25 zones is used, which is the maximum number of zones that can be used with a student licence in OmniTRANS. Production is the number of people departing from a certain zone within the specified time frame. Attraction is the number of people arriving in a certain zone within the time frame. For the evening peak hour, zones with many job opportunities are expected to have a high production, whereas residential areas are expected to have a high attraction, since people return home from work in the evening. Based on the production and attraction, and the travel deterrence (i.e. travel time) between zones for different transport modes (car, public transport, bike, walking), it is calculated how many people travel between each pair of zones with each transport mode. This is summarised in four origin-destination (OD) matrices. Finally, these travel movements are assigned to the network. So, it is calculated how many cars/bikes/pedestrians are on specific links of the network and how many people are in public transport vehicles (buses). The model is calibrated with observed traffic counts of Statens Vegvesen, until differences between model and observations are below a certain threshold.

An important notion is that the model only includes inhabitants and employees of Ålesund. Trips related to tourism are not included in the model, but should not be forgotten. For example, the Hop-on-hop-off bus departs every 30 minutes from the cruise terminal to make a trip through the city (Hop On AS, 2025). There are also other companies offering these kinds of bus tours.

The model is a static model. This gives a good first overview of the traffic flows through a city, but does not capture all (dynamic) effects of it. A static model assumes that the traffic volumes on a link are constant during the considered time period. It also assumes that all modelled trips start and end within the time period. The results give an average view of the conditions during the considered time period. Therefore, it is a good technique for investigating specific time periods, like a peak hour. A disadvantage is that the length (distance) of congestion is not part of the results of a static model. Spillback effects are therefore not identifiable from a static model. The resulting travel times, however, are the real travel times, including delays due to congestion.

A.2.2. Methodology

Development

The 25 zones are created based on their inhabited area and distance to the centre of Ålesund. Near the centre, small zones are used, while areas far away from the centre are larger. All travel movements originating or arriving in the latter areas affect the traffic system in the centre of Ålesund in the same way, because they use the same road/bus to access/egress Ålesund. This justifies the larger areas. The zones are presented in Figure A.8. Zone numbers and names are listed in Table A.1.
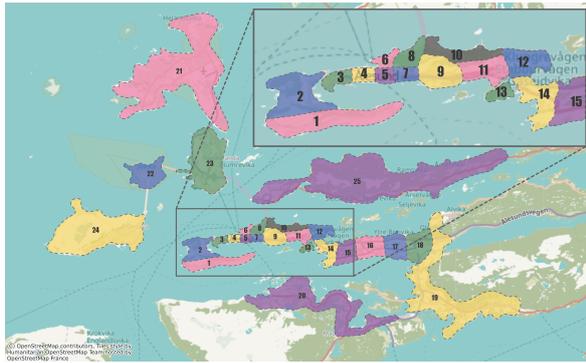
Figure A.8: Considered zones.
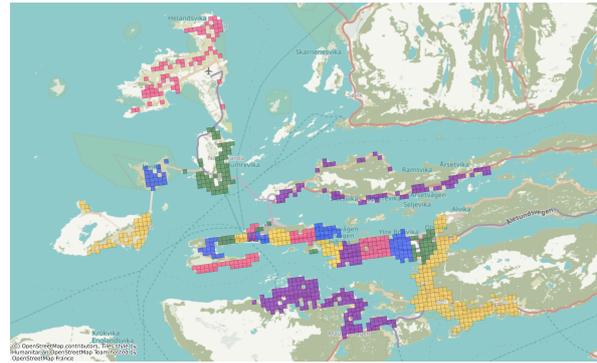
Figure A.9: Zones in grid.

Table A.1: Zone numbers and names.

Zone number	Zone name	Zone number	Zone name
1	Hessa south	15	Hatlane
2	Hessa north	16	Sjukehus
3	Aspøya west	17	Åse
4	Aspøya east	18	Moa
5	Centrum	19	Eastern towns (Spjelkavik, Breivika, Blindheim, Vegsund, Myrland, Magerholm)
6	Centrum North		
7	South of Aksla	20	Southern towns (Molvær, Langevåg, Fyllingsøen, Fiskarstrand, Mausiedvåg, Eidsnes)
8	Aksla		
9	Soccer stadium area	21	Vigra
10	Nørvøya	22	Giske
11	NTNU	23	Valderøya
12	Nørvasundet	24	Godøya
13	Borgund	25	Ellingsøya
14	Gåseid		

The required input for the model and the calibration is the following:

- Number of inhabitants and number of employees (jobs) per zone;
- Area of sport locations and cultural locations per zone;
- Speed limit, capacity, allowed road users per road in the network;
- Traffic counts at certain locations in the city.

The number of inhabitants is collected by the *Statistisk Sentralbyrå* (SSB) per grid of 250x250m. The number of employees per zone is taken from the same data source (Statistisk Sentralbyrå, 2025e). Per zone the sum of inhabitants and jobs of all the grids within the zone is taken. Figure A.9 shows the grids of 250x250m (that have at least one inhabitant or employee) that are included in each zone.

The land area of sport and cultural locations per zone is taken from the SSB as well (Statistisk Sentralbyrå, n.d.-a). It is not possible to extract the total area per zone from this data source, so they are manually computed. The traffic counts (for calibration) are taken from Statens Vegvesen (Statens Vegvesen, 2025b). The zonal data from the SSB is included in Table A.14 in Subsection A.2.8.

Phase 0: Setting up the OmniTRANS model
The first phase is to set up the network in OmniTRANS. The following steps have to be taken:

1. Adding a background map;
2. Creating the zones;
3. Adding centroids;
4. Linking zones and centroids;
5. Adding nodes;

6. Adding links;

7. Defining link types;

8. Assigning a link type to each link;

9. Adding bus stops;

10. Adding bus lines;

11. Connecting the centroids to nodes.

The background map is used to accurately build the network in the OmniTRANS software. The map is used to trace the roads and is taken from Open Street Map (OpenStreetMap contributors, 2025). The length of the digital map is scaled to the length in real-life. Any distance on the digital map in the software then corresponds to the real distance.

The zones are created as "Areas" in OmniTRANS. They are traced on the background map. The zones cannot overlap each other. One centroid is placed in each zone. This centroid represents all the aspects of a zone (the inhabitants, jobs, sports area and cultural area).

Next, the nodes are added to the network. The nodes represent the intersections of the road network or bus stops. Some nodes are only used as an access point to the network from the centroid (explained in step 11). Links are created between two nodes, if they are in real-life connected by a road. Only a selection of all roads is included in the model. All major through going roads are included, as are all the roads that the public transport (bus) uses. Smaller roads are also included if they are expected to have a high traffic intensity. This could be when they act as a short cut between certain places compared to the major roads. In the city centre, more (and smaller) roads roads are included, because the focus of this project is on the centre.

Thereafter, the link types are defined in OmniTRANS. Link types consist of the relevant characteristics of a type of road. This definition includes the speed limit, the capacity and the allowed road users on the link. The used speeds for cars and buses are 30, 40, 50, 60, 70 and 80 km/h. These are the speed limits on the roads in and around Ålesund. A speed of 4 km/h is used for walking, and 12 km/h for cycling.

Next, all links in the network are assigned a type. Special attention is paid to one-way roads. The link type in one direction includes all travel modes, the type in the other direction only cycling and walking or no modes. The ferry between Ålesund Skateflukaia and Valderøya ferjekai is added as a cycling and walking link. If this link would not be included, Vigra, Godøya, Giske and Valderøya would be unconnected to the city centre. The speed of this link is set up in such a way that the travel time of this link matches the real travel time of the ferry plus half the headway between two ferries (average waiting time). Table A.2 shows the included link types in the model. The allowed modes and the speed for motorised traffic are given. The connector is a special type of link (see later).

For some of the roads, the speed limits are considered to be infeasible. Many minor roads have a speed limit of 50 km/h, which vehicles cannot drive in reality for safety reasons (many intersections, pedestrian crossings, parked cars, no lane marking, narrow road, etc.). For these roads, an additional link type is defined, with a speed of 40 km/h. This link type is assigned to the following roads: Steinvågvegen, Kirkegata, Apotekergata, Parkgata, Kipervikgata, Keiser Wilhelms gate, Røysegata, Storgata, Buholmgata, Rådhusgata, Harald Torsviks plass, Borgundvegen (between Kipervikgata and Røysegata), Skaregata, Notenesgata, St. Olavs plass, Løvenvoldgata, Rasmus Rønnebergsgata and Lerstadsvegen.

The capacity of a road depends on many factors, like design speed, width and surroundings. For a normal 50 km/h road, the capacity is approximately 900 veh/h per direction under ideal conditions in Norway (A.R. Sætre, personal communication, September 30, 2025).

In the network, roads are classified as main, major or minor for this project. The main roads are all through-going highway-like roads outside of the built-up area. They must satisfy the following criteria:

• The road is not designed for pedestrians and cyclists (no sidewalk or cycle path);

• The speed limit is 60 km/h or higher.

Table A.2: Link types in traffic model.

link type	mode[1]	speed limit [km/h]	link type	mode[1]	speed limit [km/h]
30 all modes	C, PT, B, W	30	70 only car & PT	C, PT	70
40 all modes	C, PT, B, W	40	80 only car & PT	C, PT	80
50 all modes	C, PT, B, W	50	50 no car	PT, B, W	50
60 all modes	C, PT, B, W	60	40 only PT	PT	40
70 all modes	C, PT, B, W	70	only active modes	B, W	–
80 all modes	C, PT, B, W	80	ferry link	B, W	–
50 only car & PT	C, PT	50	minor through roads	C, PT, B, W	40
60 only car & PT	C, PT	60	connector	C, B, W	50

[1] C: car; PT: public transport; B: bicycle; W: walking

The capacity on a two lane road is 2,800 veh/h under ideal conditions for both directions together (Statens Vegvesen, 1990). A correction factor of 0.8 is assumed for non-ideal conditions, and a 50/50 division between traffic volumes in both directions is used. This leads to a capacity of 1,120 veh/h per direction, and 2,240 veh/2h in the OmniTRANS model for the main roads.

In a city, road capacity is also determined by the saturation flow of traffic lights (how many vehicles can pass a traffic light per hour). Therefore, the green and red time are measured at the intersection Keiser Wilhelms gate - Korsegata - Sjøgata for the major direction (Keiser Wilhelms gate $\leftrightarrow$ Sjøgata) and the minor direction (Keiser Wilhelms gate $\rightarrow$ Korsegata & Sjøgata $\rightarrow$ Keiser Wilhelms gate). The measuring is performed with a timer on a smartphone, and it is done on a Monday during the evening peak. A total of 10 green-red cycles is observed for all directions. It is assumed that every 2 seconds a vehicle can pass the light. Counting the number of passing vehicles is considered to be less reliable, since it is unknown if the capacity is reached at the moment of counting. Then, the average cycle time (green + red), average green time and average red time are computed. Based on the average cycle time, the number of cycles per hour is computed. This is used to compute the amount of green seconds per hour, which together with the 2 seconds per car is used to compute the capacity. Finally, the capacity is computed for a 2-hour period, since this is also the period the OmniTRANS model considers (15-17h).

$$C = 2 \cdot \frac{N \cdot \bar{t}_g}{2} = N \cdot \bar{t}_g \qquad \text{[veh/2hours]} \qquad (A.1)$$

with N the number of cycles per hour and $\bar{t}_g$ the average green time.

The calculated capacity of the major direction at this intersection is used for all major roads in Ålesund. The capacity of the minor direction is used for all minor roads in the city. Although not all roads have traffic lights, this calculated capacity is used because the traffic lights are a determining factor in the road network. On adjacent major roads, the maximum amount of cars is equal to what the traffic lights let through. For the minor roads, the capacity is also lowered by parked cars, intersections and narrower lanes.

For both type of roads, two measurements have been taken to determine the capacity. The average of the two is used as final capacity, rounded to the nearest higher multiple of 50. A road (section) is considered to be a major road if it satisfies the following criteria:

- The road has priority at all intersections;
- The road has lane markings;
- There are no parked cars directly next to the road.

All other roads are classified as minor roads. This classification is done per road section, using Google Maps or visits to the road. Table A.3 shows the computed capacities. The computed capacity for the main roads approximately matches the capacity under ideal conditions ($900 \cdot 2 = 1,800$ veh/2h).

For all cycle paths and sidewalks, a capacity of 720 cyclists/pedestrians per hour is used. This corresponds to one cyclist/pedestrian per five seconds. All capacities are doubled when putting them in OmniTRANS, because it is a 2-hour model (15-17h). It is expected that the capacities for these modes do not have any effect, since the modal share is low.

Table A.3: Capacity of main, major and minor roads in OmniTRANS model.

Road type	Capacity in model [veh/2h]
Main	2,240
Major	1,600
Minor	650

Next, a bus stop is added to each node with a bus stop in real-life. In principle, it would be possible to include all bus stops. However, since the modal share of public transport is low, the exact boarding/alighting location of passengers is of limited relevance. Public transport usage between zones is more interesting and requires a lower level of detail, which is chosen for this project.

Then, the bus lines are added to the network. Many bus lines do not have a single route, but multiple variants. All bus lines and their variants that are included in the model are presented in Table A.15 in Subsection A.2.8. For the frequency, the number of buses driving in the project area between 15h and 17h are included. Also when a bus just enters the network at 16:50, or if it reaches its destination at 15:05, it is included. This leads to an overestimation of the public transport supply. However, excluding them leads to an underestimation. A bus has 45 seats (Statistisk Sentralbyrå, 2025a) and an assumed crush capacity of 60 people.

Connectors link the centroids to the nodes in the network. Per zone, 1 to 10 connectors are used. This depends on the local infrastructure of the zone and the number of bus stops in the zone. The connectors divide the travel demand over different access/egress points of the network. Travellers will choose the connector that leads to the lowest travel time for their entire trip.

This likely means that they choose the connector, and thus node on the network, that is closest to their final destination and/or use the closest connector to their origin. This can give distorted demands, because it is desirable to distribute travellers throughout a zone according to the housing and job density. Therefore, the capacity of a connector depends on the total production and attraction of a zone. For the connectors from a centroid towards the network, the capacity of a single connector is determined by dividing the total production by the number of connectors, rounded upwards to multiples of 50. For the connectors in the other direction, the attraction is used. The multiples of 50 are chosen in order to keep the model usable with slight changes in the production and/or attraction. By restricting the capacity and choosing a certain BPR-function (see phase 4), the model is forced to distribute passengers over all connectors, which reflects reality better. For zones with only one connector, the capacity is simply put at 9999, as all travellers have to use that connector anyway. Connectors can be used by passenger cars, pedestrians and cyclists. Since the number of pedestrians and cyclists is expected to be low, the connector-capacity is initially not applied for these modes, because the exact movements within a zone are less relevant since congestion is unlikely to occur for these modes.

Phase 1: Trip production/attraction
In this section the production and attraction formulae are determined. Many factors are determined using literature. It should be noted, however, that these factors are unlikely to be fully correct. After the model has been developed and run, these factors can be adapted to more accurately capture the reality, in the calibration process. The scope of this project, regarding production and attraction, is limited to the variables mentioned in this section.

First, the production (P) of trips per zone is calculated. This is the number of departures from each zone in the evening peak hour. First of all, production is caused by employees going home. The number of employees per zone is known. In Norway, 26% of the work-related trips start between 15h and 17h (Opinion AS, 2025). This is the percentage of all commuter traffic during a day in that time period, and thus includes the morning peak as well. The factor should be two times as high to represent the home-going evening trips: 0.52. Nowadays, working from home is popular. In Norway, 57.4% of the employees never works at home, 36.0% works less than half of the working hours at home, and 6.5% works more than half of the working hours at home (Statistisk Sentralbyrå, 2024). It is assumed that the second category works 25% of the working hours at home (75% goes to work), and the third category works 75% of the working hours at home (25% goes to work). The percentage of employees going to

work and thus using the infrastructure, is therefore:

$$\begin{aligned} \text{\% non-home working employees} &= \text{\% never at home} + 0.75 \cdot \text{\% less than half-time at home} \\ &+ 0.25 \cdot \text{\% more than half-time at home} = 0.86025 \end{aligned} \tag{A.2}$$

So, on an average working day, 86.025% of the employees goes to work.

In addition to commuting, travel demand also arises from sporting and cultural activities. For sports, the motives are divided into two age groups: children aged 15 years and younger, and individuals older than 15 years.

For the first group, it is assumed that children are accompanied by one of their parents or caregivers when travelling to sports activities. According to a national survey (Statistisk Sentralbyrå, n.d.-b), 72.2% of children in this age group participate in an organized sport such as football, handball, gymnastics, or swimming several times per week. In Ålesund, there are 6,670 children aged 15 years or younger (Statistisk Sentralbyrå, 2025c). Applying the participation rate, about $72.2\% \cdot 6,670 \approx 4,816$ children regularly attend sports activities. Assuming each child participates twice per week, this generates $2 \cdot 4,816 \approx 9,632$ trips per week which equals roughly $9,632/7 \approx 1,376$ trips per day. The second group consists of people older than 15 years, a total of 52,635 individuals (Statistisk Sentralbyrå, 2025c). Within this group, 87% report practising sports at least once a month, and for many this extends to several times per week (Statistisk Sentralbyrå, n.d.-c). Unlike children, they are more likely to engage in activities such as running or cycling, which do not necessarily require travel. To stay conservative (leading to higher travel demand), we assume that on average, they engage in sports once per week. This results in $87\% \cdot 52,635 \approx 45,792$ people participating, corresponding to $45,792/7 \approx 6,542$ trips per day. Although this also includes joggers and cyclists (that do not need travel to and from their sport activity), it is chosen to use this number, even though it leads to an overestimation of the travel demand. It is not found how many people run and/or cycle. This overestimation balances out with the conservative choice for the number of sport trips in total. Taken together, the two groups account for about $1,376 + 6,542 = 7,918$ trips per day related to sports activities in Ålesund.

Approximately 15% of leisure-related trips depart between 15h and 17h (Opinion AS, 2025), during the evening peak. This is $7,918 \cdot 0.15 = 1,187.7$ trips. Scaled to the total number of inhabitants of Ålesund, this is $(1,187.7)/59,305 = 0.02$ trips per inhabitant for sport activities.

Cultural activities in the land use map of the SSB include the theatre, cinema, religion, museums and libraries (Statistisk Sentralbyrå, n.d.-a). It is assumed that the number of trips towards religious buildings during the evening peak hour is negligible. The average number of visits in one year for theatre/musical, opera, ballet/dance performance, concert, cinema, library and museum is 0.8, 0.1, 0.2, 1.8, 2.1, 3.6 and 1.4 respectively, for Norwegians aged 9 or older (Statistisk Sentralbyrå, 2023). In total, this is 10 visits per year, or 0.028 visits per day. Using the 15% trips departure during the evening peak, this is $0.15 \cdot 0.0280 = 0.0042$ visits per inhabitant (aged 9 or older) per evening peak hour. The number of inhabitants aged 10 or older is 52,974, while the total number of inhabitants is 59,198 (Statistisk Sentralbyrå, 2025c). Therefore the number of culture-related trips during the peak hour per inhabitant is $0.0042 \cdot (59,198/52,974) = 0.0046$.

The following formula is used:

$$\begin{aligned} P &= 0.52 \cdot 0.86025 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants} + 0.0046 \cdot \text{inhabitants} \\ &= 0.447 \cdot \text{jobs} + 0.0246 \cdot \text{inhabitants} \end{aligned} \tag{A.3}$$

The attraction (A) of a zone is the number of trips that arrive in a zone. This is in the evening peak hour based on the number of inhabitants of a zone, they arrive home from work. Also, people arriving at sports or cultural activities in a zone are part of the attraction.

In Norway, there are 2,882,095 employees (July 2025) (Statistisk Sentralbyrå, 2025d). The total population in July 2025 was 5,606,944 (Statistisk Sentralbyrå, 2025b), so 51.4% of the population was employed. This factor is also used to determine the number of people with a job in Ålesund, per zone. Again, the percentage of employees that does not work at home (86.025%) is incorporated in the formula. Also, 52% of inhabitants return home in the peak hour again.

Per zone, the sport and culture areas are known in m² (Statistisk Sentralbyrå, n.d.-a). Therefore, the number of people that 1 m² sport or cultural area attracts needs to be known. The most popular sports in Norway are soccer, golf and handball (Norges Idrettsforbund, 2024). In the data set, however, almost all areas indicated as sport are a soccer pitch or another large outside green area. Therefore, only the soccer pitch is used to determine the attracted number of people to a m² of sport, since this reflects the dataset best. Approximately 25 people play on a soccer pitch of approximately 7,000 m² simultaneously. An additional 1,000 m² is assumed for buildings included in the sport area (dressing room, canteen, etc.) So, a soccer field attracts $25/8000 = 0.003$ people per m² during the evening peak (15h-17h). There are two sport areas manually removed from the data. These are the Color Linestadion and a ski slope, both with a very large area. People do not go to the stadium to sport themselves, which is why it is excluded. The ski slope is excluded because it is assumed that people do not go skiing in the evening (when it is dark).

For cultural locations, it is assumed that 0.001 people are attracted to it per 1 m² area. The order of magnitude is assumed to be the same as for sports area. Also, it is assumed that cultural locations are less attractive during the evening peak hour, because there is more choice of time for culture than sport. During the evening peak, people are either going home, eating or sporting (with usually fixed starting times). Therefore, culture is less attractive during the evening peak. This leads to the lower assumed factor (0.001).

The area of the Sunnmøre Museum and Atlanterhavsparken are manually removed from the data. Both have a high area, but close during the evening peak. Therefore, their zones will get a disproportionate attraction if they are included in the model.

$$A = 0.514 \cdot 0.52 \cdot 0.86025 \cdot \text{inhabitants} + 0.003 \cdot \text{sport area} + 0.001 \cdot \text{cultural area}$$
$$= 0.230 \cdot \text{inhabitants} + 0.003 \cdot \text{sport area} + 0.001 \cdot \text{cultural area}$$
(A.4)

An important criterion is that the sum of all attractions regarding commuters (work-home) (approximately) equals the sum of all productions of commuters. The same holds for the sport and culture motive. The proposed factors meet this criterion.

The sum of all attractions and productions should be exactly equal. This is impossible to realise with the factors of formula Equation A.3 and Equation A.4. Therefore, the productions are balanced to the attractions after they have been calculated. Attractions are chosen as reference, because they are based on household data to a higher degree than productions, in this situation. Household data is considered to be more accurate.

Phase 2: Trip distribution & Phase 3: Modal split
In the next phase, the trip distribution and modal split is computed simultaneously. Trip distribution refers to where people travel to from where. The result is summarised in an origin-destination (OD) matrix per travel mode. This division per mode is referred to as the modal split.

First, skim matrices are computed for every mode. These matrices have size 25x25 (the number of zones) and contain the shortest travel time between all combinations of zones. For example, cell $(4, 24)$ shows the travel time from zone 4 to zone 24. The matrices are not symmetrical, since travel times can differ between directions, for example due to one-way streets. The diagonal shows the intrazonal travel time: the travel time within a zone for people that do not leave their zone. In this project, half of the average travel time towards the closest neighbouring zone is used as intrazonal travel time.

The travel times between each combination of zones for each mode is computed by the software. For the car, bike and walking, the computation is performed using the free speed (speed limit) and length of the link. A downside of this technique is that the travel time is also affected by other factors than link length and speed limit, like intersections, width of the road and more, which are not incorporated in the method.

For public transport, four skim matrices are computed: the travel time, waiting time, number of transfers and generalised costs matrices. For all matrices, the minimum value per OD-pair is used. The generalised costs (GC_{PT}) are used for the further calculations. This includes the total in-vehicle time, waiting time and a penalty for transfers. The route with the lowest generalised costs is not necessarily the route with the lowest in-vehicle travel time, waiting time and number of transfer separately.

One minute of waiting time in Norway is valued as 1.8 minutes of in-vehicle time for short waiting times ($\leq$ 7.5 min), 1.2 minutes in-vehicle time for waiting times between 7.5 and 10 minutes, and 0.4 minute in-vehicle time for long waits ($\geq$ 15 min) (Killi, 1999). In this project, the middle factor of 1.2 is used, since this is the weighted average of the factors (weighted to occurring wait times in the wait skim matrix). A transfer counts as 10 minutes of in-vehicle time (Killi, 1999). Equation A.5 gives the formula for generalised costs.

$$\mathrm{GC_{PT}} = t_{\text{in-veh}} + 1.2 \cdot t_{\text{wait}} + 10 \cdot N_{\text{transfers}} \tag{A.5}$$

Then, the travel deterrence is calculated for each combination of zones for each travel mode. This captures the resistance to travel between a pair of zones. A higher travel time corresponds to a higher deterrence, and thus less people travelling between the zones, all other variables being constant. The model is only constructed using travel time as explanatory variable for the deterrence.

Costs also influences travel decisions, but are not included in the model. All bus trips within the project area have the same fixed costs, so once somebody chooses the bus, the costs do not have an influence any more. The costs per kilometre for electric, diesel and benzine cars is different, which makes it difficult to incorporate it in the model. In addition, fuel prices differ per day in Ålesund. Given the limited time for the project, it is therefore chosen not to include costs in the deterrence functions.

The deterrence function differs per mode. A fixed increase in travel time by car is perceived less badly than by foot. Also, certain travel times are unacceptable by foot or bike, but still acceptable by car and public transport.

A deterrence function should satisfy the following four conditions (Cats, 2024):

- It should monotonically decrease with travel costs;
- Its integral should be finite;
- The impact of a fixed cost difference should depend on the absolute level;
- It should have a marginally diminishing relative impact.

An exponential function (Equation A.6) is taken for each travel mode. This function satisfies all criteria, and is often used for this purpose (Bovy et al., 2006). The travel time between zone i and j with mode v is indicated with c_{ijv}.

$$f(c_{ijv}) = \alpha_v \cdot \exp\left(-\beta_v \cdot c_{ijv}\right) \tag{A.6}$$

The α-value captures all other effects than the travel time (c_{ijv}), for example mode preference. The β_v-value captures the sensitivity to the travel time. A higher β_v corresponds to a more rapid decline in willingness to use that mode for an increase in travel time. The initial values for α and β can be adapted during the validation of the model. The β-values are chosen according to the relative sensitivity of increased travel time for the different modes. A one minute increase in travel time for pedestrians is perceived worse than for cyclists, which in turn is worse than public transport, which is worse than the car, because of the physical effort. The values 1, 2, 3 and 4 are initially used for the β-values. The α-values are chosen with the current modal split in mind. However, simply using the fractions of the modal split (0.78, 0.14, 0.06 and 0.02 for car, bike, bus, walking respectively) as α-values will not reflect reality well. This is due to the shape of the deterrence functions. A low α in combination with a high β results in a mode being very unattractive (almost 0) for low travel times, it could be even so low as most travel times between adjacent zones. Travel times between non-neighbouring zones would be too high for travellers to choose walking or cycling. So, the modal share of walking, for example, would be underestimated, and the modal share of car overestimated. Therefore, the factors shown in Table A.4 are selected as initial values for α and β. The α-value of the car (a fast mode) is lowered compared to its modal share, and the α-values of the other modes is increased. The values of α reflect the order of modal shares (car has highest α, pedestrian the lowest). After the modal has run, the modal split can be checked and the factors could be altered if necessary. Figure A.10 shows the deterrence function of the different modes.

Table A.4: α and β values per travel mode (v).

	α_v	β_v
Car	0.45	1
Bike	0.30	3
Public transport	0.20	2
Pedestrian	0.15	4
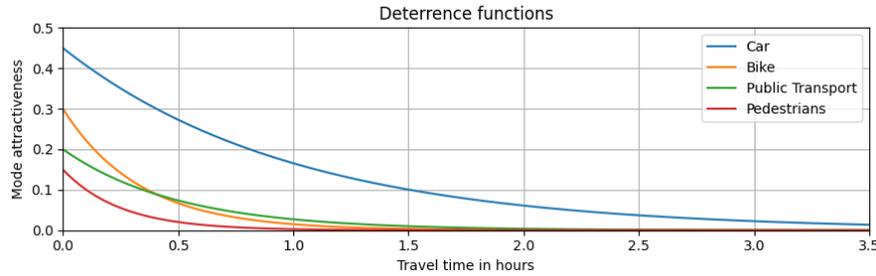
Figure A.10: Deterrence function per travel mode (v) with corresponding values from Table A.4.

Once the deterrence functions are determined, a new matrix is computed. This matrix has 25 rows (all zones) and 100 columns (25 zones with all four travel modes). It shows the value of the deterrence function between two zones i and j for a given transport mode v. The matrix is the starting point for applying the gravity model (see Table A.5). The last row shows the computed attraction per zone, and the last column the computed production per zone (Phase 1).

Table A.5: Set-up of gravity model matrix

$f(c_{ijv})$	$j = 1$				$j = 2$				...	**Production**
	Car	PT	Bike	Walking	Car	PT	Bike	Walking	...	
$i = 1$										
$i = 2$										
$i = 3$										
$i = \ldots$										
Attraction										

The model is doubly constrained. The sum of the values in a row should be equal to the computed production (in phase 1) of that zone. Also, the sum of the values in a multicolumn (four columns: car, PT, bike, walking) should be equal to the computed attraction of that zone.

$$\sum_j \sum_v T_{ijv} = P_i \tag{A.7}$$

$$\sum_i \sum_v T_{ijv} = A_j \tag{A.8}$$

with T_{ijv} the number of trips originating in zone i and arriving in zone j made by mode v, P_i the production of zone i, and A_j the attraction of zone j.

The gravity model is applied to achieve the constraints in an iterative manner. Columns and rows are balanced alternately, until all balancing factors have converged to 1. In each iteration, a new matrix is constructed. If the balancing factors have converged, the production and attraction per zone match the calculated production and attraction in phase 1.

When columns are being balanced, the balancing factor is as followed:

$$\gamma_j = \frac{\sum_i T_{ijv}}{A_j} \tag{A.9}$$

This factor γ_j is multiplied with the values in the cells of the matrix corresponding to the same zone j.

When rows are being balanced, the balancing factor is:

$$\delta_i = \frac{\sum_j T_{ijv}}{P_i} \tag{A.10}$$

This factor δ_i is multiplied with the values in row i.

First, columns are balanced, and then rows. This process repeats itself until the balancing factors converge to 1. In OmniTRANS, this is realised by demanding an ε of 0.00001. This is the sum of the absolute difference between the computed productions (in the gravity model) and demanded productions (from phase 1) and the computed and demanded attractions, summed for all zones. A maximum of 100 iterations is performed in OmniTRANS to prevent the model from crashing. The final result is an origin-destination matrix specified per transport mode.

Phase 4: Network assignment
Finally, the transport modes are assigned to the network. The final result will be intensities per link on the road network, bicycle and walking infrastructure, and the ridership on bus links.

Before doing the assignment, the total number of people using the car has to be translated to the number of cars. 7% of the people have car passenger as mode in the current modal split, and 71% car driver. The OD-matrix for cars includes all people using the car. Therefore, all cells in the OD-matrix are multiplied by a factor $7/(71 + 7) = 0.91$ in order to get the number of cars in the network.

The cars are assigned to the network using the Deterministic User Equilibrium (DUE) assignment. In this assignment type, it is assumed that people consider congestion when selecting their route. They are assumed to be aware of the true travel times. The travel time consists of uncongested travel time (with free speed) and delays due to congestion. In this assignment method, travellers choose their optimal route (least travel time). This is not necessarily the system's optimal route choice (lowest total travel time summed over all travellers). Travellers going from the same origin to the same destination might select other routes. The true travel time is calculated per link with the Bureau of Public Roads (BPR) link performance formula:

$$t_a(q_a) = \frac{L_a}{v_a^{\mathrm{max}}} \cdot \left(1 + \alpha_a \cdot \left(\frac{q_a}{C_a}\right)^{\beta_a}\right) \tag{A.11}$$

with

- t_a travel time on link a (h)
- q_a flow (load) on link a (veh/km)
- v_a^{max} maximum speed on link a (km/h)
- C_a capacity of link a (veh/km)
- α_a, β_a parameters of link a

When the link load, q_a, nears the capacity, C_a, travel times increase, because congestion occurs. The standard values of the factors α_a and β_a are 0.15 and 4 respectively. They are used for many urban areas (Martin & McGuckin, 1998). The α_a-value indicates the factor with which the travel time increases at capacity compared to free flow conditions (Mtoi & Moses, 2014). For example, if the uncongested travel time is 20 minutes, and α_a is 0.15, the travel time at capacity is $20 + 20 \cdot 0.15 = 23$ minutes. This also means that the higher the α_a, the earlier (with lower intensities) congestion occurs. The β-value determines how fast the travel time increases when congestion occurs (Mtoi & Moses, 2014). A higher β_a leads to higher travel times when the capacity is exceeded. Figure A.11 shows the effects of different values for α_a and β on the BPR function.

The BPR-parameters have to be specified per road type. The best option is to determine the parameters based on observed link flows and speeds for all link types. However, this is out of the scope of this project. Therefore, it is chosen to use the standard $\alpha_a = 0.15$ and $\beta_a = 4$ for all 50, 60, 70 and 80 km/h roads (main and major). Over-capacity is expected that have a greater negative effect on residential
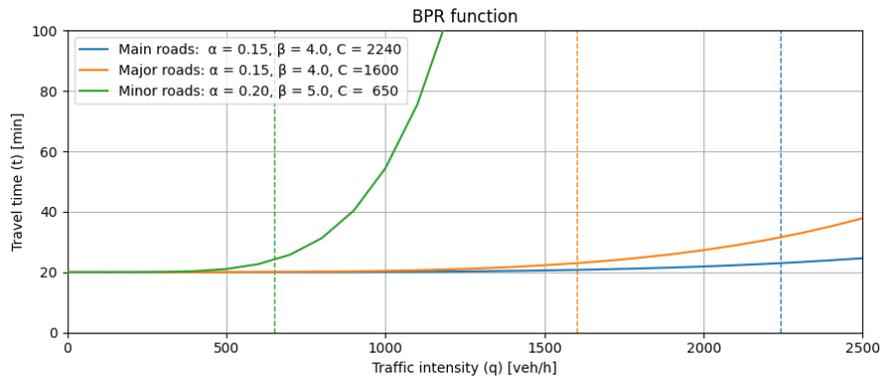
Figure A.11: Effects of α and β on BPR function.

roads (30 and 40 km/h). These minor roads are assigned an $\alpha_a = 0.20$ and a $\beta_a = 5$, resulting in a higher increase in travel time at capacity compared to free flow, and a steeper increase in travel time for increasing intensities higher than the capacity. The connectors are assigned an $\alpha_a = 0.01$ and a $\beta_a = 500$. This leads to an almost horizontal line until capacity, and then a very steep line upwards. So travel times do not change until capacity is reached, but once it is reached, they increase very rapidly, so nobody uses it any more. This method is used to be able to control the distribution of travellers over the different connectors within a zone.

The assignment is performed iteratively, for which the Method of Successive Averaging (MSA) is used. After each iteration, the link travel times are calculated again, and the vehicles are re-assigned to the network. At most 100 iterations are performed. The process stops before that if a convergence of 0.00001 is reached. This is when all paths have a relative increase/decrease below 0.00001 between two consecutive iterations. This means that all used routes between two zones have the same (true) travel time which is not larger than any unused route. This is also known as Wardrop's first principle.

The walk and bike trips are assigned to the network using the All-or-Nothing (AON) assignment. This means that all people with the same origin-destination pair use the same route, for these modes. They do not take congestion into consideration, but simply take the route that is quickest without any other traffic. Congestion is very unlikely to occur for pedestrians and cyclists in Ålesund, due to the low modal share. This makes the AON assignment suitable for these modes.

The public transport travellers are assigned using the ZENITH algorithm of the OtTransit class in OmniTRANS. It uses a frequency-based, multipath assignment type without considering crowding in the buses. Crowding is not considered, because it complicates the model unnecessarily. The modal share of public transport is really low in Ålesund, and buses currently have an average occupancy of 32% (Statistisk Sentralbyrå, 2025a), so crowding will likely not occur. If it follows from the model that it does occur, another technique will be applied. Public transport trips need an access and egress mode (going to and from the bus stop). Only walking is considered as access/egress mode. Cycling is not considered, because the modal share of cycling itself is very low, so cycling in combination with public transport is considered to be negligible. The car is not considered as access/egress mode, because it is assumed that people will make their entire trip by car if they use it, because of the very high modal share. Next, the minimum number of potential stops for access and egress has to be determined. In this project, one stop is used. This ensures that public transport is always accessible for travellers. Thereafter, routes between every set of candidates for the access and egress stops are searched for. The reverse tree generation algorithm is used for this. All lines ending at the destination stop candidate are investigated backwards. For all stops on that line, the costs of travelling from that stop to the destination stop is computed (travel time). If, during the search, a stop is found that was already found before (in another bus line), a discrete choice model is applied to determine the share of travellers that is assigned to each path. This discrete choice model considers costs (travel time) and relative frequency. During the backwards search process, stops with transfers to other bus lines could be found. In this situation, the path splits into two (or more) paths, adding a cost for transferring. In the end, all possible paths are known. Then, the discrete choice model is again applied to determine the share of travellers

that is assigned to each path. In computing the costs of paths, waiting time is again considered as 1.2 times as worse as in-vehicle time, and a transfer counts as 10 minutes in-vehicle.

Calibration Method

In the previous step, the model was developed and the intensity on the infrastructure was predicted. The next step is to calibrate the model with the observed traffic counts from Statens Vegvesen (Statens Vegvesen, 2025b). The calibration is only done for the car traffic. For other modes, no real-life data is available. However, the modal split of the model is compared to the real-life modal split. These should be (approximately) equal.

The first step is to select the locations with traffic counts to use for calibration. They are presented in Figure A.12. There are many measurement locations in and around Ålesund. Important criteria in selecting the locations for the calibration are that the measurement locations should have collected data per hour (and not only per day for example) and that they have been active recently.
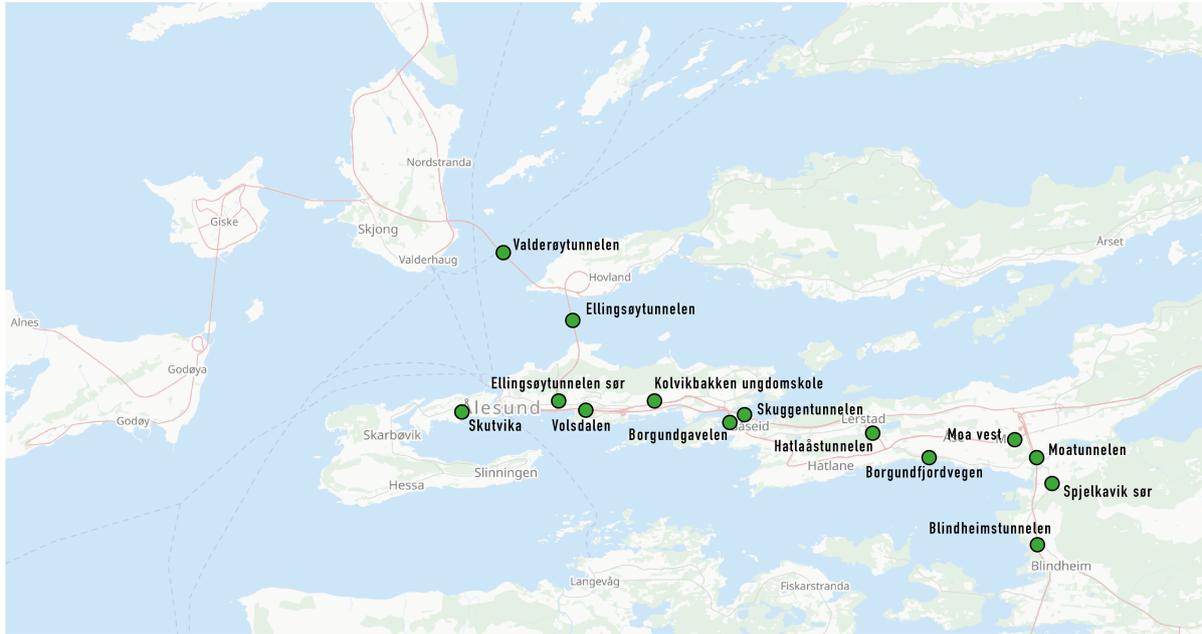
Figure A.12: Traffic counting locations.

A period of 1 year is used between October 6th 2024 and October 6th 2025. For some points, less data was available. The average number of passenger cars (length < 5.6m) between 15h-16h and 16h-17h is computed per weekday over this period. The weekend is not considered, since it includes less commuter traffic. These two hours are added together, because the traffic model considers the 15h-17h time period. Then, also the overall average is computed (the average over the 5 averages). This value is used for further calculations, unless large variations between the days of the week are identified.

For all selected locations with traffic counts, the Root Mean Square Error (RMSE) is computed (Equation A.12). It is the square root of the average squared residuals between the observed and estimated values. Large errors have a greater impact on the RMSE than small errors. The value of the RMSE approximately gives the error between model and observation. Lower RMSE-values thus indicate a better model.

$$RMSE = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{A.12}$$

with n the number of traffic count locations, y_i the observed traffic intensity at location i and $\hat{y}_i$ the modelled traffic intensity at location i. There are always two traffic count locations near each other, one for each direction.

In addition to the RMSE, the normalised RMSE (nRMSE) is also calculated. The magnitude of observations ranges from 463 to 2474, which makes interpreting the RMSE sometimes difficult. The nRMSE gives the average error between model and observation.

$$nRMSE = 100 \cdot \frac{RMSE}{\overline{y}} [\%] \tag{A.13}$$

with $\overline{y}$ the average of observations

Apart from the RMSE, the difference, Δ, (positive or negative) between model and reality of all comparison locations (Equation A.14) is also computed, as is the relative difference, RD (Equation A.15).

$$\Delta_i = \hat{y}_i - y_i \tag{A.14}$$

$$RD_i = 100 \cdot \frac{\hat{y}_i - y_i}{y_i} \tag{A.15}$$

The average real intensity at the count locations is 1121. It is chosen to use a maximum RMSE of 168, which corresponds to a deviation of approximately 15% of the true intensities. Traffic is a very stochastic phenomenon, which is difficult to predict. The model depends on only two socio-demographic variables and two geographical variables. They are not able to capture all traffic motives, so a nRMSE of 15% is considered to be good. In addition, no individual absolute relative difference may be larger than 20%. So, the model is accepted if:

- $RMSE \leq 168$;
- $|RD_i| \leq 20\%$ for all i.

If the model does not meet the criteria, it has to be improved. Table A.6 shows possible actions. Apart from these actions, connectors could also be relocated to better reflect reality.

Table A.6: Actions if model has to be improved.

Observation		Action
All model intensities are too low or too high	$\rightarrow$	Change production and attraction formulae
Some model intensities are too low, others too high	$\rightarrow$	Change deterrence and/or BPR-functions
Modal split is not correct	$\rightarrow$	Change deterrence functions
The distribution of traffic between parallel roads is illogical	$\rightarrow$	Check capacity, speed and BPR-function of roads

A.2.3. Calibration

Table A.7 shows the different steps taken in the calibration process, and the corresponding RMSE per step. Step 0 is the initial model with input as explained in Subsection A.2.2. The RMSE in step 0 is the RMSE of the initial model. The RMSE in step 1 is the RMSE of the model with the implemented changes mentioned in step 0. So the new RMSE after a change is shown a row below. Changes are kept in successive steps, unless explicitly mentioned that they are reversed.

Table A.7: Calibration steps.

#step	RMSE	Main change
0	534	Downgrade Borgundfjordvegen from a major road to a minor road since it is not a distributor road and change orientation of connectors in zone 18 to get more travel activities near AMFI Moa, which is one of Norway's largest shopping malls (Olav Thon Gruppen, n.d.)
1	488	Change orientation of connector in zone 11 and change attraction formula. The factor for sport is reduced from 0.003 to 0.002 people per m² sport area. This is done to decrease the attraction of the northern islands, because the roads towards the islands had a too high intensity, and the islands have a high sport area compared to the other zones. $\rightarrow A = 0.230 \cdot \text{inhabitants} + 0.002 \cdot \text{sport} + 0.001 \cdot \text{cultural}$
2	436	Change typo found in the production formula in OmniTRANS.

(Continuation of Table A.7)

#step	RMSE	Main change
3	372	Decrease factor for sport further to 0.0015, because attraction of northern islands is still too high. Decrease factor for inhabitants leaving for sport and culture during the evening peak from 0.0246 to 0.02, in order to keep total number of people departing for sport/culture equal to the number of people arriving for these purposes. $\rightarrow P = 0.447 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants}$ $\rightarrow A = 0.230 \cdot \text{inhabitants} + 0.002 \cdot \text{sport} + 0.001 \cdot \text{cultural}$
4	353	Lower the factors for sport even more, aiming to decrease the attraction of the northern islands even more. $\rightarrow A = 0.230 \cdot \text{inhabitants} + 0.0005 \cdot \text{sport} + 0.001 \cdot \text{cultural}$
5	353	The changes of step 4 are reversed, because they did not lead to a lower RMSE. The focus is for now relocated to Borgundgavelen, which has a too low intensity. The intensity is tried to be increased by increasing the production and attraction of zone 13, 14 and 15. This will lead to an increase of production and attraction in all zones, since the zonal variables of these zones are all lower than average. It is chosen to increase the work-related trips. The fraction of people leaving during the evening peak is increased from 0.52 to 0.60. $\rightarrow P = 0.60 \cdot 0.86025 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants} = 0.516 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants}$ $\rightarrow A = 0.514 \cdot 0.60 \cdot 0.86025 \cdot \text{inhabitants} + 0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural}$ $\quad = 0.267 \cdot \text{inhabitants} + 0.0005 \cdot \text{sport} + 0.001 \cdot \text{cultural}$
6	417	The RMSE increased, so the model performs worse and the changes are reversed. Now, the intensity at Moa vest is tried to be increased. This is done by giving zone 18 (the shopping mall) an additional attraction and production of 700. The production and attraction of this large mall is not captured well by the explanatory variables in the model. The connector directly linked to the mall is given an increased capacity, in order to put the extra travel demand at the right spot in zone 18.
7	344	The northern islands have mostly non-office jobs, so employees cannot work at home as often as other employees. In addition, the sport and culture area at the northern islands are less attractive than in other areas of the city. The quality of these facilities is higher in the city, due to scale effects and more demand. Therefore, lower demand at the islands is expected. New binary factors are introduced in the production and attraction formulae. The variable island $= 1$ for zone 21 to 25 (the northern island) and 0 otherwise. non island $= 1$ for zone 1 to 20 and 0 otherwise. $\rightarrow P = (1.0 \cdot \text{non island} + 1.2 \cdot \text{island}) \cdot 0.52 \cdot 0.86025 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants}$ $\quad = (1.0 \cdot \text{non island} + 1.2 \cdot \text{island}) \cdot 0.447 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants}$ $\rightarrow A = 0.514 \cdot 0.52 \cdot 0.86205 \cdot \text{inhabitants} + (0.8 \cdot \text{island} + 1.0 \cdot \text{non island}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural})$ $\quad = 0.230 \cdot \text{inhabitants} + (0.8 \cdot \text{island} + 1.0 \cdot \text{non island}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural})$
8	321	More extreme values are used for the factors, because the intensity to the northern islands is still too high, and from the islands too low. $\rightarrow P = (1.0 \cdot \text{non island} + 1.5 \cdot \text{island}) \cdot 0.52 \cdot 0.86025 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants}$ $\quad = (1.0 \cdot \text{non island} + 1.5 \cdot \text{island}) \cdot 0.447 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants}$ $\rightarrow A = 0.514 \cdot 0.52 \cdot 0.86205 \cdot \text{inhabitants} + (0.5 \cdot \text{island} + 1.0 \cdot \text{non island}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural})$ $\quad = 0.230 \cdot \text{inhabitants} + (0.5 \cdot \text{island} + 1.0 \cdot \text{non island}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural})$
9	333	The RMSE increased, so the changes are reversed. The intensity at Borgundgavelen is too low, and at Skuggentunnelen too high. These roads are alternatives to each other for east-west travel movements. It is desirable to shift intensity from Skuggentunnelen to Borgundgavelen. This is done by reducing the capacity of all tunnels with a speed of 60 km/h or higher from 2240 veh/2h to 2000 veh/2h. Capacity of tunnels is lower than that of regular roads, due to increased headways (Yeung & Wong, 2014). At the same time, the α-factor in the BPR function for all main roads is increased from 0.15 to 0.50. This means that the travel time increases by 50% when capacity is reached compared to free flow situations.
10	290	The additional production and attraction at Moa shopping mall (zone 18) is increased to 800 both. In addition, the factors for the islands are changed. $\rightarrow P = (1.0 \cdot \text{non island} + 1.3 \cdot \text{island}) \cdot 0.52 \cdot 0.86025 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants}$ $\quad = (1.0 \cdot \text{non island} + 1.3 \cdot \text{island}) \cdot 0.447 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants}$ $\rightarrow A = 0.514 \cdot 0.52 \cdot 0.86205 \cdot \text{inhabitants} + (0.4 \cdot \text{island} + 1.0 \cdot \text{non island}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural})$ $\quad = 0.230 \cdot \text{inhabitants} + (0.4 \cdot \text{island} + 1.0 \cdot \text{non island}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural})$
11	283	More extreme values for the island factors are tried. $\rightarrow P = (1.0 \cdot \text{non island} + 1.4 \cdot \text{island}) \cdot 0.52 \cdot 0.86025 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants}$ $\quad = (1.0 \cdot \text{non island} + 1.4 \cdot \text{island}) \cdot 0.447 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants}$ $\rightarrow A = 0.514 \cdot 0.52 \cdot 0.86205 \cdot \text{inhabitants} + (0.3 \cdot \text{island} + 1.0 \cdot \text{non island}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural})$ $\quad = 0.230 \cdot \text{inhabitants} + (0.3 \cdot \text{island} + 1.0 \cdot \text{non island}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural})$

(Continuation of Table A.7)

#step	RMSE	Main change
12	281	The RMSE decreased, but the decrease is considered to be too low for the changes to be kept. Therefore, they are reversed. The formulae introduced in step 10 are used again. Spjelkavik sør has a too high intensity towards the south, and a too low intensity towards the north. The high intensity is caused by a connector of zone 19 that is linked to a node at this road. That node is the closest node to most of the network linked to a connector in zone 18, which causes a high usage. The connector is linked to Breivika (neighbourhood). There is no reason to use Spjelkavik sør if Breivika is not your origin or destination. Therefore, local production should be increased, and attraction decreased. This is done by altering the capacity of the connector (per direction).
13	282	Although the RMSE increased, the changes are kept, because the measurement points close to zone 18 saw a large increase in model performance. In this step, an external zone is added to the OmniTRANS network. Zone 10 did not have any inhabitants, employees, sport and culture area, and therefore had no production and attraction. Zone number 10 is reused as external zone. There are 6,150 people commuting out of the municipality, and 9,159 people commuting into the municipality (Statistisk Sentralbyrå, 2025c). In the evening peak, this is the other way around. All the northern islands (zone 20-25: Ellingsøya, Valderøya, Godøya, Vigra, Giske) are not part of the municipality. Almost all parts of zone 18 and 19 (northern towns of Sula, Breivika, Blindheim, Myrland among others) are also not in the municipality. It is assumed that 52% of the commuters travel during the evening peak (same factor as used before). This leads to 3,198 people coming into the municipality, and 4,763 people leaving the municipality during the peak. From the Statens Vegvesen counts, it is known that 1,442 people leave the municipality by car towards the northern islands. 848 people enter the municipality by car from the northern islands. Using the counting points Spjelkavik sør and Blindheimstunnelen, it is known that 2,405 people leave the municipality by car towards the south east, and 2,175 people enter by car. So in total, $848 + 2{,}175 = 3{,}023$ people enter the municipality by car at points already included in the model. $1{,}442 + 2{,}405 = 3{,}847$ leave the municipality by car at points already included in the model. This leaves $3{,}198 - 3{,}023 = 175$ people entering the model by car that are not yet accounted for. $4{,}763 - 3{,}847 = 916$ people leaving by car are not yet included. Car traffic is 78% of the total traffic. So these numbers have to be multiplied by a factor $\frac{100}{78} = 1.28$. This leads to 224 additional people entering the model, and 1,172 people leaving the model. This is added with an external zone with given production and attraction. Travel time within zone 10 is manually set to 9999, to make the deterrence to stay within the external zone very high, because intrazonal travel for zone 10 should be zero.
14	280	The RMSE slightly decreased, but the changes are kept since the external demand is an important factor in the network. Attraction to the shopping mall is too high now, it is lowered to 500 people. Also, intensities towards the city centre are too low, so it has to be made more attractive. Sport and culture in the city centre is likely more professional and/or popular. So they are more attractive. $\rightarrow A = 0.230 \cdot \text{inhabitants} + (0.4 \cdot \text{island} + 1.0 \cdot \text{non island/centre} + 1.3 \cdot \text{centre}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural})$
15	276	Change connector capacity from Breivika to centroid (zone 19) to 250 instead of 400, aiming at more traffic on Spjelkavik sør towards the south.
16	271	Again, new factors in the production and attraction formulae are tried, because the balance between traffic towards and from the islands, and towards and from the city centre is still off. $\rightarrow P = (1.0 \cdot \text{non island} + 1.4 \cdot \text{island}) \cdot 0.447 \cdot \text{jobs} + 0.02 \cdot \text{inhabitants}$ $\rightarrow A = 0.230 \cdot \text{inhabitants} + (0.3 \cdot \text{island} + 1.0 \cdot \text{non island/centre} + 1.3 \cdot \text{centre}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural})$
17	272	The RMSE increased, so the changes are reversed. There is too few traffic on Borgundgavelen towards the city, while the other direction has the right amount of traffic. Overall, there is too few traffic from the east to the city centre. It is already tried to make the city centre more attractive, which did not lead to the desired results. Another option is to increase the production in the east (zone 14-20). These areas have a high number of employees and a high number of inhabitants compared to the average. The number of inhabitants is on average for these zones twice as high as the average. The factor for departures related to sport and culture is increased from 0.02 to 0.025. $\rightarrow P = (1.0 \cdot \text{non island} + 1.4 \cdot \text{island}) \cdot 0.52 \cdot 0.86025 \cdot \text{jobs} + 0.025 \cdot \text{inhabitants}$ $= (1.0 \cdot \text{non island} + 1.4 \cdot \text{island}) \cdot 0.447 \cdot \text{jobs} + 0.025 \cdot \text{inhabitants}$
18	267	Intensities from Moa to the city centre and to the south are still too low. Therefore, the extra production of the shopping mall is increased from 800 to 2,000. The attraction remains to 500. In the evening peak, it is logical that more people leave a shopping mall than that they arrive.
19	257	Now, still too few people travel from east to west in the model. It is thought that the external production (224 people) is too low. Therefore, it is set to 1,224, so an additional 1,000 people arrive into the project area during the evening peak.

(Continuation of Table A.7)

#step	RMSE	Main change
20	222	Borgundgavelen has 200-300 cars too few in both directions, while Skuggentunnelen has 300 cars too much in both directions. So, the intensity has to shift between these roads. The capacity of all tunnels is reduced by 100 to 1,900 veh/2h, which leads to a decrease of capacity at Skuggentunnel.
21	213	The previous change had the desired effect at Skuggentunnel, but a negative side-effect is that the intensity at Hatlaåstunnel (road leading to Skuggentunnel) is too low now in both directions. The capacity of one connector in zone 15 (east of the Hatlaåstunnel) is lowered, aiming to increase the intensity in Hatlaåstunnel. In addition, production and attraction formulae are changed again, because the flow towards the islands is too high and in the other direction it is too low. $\rightarrow P = (1.0 \cdot \text{non island} + 1.5 \cdot \text{island}) \cdot 0.447 \cdot \text{jobs} + 0.025 \cdot \text{inhabitants}$ $\rightarrow A = 0.230 \cdot \text{inhabitants} + (0.3 \cdot \text{island} + 1.0 \cdot \text{non island/centre} + 1.3 \cdot \text{centre}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural})$
22	193	The intensity at Skutvika towards Spjelkavik is too low (-19.5% or -215 vehicles). This means that the the production of Hessa and/or west Aspøya has to increase. Almost all departing trips in these zones (1-3) will go towards Spjelkavik at Skutvika. These zones score lower than average in all zonal data categories, especially in number of employees. Therefore, the factor for departures for sport and culture is increased again from 0.025 to 0.030. At the same time, the factor for attraction per m² sport field is increased from 0.0015 to 0.0020. This is done to keep the total number of departures for sport and culture approximately equal to the total number of arrivals for these purposes. $\rightarrow P = (1.0 \cdot \text{non island} + 1.5 \cdot \text{island}) \cdot 0.52 \cdot 0.86025 \cdot \text{jobs} + 0.030 \cdot \text{inhabitants}$ $= (1.0 \cdot \text{non island} + 1.5 \cdot \text{island}) \cdot 0.447 \cdot \text{jobs} + 0.030 \cdot \text{inhabitants}$ $\rightarrow A = 0.514 \cdot 0.52 \cdot 0.86205 \cdot \text{inhabitants}$ $\quad + (0.3 \cdot \text{island} + 1.0 \cdot \text{non island/centre} + 1.3 \cdot \text{centre}) \cdot (0.002 \cdot \text{sport} + 0.001 \cdot \text{cultural})$ $= 0.230 \cdot \text{inhabitants}$ $\quad + (0.3 \cdot \text{island} + 1.0 \cdot \text{non island/centre} + 1.3 \cdot \text{centre}) \cdot (0.002 \cdot \text{sport} + 0.001 \cdot \text{cultural})$
23	208	The RMSE increased, so the changes are reversed. More extreme values for the factors are tried now. $\rightarrow P = (1.0 \cdot \text{non island} + 1.6 \cdot \text{island}) \cdot 0.447 \cdot \text{jobs} + 0.030 \cdot \text{inhabitants}$ $\rightarrow A = 0.230 \cdot \text{inhabitants} + (0.2 \cdot \text{island} + 1.0 \cdot \text{non island/centre} + 1.4 \cdot \text{centre}) \cdot (0.002 \cdot \text{sport} + 0.001 \cdot \text{cultural})$
24	204	The RMSE is again higher than 193, so the changes are reversed. The intensity in Hatlaåstunnel is too low towards Spjelkavik (-29.6%). Too much traffic coming from Skuggentunnelen uses Lerstadvegen instead of Hatlaåstunnel. This means that Lerstadvegen has to be made less attractive. In the other direction, traffic intensity is also too low (-9.4%). At Moa vest, traffic intensity is also too low in both directions. This road acts as an alternative road to Lerstadvegen, and is reachable from the Skuggentunnel via the Hatlaåstunnel. The same holds for Borgundfjordvegen, which also has a too low intensity in the model. A decrease of capacity of 300 veh/2h is tried at Lerstadvegen. This could be caused by the ongoing road works, which affects a part of the timeframe of the used data set of Statens Vegvesen for calibration of the data. The new capacity on Lerstadvegen is 1200 veh/2h.
25	209	The change had the desired effect at Lerstadvegen/Skuggentunnel/Hatlaåstunnel, but the RMSE increases to 209 (compared to 193 in step 22). So the changes are reversed. Instead, a lower capacity reduction is tried. A capacity of 1400 veh/2h on Lerstadvegen is now tested.
26	201	Although the model predicts intensity in Hatlaåstunnel approximately correctly if the capacity of Lerstadvegen is lowered, the overall model performance decreases. This is mostly caused by lower traffic intensities at Borgundgavelen and Moatunnelen, both on routes that become less attractive if Hatlaåstunnel becomes more attractive. The model mainly performs badly in Moatunnelen, Skutvika sør and Blindheimtunnelen. These are all roads that are also used by traffic originating and arriving in external zones, which are not included in the model. When ignoring these three points, the model slightly performs better than after step 22. Therefore, it is decided to go forward with this model, since the project's focus is not on the three underperforming points. Borgundgavelen has -144 and -172 cars, while Skuggentunnel has 210 and 230 too much. These can be balanced out again. Capacity at Skuggentunnelen is lowered to 1800 veh/2h.
27	196	Attraction of the northern islands is too high. Ellingsøytunnelen sør (+20.2%), Ellingsøytunnelen (+23.1%) and Valderøytunnelen (+24.2%) all have a too high modelled traffic intensity. Production of the islands is slightly too low. Only the attraction formula is changed. The factor for cultural and sport related travel to the islands is lowered from 0.3 to 0.15. $\rightarrow A = 0.230 \cdot \text{inhabitants} + (0.15 \cdot \text{island} + 1.0 \cdot \text{non island/centre} + 1.3 \cdot \text{centre}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural})$
28	190	-

End of Table A.7

The last step decreased the RMSE of the total model to 190 (nRMSE = 16.2%). When excluding the

three measurement points at the edge of the model area (Spjelkavik sør, Blindheimstunnelen and Moa tunnelen), the RMSE is 164 (nRMSE = 14.3%).

The model after step 27 is kept as final model.

There were two requirements set up for the model:

- $RMSE \leq 168$
- $|RD_i| \leq 20\%$ for all i

The RMSE using all measurement points is 190, and the nRMSE is 16.20%. This is still higher than the requirements, but given the time constraints of this project and application of the model that still has to be done considered to be good enough. Table A.8 gives per measurement point the observed and predicted intensity, including the difference and relative difference between the two.

When disregarding the entry/access roads in the south-east of the project area (Blindheimstunnelen, Skutvika sør and Moatunnelen), the RMSE is 163.89 and the nRMSE 14.30%. Since the roads of these measurement points can also be used by traffic with neither the destination nor the origin in Ålesund, it is justified to give less weight to the correctness of the model prediction at these locations. Moreover, the main focus of this project is on the city centre part of the network.

If only the seven most centrally located measurement points are taken into consideration, the RMSE is 151.82 and the nRMSE is 11.87%. These seven points are Borgundgavelen, Ellingsøytunnelen sør, Ellingsøytunnelen, Skuggentunnelen, Skutvika, Volsdalen and Kolvikbakken ungdomskole. The RMSE and nRMSE for these locations indicate a good model performance, even better than the 15% requirement. The centrally located points are of most relevance, since the focus of this project is on traffic flows in the city centre.

The other requirement is also not met for all measurement locations. There are locations with an $RD \geq 20\%$. The largest RD occurs at the roads that could also be used for through-going traffic (no origin or destination in Ålesund).

There are in total 17,160 people travelling in the network during the evening peak. Table A.9 shows the observed and modelled modal shares of the four considered modes. Although the modal split is not exactly right, the model is considered to be good enough. The modal under-estimates the share of active modes, and over-estimates the share of the car and public transport. This is something to keep in mind when interpreting the model.

In addition, as previously mentioned, the model only accounts for inhabitants of Ålesund. Tourism is not included in the model.

A.2.4. Results
This section first describes the final model and then gives the results for the current network.

Final model
In this section, the input of the final model is given. Some significant changes to the model have been made in the calibration steps (Subsection A.2.3) compared to the initial model described in Subsection A.2.2. Therefore, an overview of the formulae, input and changes to the model are described in this section.

Equation A.16 and A.17 give the production and attraction formula used in the final model. Table A.14 in Subsection A.2.8 shows the zonal data (variables in production and attraction formulae) for the traffic model.

$$
\begin{aligned}
P &= (1.0 \cdot \text{non island} + 1.5 \cdot \text{island}) \cdot 0.52 \cdot 0.86025 \cdot \text{jobs} + 0.025 \cdot \text{inhabitants} \\
&= (1.0 \cdot \text{non island} + 1.5 \cdot \text{island}) \cdot 0.447 \cdot \text{jobs} + 0.025 \cdot \text{inhabitants}
\end{aligned}
\tag{A.16}
$$

$$
\begin{aligned}
A &= 0.514 \cdot 0.52 \cdot 0.86205 \cdot \text{inhabitants} \\
&\quad + (0.15 \cdot \text{island} + 1.0 \cdot \text{non island/centre} + 1.3 \cdot \text{centre}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural}) \\
&= 0.230 \cdot \text{inhabitants} \\
&\quad + (0.15 \cdot \text{island} + 1.0 \cdot \text{non island/centre} + 1.3 \cdot \text{centre}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural}
\end{aligned}
\tag{A.17}
$$

Table A.8: Model results and indicators.

Location	Direction	Observation	Model prediction	Δ	RD
Borgundgavelen	→ Nørve	749	701	-48	-6.4%
	→ Gåseid	1,038	970	-68	-6.3%
Ellingsøytunnelen sør	→ Ellingsøya	1,488	1,752	+264	+18.7%
	→ Ålesund	1,277	994	-283	-22.1%
Ellingsøytunnelen	→ Ellingsøya	1,442	1,738	+296	+20.6%
	→ Ålesund	848	913	65	7.8%
Hatlaåstunnelen	→ Spjelkavik	887	662	-225	-25.2%
	→ Ålesund	958	894	-64	-6.7%
Moa vest	→ Spjelkavik	1,274	1,253	-21	-1.6%
	→ Ålesund	1,346	1,259	-87	-6.4%
Moatunnelen	→ Volda	1,376	936	-440	-32.0%
	→ Ålesund	890	864	-26	-2.8%
Skuggentunnelen	→ Spjelkavik	1,964	2,065	+101	+5.2%
	→ Ålesund	1,953	2,051	+98	+5.0%
Skutvika	→ Spjelkavik	697	557	-140	-19.8%
	→ Ålesund	897	898	+1	+0.1%
Spjelkavik sør	→ Spjelkavik	868	500	-368	-42.3%
	→ Blindheim	463	662	+199	+43.0%
Valderøytunnelen	→ Valderøya	1,112	1,349	+237	+21.3%
	→ Ellingsøya	714	635	-79	-10.8%
Volsdalen	→ Spjelkavik	2,180	2,229	+49	+2.3%
	→ Ålesund	2,080	2,233	+153	+7.3%
Borgundfjordvegen	→ Spjelkavik	603	622	+19	+3.1%
	→ Ålesund	429	475	+46	+10.9%
Blindheimstunnelen	→ Volda	2,474	2,151	-333	-13.0%
	→ Ålesund	1,604	1,301	-303	-18.8%
Kolvikbakken ungdomskole	→ Ålesund sentrum	669	572	-97	-14.4%
	→ Nørvesund	632	625	-7	-1.0%

Table A.9: Observed and modelled modal split.

Mode	Observed share	Modelled share
Car (driver + passenger)	78%	81%
Public transport	6%	9%
Bike	14%	9%
Walking	2%	1%

The following changes are made to the computed production and attraction:

- Zone 10 (external): production of 1,224 instead of 0;
- Zone 10 (external): attraction of 1,174 instead of 0;
- Zone 18 (Moa): additional production of 2,000;
- Zone 18 (Moa): additional attraction of 500.

The capacity of all tunnels with a speed of 60 km/h or higher is 1,900 veh/2h in the model. All other capacities are implemented in the model as introduced in Table A.3.

The deterrence functions as introduced in Equation A.6 are used with the parameter values given in Table A.4. The BPR function as introduced in Equation A.11 is used with α and β values given in Table A.10.

Table A.10: α and β-values in BPR-function per road type.

Road type	α	β
Main	0.50	4
Major	0.15	4
Minor	0.20	5

Application to current situation

Figure A.13, A.14 and A.15 show the output of the model for the current network configuration. The colours, ranging from green to red, indicate the intensity-capacity (IC) ratio, with green meaning free-flow situations, and red meaning congestion. IC ratios per colour are indicated in Table A.11. The numbers in Figure A.14 and A.15 indicate the intensity on the road sections during the evening peak between 15h and 17h.

As can be seen, the main east-west connection into and out of the city (to Gåseid and Hatlane) is congested during the evening peak. The three access roads to Ålesund in the east (Lerstadvegen, E136 and Borgundfjordvegen) are also nearing their capacity. All these roads cannot handle more car traffic than there currently is. There are already road projects, like a new tunnel in the east of the city, that aim to facilitate growth in car traffic. The routes towards the northern islands are busy, but congestion does not occur. The road from the northern islands to the city has free-flow conditions.

Table A.11: IC ratios per colour indication.

Colour	IC ratio
Green	< 0.55
Yellow	0.55 - 0.70
Orange	0.70 - 0.90
Red	> 0.90
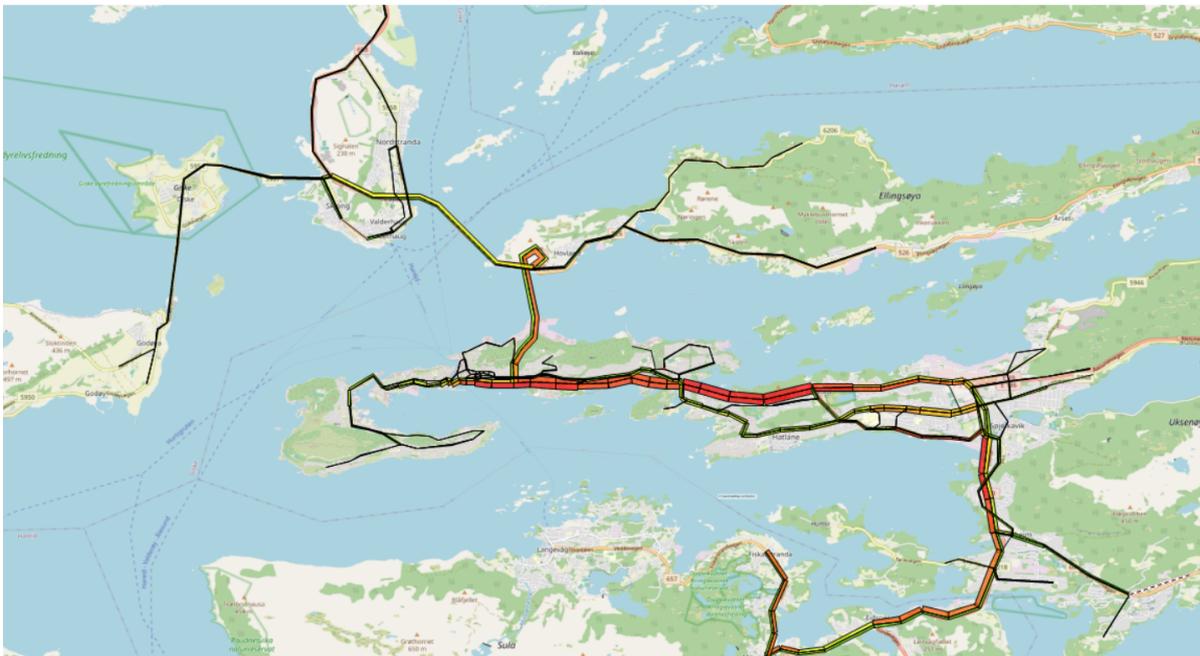
Figure A.13: Current IC ratios on car network.
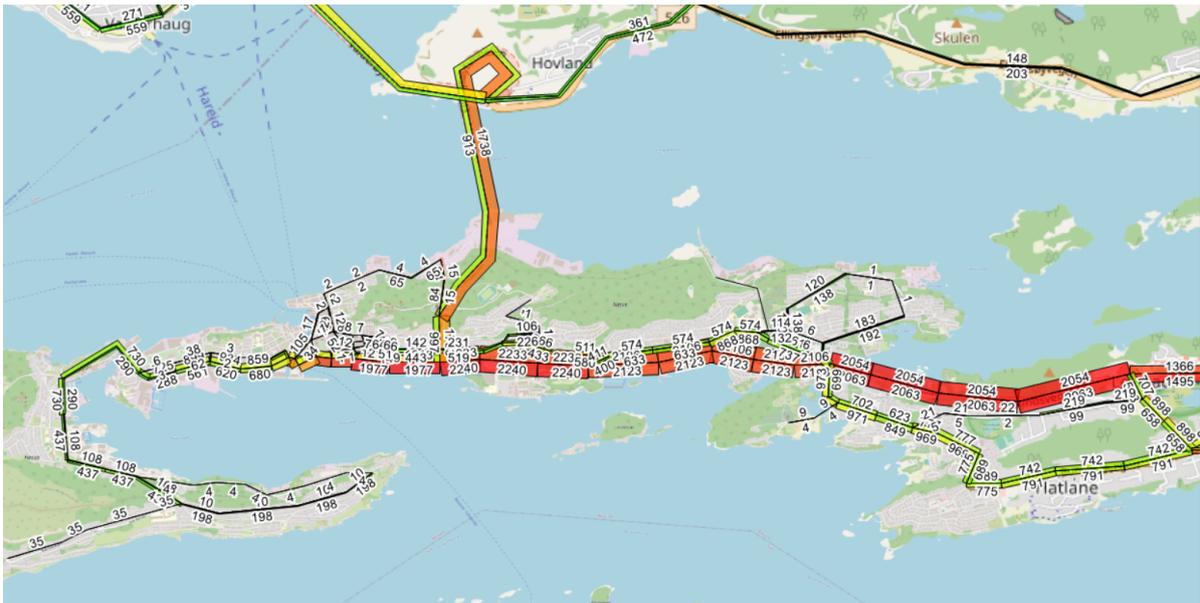
Figure A.14: Current intensities on car network, zoomed to city centre.
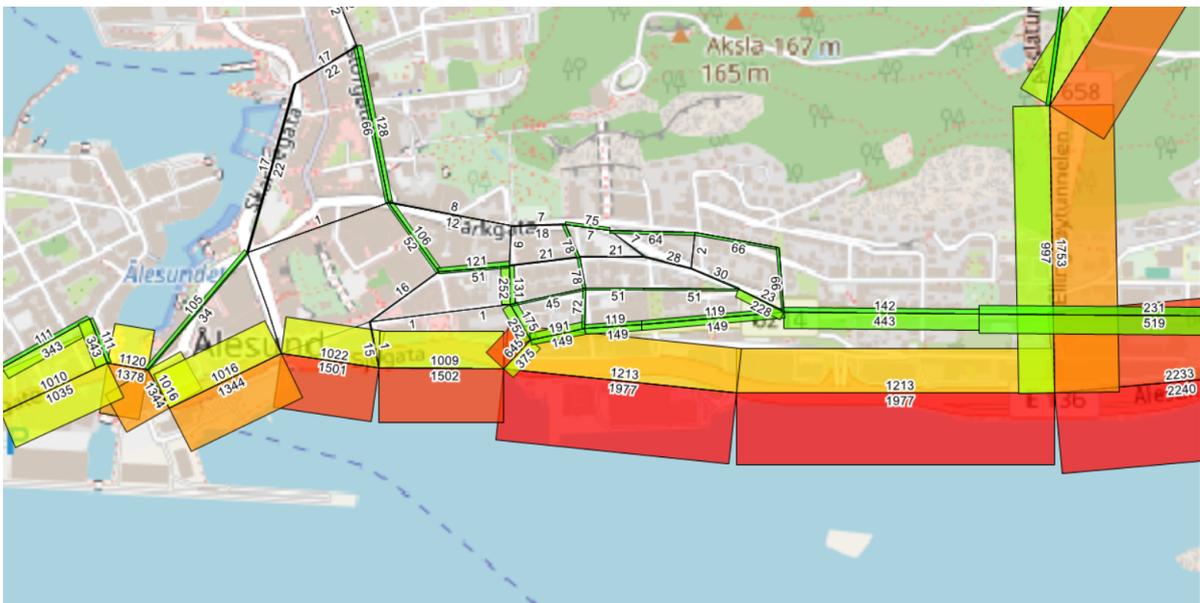
Figure A.15: Current intensities on car network, extra zoomed into city centre.

Hellebrua (left in Figure A.15) is crowded in both directions. The intensity towards the east is 1,378 and towards the west 1,120 vehicles during the evening peak, on a capacity of 1,600 veh/2h. In general, car traffic intensity towards the east cannot grow in the city centre during the evening peak, as all roads are already at or near their capacity. Increase towards the west (into the city) is still possible to a certain degree. Hellebrua is a critical link in the network. A temporary closure of this bridge due to, for example, an accident will lead to a lot of congestion, as more than 1,000 cars are not able to reach their destination. This would probably lead to a gridlock on Aspøya and on Norvøya. This problem is solved in the future, since an additional bridge parallel to Hellebrua will be built as part of the Sørsida project.

The model also clearly shows the asymmetry in traffic flows during the evening peak. Intensities out of the city centre are higher than into the city centre. This is caused by the high amount of jobs in the city centre and high amount of houses in other areas. This asymmetry is typical for an evening peak traffic

model.

Figure A.16 shows the free flow and congested travel times between selected zones in the current network configuration. The origin-destination pairs are selected based on their locations in their network. The main east-west and north-south connections are selected, without getting too much overlap between the selected routes.
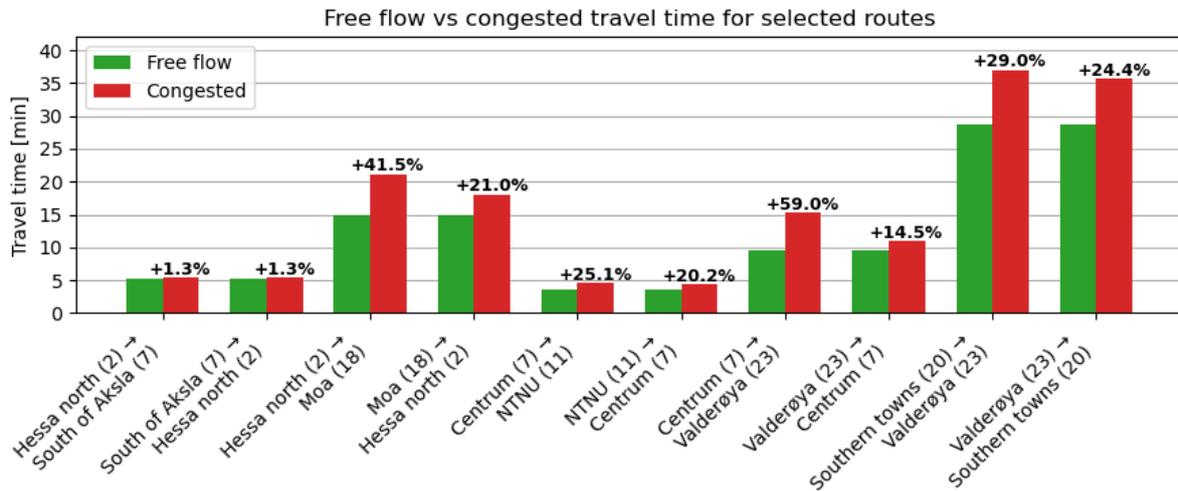
Figure A.16: Free flow vs congested travel times for selected routes.

West of the city centre, on Aspøya, travel times do not increase in the evening peak compared to free flow conditions. This follows from the trvavel times between Hessa north and south of Aksla. This also follows from the IC ratios on these road sections, which are indicated in green and yellow in Figure A.14, meaning an IC ratio below 0.6. Congestion does not occur on these road sections. East of the city centre, congestion and delays do occur. This follows from all other origin-destination pairs in Figure A.16. Travel times out of the city (towards the east or north) increase to a higher extent during the evening peak compared to free flow conditions than travel times into the city. Travel time from Hessa north to Moa is 62% higher during the evening peak than in free flow conditions, whereas it only is 13% higher in the other direction. Absolute travel time delays are all below 10 minutes. Apparently, a 10 minute delay is acceptable for car users in Ålesund.

Figure A.17 shows the ridership on bus lines in the city centre. In general, usage of public transport is low. Logically, most people use the bus near the city centre. The bus lines between the NTNU campus and the city centre (Keiser Wilhelms gate) are the most used. Also, the bus lines that use the main road (E136) to the east from the city centre have a relatively high usage. As with car traffic, intensities out of the city centre are higher than into the city centre, which is logical for an evening peak model. The separate bus network analysis in Section A.3 goes more into depth in the saturation level on specific bus links, and the potential increase of public transport usage.

Walking and cycling have low modal shares. In total, 137 and 1,506 use these modes respectively. Most of the trips have their origin and destination in the same zone, and are not visible on the network in OmniTRANS. It can be concluded that active modes are almost only used for short trips in the city. However, as follows from Table A.9, the share of these modes is under-estimated by the model. In reality, there are likely people using these modes (mostly the bike) for longer commuter distances. The intensity is so low that there will not be any problems in the cycling and pedestrian network.
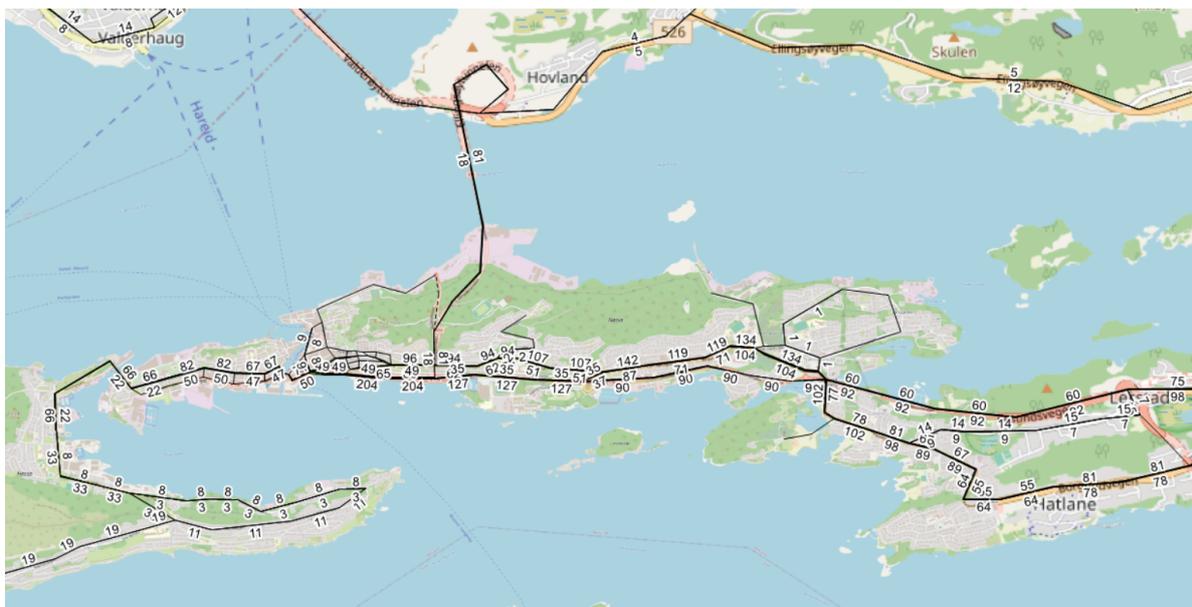
Figure A.17: Current intensities in public transport network, zoomed into city centre.

Application to future scenarios

Now, the model is applied for multiple scenarios:

- New Brosund bridge;
- New concert hall in the reused Devold building in Sørsida (also included in the main text);
- Increased bus frequency irrespective of other developments.

The OmniTRANS model is also used to select the optimal location for a new connection between Hessa and Aspøya, and to determine the development possibilities on Hessa in relation to the capacity of the newly designed Steinvåg bridge. The results of these applications are described in chapter 3.

New Brosund bridge

In the near future, the road configuration in the city centre will change as part of the Sørsida project. The new Brosund bridge will be built parallel to the Hellebrua, as introduced in Section A.1. This case will be the base scenario for all other developments that will be implemented in the model. Figure A.18 shows the intensities and IC ratios in this situation. Traffic is divided between the two parallel bridges. The IC ratio on Hellebrua in Figure A.15 is orange (0.70-0.90) and yellow (0.55-0.70), indicating almost no congestion to medium levels of congestion. In the new situation, there is free flow on the bridges, indicated in green (IC < 0.55). However, traffic volumes east of the bridge do not change, so the new bridge does not reduce congestion there. The heaviest congestion occurs east of the Hellebrua. Therefore, the new bridge will not solve the overall congestion problem in Ålesund.
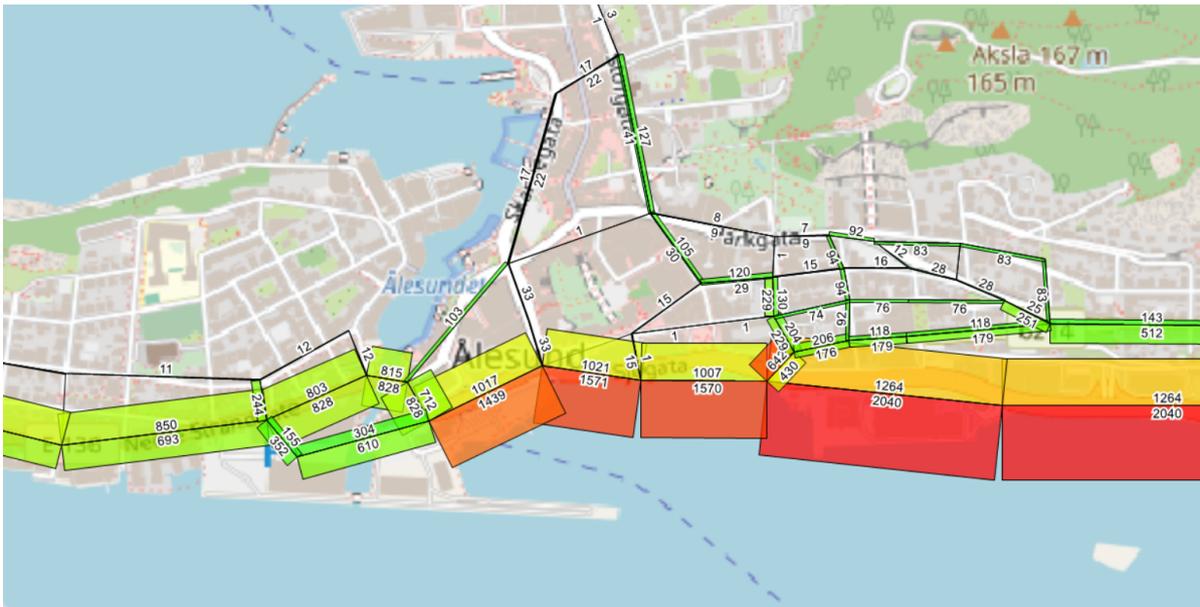
Figure A.18: Car network intensities near Hellebrua in new road configuration.

Concert hall

In the main text, the concert hall case is introduced. Different scenarios are described in Section 2.3. The technical changes to the model for these scenarios are explained in this section.

The original model is an evening peak model. It has to be adapted to the 17-19h time frame. This is done by changing the fraction of employees that is commuting in the model. It is 0.52 for the evening peak, this is halved to 0.24 for the 17-19h time frame. 48% of the employees does not travel during the evening peak. The travel share before and after the peak is approximately equal (Opinion AS, 2025).

Equation A.18 and Equation A.19 are the production and attraction formulae for the model between 17h and 19h.

$$
\begin{aligned}
P &= (1.0 \cdot \text{non island} + 1.5 \cdot \text{island}) \cdot 0.24 \cdot 0.86025 \cdot \text{jobs} + 0.025 \cdot \text{inhabitants} \\
&= (1.0 \cdot \text{non island} + 1.5 \cdot \text{island}) \cdot 0.206 \cdot \text{jobs} + 0.025 \cdot \text{inhabitants}
\end{aligned}
\tag{A.18}
$$

$$
\begin{aligned}
A &= 0.514 \cdot 0.24 \cdot 0.86205 \cdot \text{inhabitants} \\
&\quad + (0.15 \cdot \text{island} + 1.0 \cdot \text{non island/centre} + 1.3 \cdot \text{centre}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural}) \\
&= 0.106 \cdot \text{inhabitants} \\
&\quad + (0.15 \cdot \text{island} + 1.0 \cdot \text{non island/centre} + 1.3 \cdot \text{centre}) \cdot (0.0015 \cdot \text{sport} + 0.001 \cdot \text{cultural}
\end{aligned}
\tag{A.19}
$$

The demand from the external zone and the added demand in zone 18 (due to the large shopping mall) are reduced by the same factor as the regular production and attraction for the scenarios in time frame 17-19h.

- External production: $0.24 \cdot 1,224/0.52 = 565$;
- External attraction: $0.24 \cdot 1,174/0.52 = 542$;
- Extra production Moa: $0.24 \cdot 2,000/0.52 = 923$;
- Extra attraction Moa: $0.24 \cdot 500/0.52 = 231$.

The model already incorporates the travel purpose 'culture'. The number of inhabitants of Ålesund who depart to go to cultural activities is already included in the model (the production). It is assumed that people only change their destination due to the new concert hall and that no additional people travel for the purpose culture. In the long term, this could be the case once people have changed their habits.

The additional attraction of the concert hall is added to zone 4 (Aspøya east) in the traffic model. The concert hall will be placed in this zone.

Table A.12 shows the increased frequencies of the separate 'sub' bus lines 1. The total frequency of line 1 is increased by 50%. Some frequencies are rounded down to the nearest integer, others rounded upwards, because the frequency has to be an integer.

Table A.12: Old and new frequencies of bus line 1.

no. in model	head sign	current freq. in model	new freq. in model
	Bus 1-east		
1	Sævollen - Slinningsodden - Myrland Snuplass	1	2
2	Keiser Wilhelms Gate - Gatestopp Moa	4	6
3	Sævollen - Myrland Snuplass	2	3
4	Keiser Wilhelms Gate - Myrland Snuplass	2	3
5	Sævollen - Keiser Wilhelms Gate	1	1
6	Slinningsodden - Myrland Snuplass	3	5
7	Sævollen - Gatestopp Moa	3	4
8	Slinningsodden - Gatestopp Moa	1	1
	Bus 1-west		
9	Gatestopp Moa - Sævollen	3	4
10	Gatestopp Moa - Keiser Wilhelms Gate	6	9
11	Gatestopp Moa - Slinningsodden	1	1
12	Myrland Snuplass - Sævollen	3	5
13	Myrland Snuplass - Keiser Wilhelms Gate	5	7
14	Myrland Snuplass - Slinningsodden	1	2
15	Keiser Wilhelms Gate - Slinningsodden	3	5

During the peak hour, 332 cars go to zone 4 if there is no concert taking place. This number increases to 696 cars with a concert with 500 visitors. So, 364 cars are attracted to the concert. These amounts already consider car passengers, so it is not the number of people arriving by car, but the number of cars itself. After the peak hour, 157 cars have zone 4 as destination. This increases to 896 with a concert of 1,000 visitors, meaning that 739 additional cars are heading to zone 4.

All other results for these scenarios are included in Chapter 3.

Increased bus frequency irrespective of other developments
Three situations with respect to bus frequencies are investigated. The frequency of buses during the evening is increased in the model, to test if the modal share of public transport increases.

- 50% increase of frequency on lines 1, 2, 3 and 4 (main local bus lines) → 49 additional buses;
- 50% increase of frequency on lines 10, 11, 12, 13, 14, 31 and 32 (minor local bus lines) → 29 additional buses;
- 50% increase of frequency on all before mentioned bus lines → 78 additional buses.

A 50% increase in frequency is chosen, because it leads to substantial more buses, and thus shorter waiting times, but is also still relatively feasible to implement. Table A.13 shows the modal split of all transport modes for the different scenarios regarding frequency of bus lines.

Table A.13: Old and new modal split (passengers and percentages) from model.

Scenario	Car share	PT share	Bike share	Walk share
Current frequencies	14,610 (82.2%)	1,507 (8.5%)	1,506 (8.5%)	137 (0.8%)
Increased frequency main local bus lines	14,499 (81.6%)	1,629 (9.2%)	1,495 (8.4%)	137 (0.8%)
Increased frequency minor local bus lines	14,586 (82.1%)	1,530 (8.6%)	1,506 (8.5%)	138 (0.8%)
Increased frequency all local bus lines	14,483 (81.6%)	1,645 (9.3%)	1,494 (8.4%)	137 (0.8%)

It is concluded from Table A.13 that the modal share of public transport increases with increasing frequency of bus lines. However, 78 additional buses (50% increase of frequency on all local buses) only lead to 138 more people in the bus. This is financially not feasible for the bus operator, because

the investment costs for new buses and operational costs (fuel/electricity, salary of bus driver, etc.) are not covered by additional revenue. The number cars during the evening peak decreases by 127 in the most extreme scenario. This will not solve the congestion problem in Ålesund.

Public transport competes mainly with the car in Ålesund. The modal share of biking and walking remains (almost) constant in all scenarios, while the modal share of the car decreases due to the increased frequency of buses. However, the inhabitants of Ålesund have a high preference for the car, since a large improvement of the bus network does not lead to a major modal shift.

Frequency is not the only aspect that can be changed in order to get more people in the bus. Design of bus stops (shelter for bad weather), real-time information (in an app and at the bus stops) and ticket fare are examples of other aspects. Another option is to discourage people from using the main concurrent, the car. This can be done by, for example, removing parking or increasing car ownership taxes. These aspects are all not possible to implement in the traffic model, but could be investigated with other techniques, like choice modelling and questionnaires. However, the frequency of bus lines is already at (or near) its optimal, because a large increase in buses does not result in a significant increase in bus ridership.

A.2.5. Discussion

The model shows that the main road in Ålesund is already congested during the evening peak. This implicates that additional growth of car traffic is not possible. Even larger delays will occur and spill backs are to be expected, leading to a grid lock of the network. The model also shows a low modal share of public transport, which is not increased by significant higher bus frequencies. This indicates that the level of service of the bus network is already high regarding the amount of buses in the timetable. It is not worth it to invest in higher frequencies. Therefore, other measures have to be taken to make the public transport more attractive, because the modal share has to increase to be able to satisfy the travel demand in the future.

The model is able to predict traffic volumes with a fairly high degree of certainty. The normalised RMSE of the model is 16.2%. However, some simplifications were made in developing the model.

First of all, only four explanatory variables are used for calculating the production and attraction per zone. It is implicitly assumed that all inhabitants of the project area make decisions based on these variables only. Some travel purposes are not included, like visiting friends or family. Also, different demographic groups might make travel decisions differently, while it is now assumed that everyone does it the same. Besides, trucks or other large vehicles are not added to the network intensities, but should not be forgotten. Also the buses with cruise tourists use the network during the evening peak.

Capacity of road sections is used for assigning cars to the network (in the BPR function) and to show IC ratios after the assignment. The IC ratio is an important aspect in interpreting the results of the assignment process. So, the capacity is an important factor in the model, but it is very difficult to determine. To be accurate, measurements of flow and speeds should be taken for a long period, in order to determine the capacity of a road section with a fundamental diagram. This is not done in this project.

Additionally, congestion is not taken into account in determining the in-vehicle time of trips taken by bus. This would add a high level of complexity to the OmniTRANS model, so it is chosen to neglect this given the limited time for this project. Also, in the combined phase 2-3 of the 4-phase model, people choose their mode based on free flow travel times. However, they probably know that congestion occurs and have an idea of the true travel time in advance. Both the bus and the car are affected by congestion, meaning that they are less attractive than the model predicts. This could be the cause of the over-estimation of the modal share of these two modes.

Finally, the model is static for a two hour period. This gives a good first indication of the traffic situation in the network, but does not capture all dynamic effects. The length of congestion is for example not determined in the model, so potential grid locks cannot be identified. Also, peaks periods within the evening peak, with even higher than average traffic volumes, are not included in this model.

A.2.6. Conclusion

The most busy parts of the car network are already at their capacity during the evening peak. Some road sections have an IC ratio greater than 1.0, for example the main east-west connection in the city. Further increase in car traffic is not possible on those road sections, because it will lead to an oversaturated network, with high levels of congestion and long delays. There is no congestion yet on other road sections, for example the roads towards the northern islands and the road towards Hessa. These roads could see an increase in car traffic without congestion directly occurring. However, since increase in car traffic there will coincide with increase in car traffic on the main east-west connection, car traffic in general cannot grow in Ålesund. The new Brosund bridge (parallel to Hellebrua) will increase the network robustness once it has been constructed, but it will not solve the congestion problems in the city. Public transport usage is currently low in Ålesund. The bus is not attractive enough for people to use it, but a higher 50% frequency on all lines does not lead to a large increase in bus ridership. Walking and cycling also have low modal shares. These modes are mainly used for very short distances.

A.2.7. Recommendations

A lower modal share of car traffic is required to prevent the transport system from failing in the future. Additional research is required to the motives of travellers when choosing their travel mode. Policy measures for increasing the public transport ridership and decreasing car traffic could be to discourage car usage by removing parking facilities or introducing a car tax of some sort. Other options are to encourage public transport use, for example by improving waiting facilities (now there is often only a sign) and strong branding at bus stops. Of course, costs could also play an important role in mode choice, but are not considered in this traffic model. All mentioned policy measures have to be investigated first before implementing it, to determine if it will have the desired effect. The strong recommendation is to investigate all measures that potentially lead to a modal shift from car to public transport (not limited to the before mentioned ones), because a lower modal share of car traffic is required to prevent a total grid lock in the city of Ålesund in the future.

A.2.8. Additional tables for traffic model

Table A.14 shows the input variables for the traffic model.

Table A.14: Input data for traffic model (all taken from Statistisk Sentralbyrå, 2025e).

zone	culture_area	jobs	residents	sports_area	island	non_island	centre	non_island/centre
1	345	2,722	4,872	16,159	0	1	0	1
2	4,302	3,069	3,980	50,860	0	1	0	1
3	0	1,171	1,567	0	0	1	0	1
4	5,657	2,888	1,954	0	0	1	1	0
5	14,874	3,611	1,037	4,705	0	1	1	0
6	1,292	445	963	0	0	1	1	0
7	492	773	1,698	2,181	0	1	1	0
8	0	60	71	0	0	1	0	1
9	7,020	758	2,754	29,340	0	1	1	0
10	0	0	0	0	0	1	0	1
11	4,445	1,714	1,861	9,775	0	1	0	1
12	1,952	909	1,919	9,125	0	1	0	1
13	4,654	12	35	0	0	1	0	1
14	6,061	569	1,712	3,544	0	1	0	1
15	2,452	584	2,703	23,979	0	1	0	1
16	0	3,584	3,055	21,419	0	1	0	1
17	11,918	1,069	3,739	17,104	0	1	0	1
18	2,637	3,690	2,942	60,579	0	1	0	1
19	11,974	4,244	13,652	147,896	0	1	0	1
20	31,291	2,119	7,873	100,388	0	1	0	1
21	9,351	124	1,562	74,927	1	0	0	0
22	9,470	85	817	21,007	1	0	0	0
23	8,664	848	4,022	42,770	1	0	0	0
24	9,343	185	1,097	18,470	1	0	0	0
25	5,501	618	2,413	25,666	1	0	0	0

Table A.15 presents all the buses included in the OmniTRANS model. Most bus lines in Ålesund do not

have a single route they drive, there are often variants of the same route, as can be seen in Table A.15. Bus lines with an asterisk (*) are merged bus lines. Lines are merged when they have the exact same route within the main project area, but start/end at different locations outside of the main project area. This happens, for example, at Vigra, where buses start/end at different locations at the island. This is not relevant for the overall project.

Table A.15: Bus lines included in OmniTRANS model.

no. in model	head sign	frequency in model	travel time [min]
	Bus 1-east		
1	Sævollen - Slinningsodden - Myrland Snuplass	1	75
2	Keiser Wilhelms Gate - Gatestopp Moa	4	30
3	Sævollen - Myrland Snuplass	2	67
4	Keiser Wilhelms Gate - Myrland Snuplass	2	45
5	Sævollen - Keiser Wilhelms Gate	1	22
6	Slinningsodden - Myrland Snuplass	3	68
7	Sævollen - Gatestopp Moa	3	52
8	Slinningsodden - Gatestopp Moa	1	53
	Bus 1-west		
9	Gatestopp Moa - Sævollen	3	50
10	Gatestopp Moa - Keiser Wilhelms Gate	6	30
11	Gatestopp Moa - Slinningsodden	1	49
12	Myrland Snuplass - Sævollen	3	65
13	Myrland Snuplass - Keiser Wilhelms Gate	5	45
14	Myrland Snuplass - Slinningsodden	1	64
15	Keiser Wilhelms Gate - Slinningsodden	3	19
	Bus 2-east		
16	Keiser Wilhelms Gate - Skråvika	8	36
17	Keiser Wilhelms Gate - Magerholm ferjekai	8	45
	Bus 2-west		
18	Skråvika - Keiser Wilhelmgs Gate	8	39
19	Magerholm ferjekai - Keiser Wilhelms Gate	7	46
20	Gatestopp Moa - Keiser Wilhelms Gate	1	23
	Bus 3-north		
21*	Korsegata - Roald	4	35
22	Korsegata - Sætra	2	25
23	Moa Trafikkterminal - Sætra	2	40
	Bus 3-south		
24	Gjøsundsæter - Korsegata	3	31
25	Roald - Korsegata	2	40
	Bus 4-west		
26*	Gatestopp Moa - Lerheimskaia	5	21
	Bus 4-east		
27*	Lerheimskaia - Gatestopp Moa	6	34
	Bus 10		
28	Keiser Wilhelms Gate - Fjelltun - Keiser Wilhelms Gate	3	20
	Bus 11		
29	Keiser Wilhelms Gate - Larsgården - Keiser Wilhelms Gate	3	30
	Bus 12-east		
30	Keiser Wilhelms Gate - Vaskeriet	5	30
	Bus 12-west		
31	Vaskeriet - Gatestopp Moa	4	8
32	Gatestopp Moa - Keiser Wilhelms Gate	5	25
	Bus 13-north		

(Continues on next page)

(Continuation of Table A.15)

no. in model	head sign	frequency in model	travel time [min]
33	Moa Trafikkterminal - Olsvik - Moa Trafikkterminal	3	14
Bus 13-south			
34	Moa Trafikkterminal - Furmyr - Moa Trafikkterminal	3	15
Bus 14-south			
35*	Gatestopp Moa - Humla	2	8
Bus 14-north			
36	Humla - Gatestopp Moa	2	8
Bus 31-east			
37	Kverve - Roth	1	18
38*	Kverve - Lorgja øst	3	13
39	Korsegata - Roth	3	29
Bus 31-west			
40	Stokke øst - Korsegata	2	24
41	Lorgja øst - Hoff vest	1	10
Bus 32-west			
42	Ytterland - Alnes - Juv snuplass	1	43
43	Ytterland - Alnes	1	25
44	Ytterland - Juv snuplass - Alnes	1	45
45	Korsegata - Alnes	1	60
Bus 32-east			
46	Alnes - Ytterland	1	30
47*	Juv snuplass - Ytterland	2	30
Bus 210-north			
48	Korsegata - east of Moa Trafikkterminal	2	30
Bus 230-east			
49	Korsegata - east of Moa Trafikkterminal	1	30
50	Ålesund Sjukehus - east of Moa Trafikkterminal	1	10
Bus 250-east			
51	Korsegata - Emblemsvåg	2	44
52	Korsegata - Emblemsvåg (via a shortcut)	1	33
Bus 250-west			
53	Emblemsvåg - Korsegata (via a shortcut)	2	33
54	Emblemsvåg - Korsegata	1	44
Bus 310-north			
55	Sulesund ferjekai - Ålesund Sjukehus	1	35
Bus 310-south			
56	Ålesund Sjukehus - Sulesund ferjekai	1	35
Bus 100-east			
57	Skateflukaia - east of Moa Trafikkterminal	6	40
Bus 100-west			
58	east of Moa Trafikkterminal - Skateflukaia	5	40
Bus 101-north			
59	Solavågen ferjekai (Veibust) - Skateflukaia	3	25
Bus 101-south			
60	Skateflukaia - Solavågen ferjekai (Veibust)	5	25
Bus 681-east			

(Continuation of Table A.15)

no. in model	head sign	frequency in model	travel time [min]
61	Skateflukaia - east of Moa Trafikkterminal	1	30
Bus 681-west			
62	east of Moa Trafikkterminal - Skateflukaia	1	30

End of Table A.15

A.3. Bus Network Performance Analysis

A.3.1. Introduction to model

Public transport systems can be assessed from both a structural and an operational perspective. On the one hand, the topology of the network determines how well stops and routes are connected, influencing accessibility and transfer possibilities. On the other hand, passenger demand and vehicle capacity shape how the network performs in daily operations and under disruptions. Since Ålesund aims to increase public transport usage, understanding the current network's structure and performance is crucial for designing measures that improve passenger satisfaction. The main objective of this analysis is to investigate whether the relatively low use of public transport in Ålesund can be linked to the structural characteristics of the network itself. By examining its connectivity, accessibility, and passenger distribution, the analysis aims to reveal whether spatial or topological limitations contribute to the low ridership observed in the city.

A.3.2. Methodology

Public transport networks play a vital role in ensuring accessible and sustainable urban mobility. Their performance depends not only on how frequently buses run or how many areas they serve, but also on the underlying structure of the network itself. Graph theory provides a systematic way to represent and analyse such networks by treating stops and lines as nodes and links in a graph.

The Ålesund bus network, operated by *FRAM*, consists of 12 bus lines and 3 ferry routes serving a total of 303 stops (FRAM, 2025b). In addition, *Vy Buss* operates long-distance bus services to destinations such as Bergen and Oslo, as well as route FB65 to Ålesund Airport, Vigra (Vy, 2025). These *Vy Buss* services are not included in the present network analysis.

The network was built using `GTFS` data (General Transit Feed Specification), which is a standardized format containing detailed public transport information such as routes, stops, schedules, and travel times. For Møre og Romsdal, this data can be gathered from *Entur* (Entur Developer, 2025), the national open data platform for public transport in Norway. From this dataset, the bus network was reconstructed and analysed in terms of both its structure and functionality.

To capture the role of ferries in regional accessibility, two network situations are investigated: one including only the bus services, and one combining both bus and ferry routes. Although ferry travel involves different costs and operational characteristics than bus transport, ferries form an important part of Ålesund's public transport system. Comparing both situations provides insight into how ferry connections influence, for example, overall network connectivity, travel paths, and passenger distribution.

The network is studied through two complementary graph representations. The first is an L-space, which connects stops that are directly linked along a bus line, highlighting the physical structure of the network as seen on a typical route map. The second is a P-space, which connects all stops served by the same line, emphasizing transfer opportunities and the ease of switching between routes. For both representations, a set of global and local indicators is calculated to evaluate the network's efficiency and robustness. These include measures such as the number of nodes, network diameter, and degree of connectivity, along with centrality metrics identifying the most important stops. Both weighted and unweighted versions are considered, allowing the influence of service frequency and travel time to be included in the analysis.

Network structure analysis

The workflow for the network structure analysis consists of three main steps:

1. Importing and processing `GTFS` data of the Ålesund bus network;
2. Constructing two graph representations (L-space and P-space);
3. Computing global and local network indicators.

All analyses were conducted in Python, primarily making use of the `gtfskit`, `pandas`, and `networkx` libraries.

Importing and processing `GTFS` data

The `GTFS` feed for Møre og Romsdal contains detailed information about routes, stops, trips, and timeta-

bles for all regional operators. The raw `GTFS` data were first parsed into an `SQLite` database using a self-developed Python pipeline (MobilityData, 2025), based on the reference scripts distributed in the course *CIEQ6232 Public Transport Demand and Network Planning and Operations* (Cats et al., 2025). This pipeline integrates the main `GTFS` files (`agency.txt`, `routes.txt`, `trips.txt`, `stop_times.txt`, `stops.txt`, `shapes.txt`, `calendar.txt`, `calendar_dates.txt`, `frequencies.txt` and `transfers.txt`) into a dataset suitable for network analysis. Only services of type bus (also containing ferries) are included in the analysis.

To ensure the resulting graph accurately represents the operational system, several preprocessing steps were applied:

- September 12th, 2025 was selected as the reference day, representing a weekday with the highest number of trips of September. A list of active bus lines and their number of `trip_id`s was compiled, as shown in Table A.16. The `stop_times.txt` file was then filtered to include only these trips, after which the `SQLite` file was rebuilt.

Table A.16: Number of trips per bus line in Ålesund region.

Line	Name	#trips	Line	Name	#trips
1	Hessa-Myrland	170	14	Humla	17
2	Ålesund-Lerstad-Magerholm	122	31	Ålesund-Ellingsøya	43
3	Ålesund-Valderøya-Vigra	63	32	Ålesund-Godøya	32
4	Langevåg-Fiskarstrand-Moa-Ålesund	60	41	Sulesund-Mauseidvåg	10
10	Fjelltun	13	1145	Hareid-Valderøya-Ålesund [ferry]	32
11	Larsgården	21	1148	Ålesund-Langevåg [ferry]	42
12	Sentrum-Lerstad-Moa-Fremmerholen	79	1149	Ålesund-Hamnsund [ferry]	24
13	Olsvik-Moa-Furmyr	29			

- Stops sharing the same names within a radius of 1 km were merged. This ensures that nodes are represented as single entities rather than clusters of near-duplicate stops.

- The stops *Keiser Wilhelms gate* and *Korsegata*, located just around the corner of eachother in Ålesund's city centre, were merged into a single hub node to represent their integration within the *Bypakke Ålesund* mobility initiative (as explained in Subsection A.1.3).

- Ferry-only terminals were removed, whereas terminals with direct walking connections to the bus network (*Ålesund hurtigbåtkai Skateflukaia* and *Ålesund rutebilstasjon hurtigbåtkai* with *Kollektivknutepunkt*) were merged.

- The stop name *Simabakken* occurred twice in the dataset; once on the island of Valderøya and once on Sula. To ensure unique node identifiers, these were renamed to *Simabakken Nord* and *Simabakken Sør*, respectively.

- Edges operated by only one vehicle over the reference day were removed to improve representativeness of the network. In addition, a small set of edges operated by only two vehicles per day were manually deleted, as these rare connections would otherwise act as unrealistic shortcuts in the analysis.

- Edges with missing or zero travel times (`duration_avg = 0`) were completed using the travel time of the opposite-direction edge when available. When not available it is estimated through a distance–time regression (`duration_avg = 0.0749 · d`), with $R^2 = 0.536$).

- Isolated sources (stops with only departures), sinks (stops with only arrivals), or zero-degree nodes (stops with neither departures nor arrivals) were removed to obtain a single strongly connected network, meaning that all stops are mutually reachable via the available bus routes.

The final processed graph thus reflects the actual structure and service patterns of the Ålesund bus network, enabling both topological and weighted (frequency and travel time) analyses in the subsequent steps.

Constructing graph representations (L-space and P-space)
The graphs are constructed using the functions `g = load_gtfs("aalesund.sqlite")`, `L = load_graph` `("aalesund.pkl")` (for L-space, a pickle file for fast loading) and `P = P_space(g, L, start_hour`

=4, end_hour=24, mode="Bus") (Cats et al., 2025). Resulting in the following representations, see Figure A.19 and A.20.
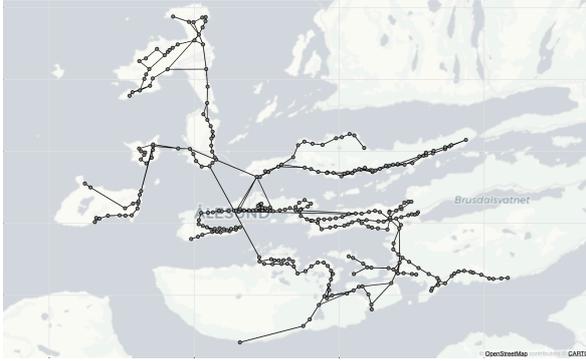
Figure A.19: L-space representation of the bus network of Ålesund.
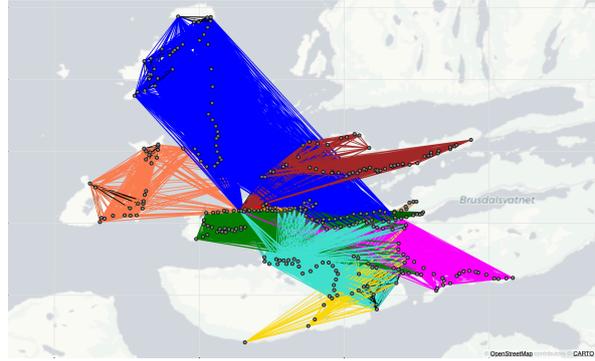
Figure A.20: P-space representation of the bus network of Ålesund.

Computing global and local network indicators

Global indicators capture the overall topology and efficiency of the network as a whole. Global indicators include:

- Number of nodes $|V|$, representing bus stops in the network, and links $|E|$, representing connections between stops. In L-space, links connect consecutive stops along a bus route, and in P-space, links connect all stops served by the same line (transfer potential), as can be seen in Figure A.19 and A.20.

- The diameter of a graph is the node count (or travel time (L-space) and waiting time (P-space) in weighted version) of the longest shortest path l_{ij} between any two nodes.

$$d = \max_{i,j \in V} l_{ij} \qquad (A.20)$$

- The average shortest path (ASP) is the mean number of steps (or travel time (L-space) and waiting time (P-space) in weighted version) needed to travel between two randomly chosen stops via the shortest available route. It reflects the network's overall navigability and efficiency: the lower the value, the easier it is to move between stops.

$$g = \frac{\sum_{i \neq j} l_{ij}}{|V|^2 - |V|} \qquad (A.21)$$

- Connectivity (or gamma index) quantifies how well nodes are linked overall, so how many links exist relative to the maximum possible amount of links in a connected graph of the same size. Calculated for L-space only.

$$\gamma = \frac{|E|}{3|V| - 6} \qquad (A.22)$$

- Meshedness (or alpha index) captures how grid-like the network is, higher meshedness means more alternative paths and greater resilience to disruptions. Calculated for L-space only.

$$\alpha = \frac{|E| - |V| + 1}{2|V| - 5} \qquad (A.23)$$

These were computed using functions such as `nx.diameter`, `nx.average_shortest_path_length`, and custom implementations for the α and γ indices based on their equations (see Equation A.22 and A.23) for planar graphs.

Local indicators describe the position and relative importance of individual stops within the network structure. Local indicators include:

- Degree k_i of a node equals the number of links a_{ij} connected to it, normalised by the maximum possible. In public transport terms, it shows how many direct connections a stop has. High-degree nodes are often major transfer hubs or terminals. Calculated for only unweighted scenarios.

$$k_i = \sum_i a_{ij} \qquad (A.24)$$

- Closeness c_i measures how near a node is to all others $(n-1)$ in the network, based on the sum of shortest path lengths l_{ij}. A stop with high closeness can reach all others quickly, so it tends to represent a geographically or functionally central location. Weighted closeness incorporates travel times instead of topological distance.

$$c_i = \left(\sum_{i \neq j} l_{ij} \right)^{-1} / (n-1) \qquad (A.25)$$

- Betweenness b_i quantifies how often a node lies on shortest paths between other nodes. It includes the share of shortest paths that traverse through a certain node/link, where $\sigma_{jk}(i)$ is the share of shortest paths between node j and k that traverse node/link i. In transit networks, it indicates transfer importance: stops with high betweenness act as critical connectors or transfer hubs.

$$b_i = \sum_{j \neq i \neq k} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \qquad (A.26)$$

By computing these indicators, both the overall structure and the functional role of individual stops within the network can be better understood. Global indicators reveal how the system performs as a whole, and whether the network is robust or vulnerable to disruptions. Local indicators highlight critical nodes that serve as key transfer points or potential bottlenecks. Together, these measures provide valuable input for network design, performance evaluation and planning interventions. They identify where additional routes, increased frequencies or improved transfer facilities could most effectively enhance the public transport network.

Network design and passenger flow distribution

While the structural characteristics of a public transport network are fundamental, passenger experience depends on how travel demand interacts with service supply. Concepts such as robustness (the system's ability to maintain service under disruptions) and resilience (its capacity to recover quickly after disruptions) are crucial to assessing operational performance. In Ålesund, where the bus network is geographically constrained by the surrounding islands, disruptions can have large impacts, as alternative routes or detours are often limited.

To gain insight into how passengers use the network, travel demand was estimated using a gravity-based model, which assumes that the number of trips between two zones depends on their population sizes and the distance separating them. The resulting demand estimates were translated into an origin–destination (OD) matrix, indicating the number of trips between each pair of network zones.

The overall workflow for the network design and passenger flow analysis comprises four main steps:

1. Computing the shortest paths between all node pairs;
2. Constructing the OD matrix using the gravity model;
3. Assigning passenger flows to the network based on these paths;
4. Computing saturation levels of vehicles.

Compute shortest paths between all pairs of nodes

Shortest paths were computed between all pairs of nodes in the L-space graph, using in-vehicle travel time (`duration_avg`) as the edge weight. For each node pair (i, j), the shortest path sp_i represents the route with the minimum total in-vehicle travel time.

To better reflect perceived passenger costs, these paths were further evaluated using Generalized Travel Cost (GTC) values, which incorporate in-vehicle time, waiting time, and transfer penalties. For each path, the total waiting time and number of transfers were derived from the corresponding connections in P-space, based on the sequence of lines and the number of hops. The GTC for each shortest path was then calculated as:

$$\text{GTC}(sp_i) = t_{\text{in-veh}}(sp_i) + \alpha \cdot t_{\text{wait}}(sp_i) + \beta \cdot N_{\text{transfers}}(sp_i) \tag{A.27}$$

where $\alpha = 1.2$ represents the weighting factor for waiting time, and $\beta = 10$ is the time-equivalent penalty for transfers (as defined in Equation A.5). A total of $m = 3$ shortest paths were computed for each node pair to allow for alternative routing options.

Create an origin-destination matrix
To analyse how passengers are distributed across the network, an OD matrix was constructed using a gravity-based model. The model assumes that the number of trips between two stops depends on the attractiveness of the destination and the impedance of travel between them.

Let x_{ij} denote the estimated number of passengers travelling from stop i to stop j. It is defined as:

$$x_{ij} = \frac{q_j \cdot f_{ij}}{\sum_{j \in S; j \neq i} q_j \cdot f_{ij}} \cdot q_i \tag{A.28}$$

where q_i is the number of passenger trips originating from stop i, S is the set of all stops in the network, and f_{ij} represents the impedance function between i and j.

The impedance function captures the decreasing likelihood of travelling as travel time increases and is defined as:

$$f_{ij} = \alpha \cdot e^{-\beta \cdot \text{GTC}_{ij}} \tag{A.29}$$

for all $j \neq i$, where GTC_{ij} is the Generalised Travel Cost (in minutes) between stops i and j. The parameters $\alpha = 2$ and $\beta = 0.2$ are defined in Table A.4.

The stop productions are derived from the spatial distribution of population. A set of population points $z \in \mathcal{Z}$ (Statistisk Sentralbyrå, 2025e), with attributes pop(z) and coordinates, is assigned to nearby stops according to the following rule. For each population point, candidate stops within an access radius of 250 m are identified; if multiple candidates exist, the stop with the highest weighted betweenness is selected to reflect the attractiveness of transfer-rich locations. If no stop lies within 250 m, the nearest stop within a broader search radius ($d = 1500$ m) is used. Points without a stop within d are excluded from the service region. The population assigned to stop i is then:

$$p_i = \sum_{z \in \mathcal{Z}_i} \text{pop}(z) \tag{A.30}$$

where $\mathcal{Z}_i$ denotes the subset of population points assigned to stop i. Daily stop productions are taken proportional to these assigned populations:

$$q_i = \frac{p_i}{\sum_{i \in S} p_i} \cdot Q \tag{A.31}$$

with Q the total number of passengers per day. In this study, Q is computed from the scheduled supply as $Q = N_{\text{trips}} \cdot O \cdot \overline{s}_{\text{bus}}$, where N_{trips} is the number of bus trips on the reference day (September 12, 2025) equal to 757, O is the occupancy rate in buses in Ålesund equal to 32%, and $\overline{s}_{\text{bus}}$ is the average number of seats per bus in Ålesund equal to 45 (Statistisk Sentralbyrå, 2025a). Resulting in $Q = 10,901$ passengers per day.

Passenger assignment
Once the OD matrix was established, passenger demand was assigned to the network. For each OD pair, travellers were assumed to choose among $m = 3$ route alternatives, corresponding to the shortest paths in terms of in-vehicle travel time.

Passenger route choice was modelled using a discrete choice framework, where each alternative i is characterised by a set of attributes that influence its attractiveness; specifically, in-vehicle travel time, waiting time, and the number of transfers. The utility of each alternative is expressed as its Generalized Travel Cost (GTC), defined in Equation A.27:

$$U_i = \text{GTC}(sp_i) = t_{\text{in-veh}}(sp_i) + \alpha \cdot t_{\text{wait}}(sp_i) + \beta \cdot N_{\text{transfers}}(sp_i) \tag{A.32}$$

where U_i represents the systematic utility associated with route i. A higher U_i denotes a less attractive route. As defined in Equation A.5, $\alpha = 1.2$ represents the weighting factor for waiting time, and $\beta = 10$ is the time-equivalent penalty for transfers.

To determine the probability that a passenger selects each route, a multinomial logit model was applied. The probability of choosing alternative i is given by:

$$P_i = \frac{e^{-\beta U_i}}{\sum_{j=1}^{m} e^{-\beta U_j}} \tag{A.33}$$

where P_i is the choice probability of alternative i, and the denominator sums over all available routes j in the choice set with length m. The scale parameter β is set to 1, following the standard assumption for a basic multinomial logit model without estimation or nesting.

Equation A.33 assumes that passengers prefer routes with lower generalized travel costs, while still allowing for some variability in individual preferences. The resulting probabilities P_i were then applied to distribute the passenger demand from each OD pair across the three alternative paths. For every link in the network, the corresponding passenger loads were incrementally updated, yielding the final link load attribute (`link_load`) for each directed edge.

Network saturation

To assess the operational capacity utilisation of the bus network, saturation levels were computed for each link. Saturation indicates the proportion of a vehicle's capacity that is used on average, and therefore reflects how heavily loaded different parts of the network are. High saturation values point to potential overcrowding or insufficient service frequency, whereas low values indicate underutilised links.

For each directed edge (u, v), the average passenger load per vehicle was calculated by dividing the total passenger load on the edge (`link_load`) by the number of vehicles operating on that edge (`n_vehicles`):

$$\texttt{vehicle\_load}_{u \to v} = \frac{\texttt{link\_load}_{u \to v}}{\texttt{n\_vehicles}_{u \to v}} \tag{A.34}$$

Subsequently, the `vehicle_load` was normalised by the corresponding vehicle capacity to obtain the saturation ratio:

$$\texttt{saturation}_{u \to v} = \frac{\texttt{vehicle\_load}_{u \to v}}{C} \tag{A.35}$$

where $C = 45$ passengers represents the average capacity of standard city buses in Ålesund (Statistisk Sentralbyrå, 2025a). For ferry routes, higher capacities were applied based on vessel specifications provided by Brødrene Aa (Brødrene Aa, 2024) and operator information from *FRAM* (FRAM, 2025a):

- $C = 250$ passengers for line 1145 (means capacity, operated by *Valderøy*, type P30, and *Godøy*, type P35);
- $C = 130$ passengers for lines 1148 and 1149 (operated by *Nørvøy* and *Kalvøy*, both type P25).

The resulting saturation values provide insight into how passenger demand is distributed across the network. Links with high saturation indicate more crowded corridors, while low saturation values point to less used connections (and maybe even (almost) empty buses). This measure therefore helps to identify spatial patterns in network usage and to pinpoint sections where service supply may exceed or fall short of actual demand.

A.3.3. Results

This section presents the results of the network structure analysis, passenger flow distribution, and capacity utilisation for the Ålesund public transport network. The findings highlight key structural characteristics, identify important nodes and corridors, and show spatial patterns in passenger demand.

Network structure analysis
Global network indicators
To better understand the role of ferry services within Ålesund's public transport system, the global network indicators were computed for two versions of the network: one excluding the ferry lines (Table A.17) and one including them (Table A.18).

Table A.17: Global Network Indicators (both L- and P-space) without Ferry Links.

Indicator	L-space	P-space	Indicator	L-space	P-space
Nodes	296	296	Avg. Shortest Path (unweighted)	24.35	2.23
Links	510	12,654	Avg. Shortest Path (weighted)	2,403.21	105.55
Diameter (unweighted)	72.00	6.00	Connectivity (gamma index)	0.58	-
Diameter (weighted)	6,888.71	620.00	Meshedness (alpha index)	0.37	-

Table A.18: Global Network Indicators (both L- and P-space) with Ferry Links.

Indicator	L-space	P-space	Indicator	L-space	P-space
Nodes	296	296	Avg. Shortest Path (unweighted)	21.64	2.23
Links	514	12,655	Avg. Shortest Path (weighted)	2,178.05	105.51
Diameter (unweighted)	60.00	6.00	Connectivity (gamma index)	0.58	-
Diameter (weighted)	5,277.42	620.00	Meshedness (alpha index)	0.37	-

The comparison between the two network versions reveals some structural differences, for example in network diameter and accessibility between the islands. When ferry routes are included (Table A.18), both the unweighted and weighted diameters decrease noticeably (from 72 to 60 stops and from 6,889 seconds (115 min) to 5,277 seconds (88 min), respectively), indicating that ferry connections shorten the longest possible trips across the region. The average shortest path length also decreases (by roughly -11% unweighted and -9% weighted), showing that the overall accessibility of the network improves when ferry services are available.

Despite these improvements in accessibility, the connectivity ($\gamma = 0.58$) and meshedness ($\alpha = 0.37$) indices remain unchanged, suggesting that ferry links mainly enhance reachability instead of altering the network's topological structure. This means the ferries act as efficient long-range connectors, without significantly increasing the number alternative paths.

Lastly, the indicators in P-space remain virtually identical across both scenarios, which implies that ferry services influence the physical connectivity of the network (L-space) rather than the transfer opportunities between lines (P-space). In other words, while the number of possible transfers stays the same, ferries provide much faster connections between the mainland and the islands.

Figure A.21: The longest shortest path (unw.) without ferries [*Rørvik* (top) → *Lerheimskaia* (bottom)].

Figure A.22: The longest shortest path (unw.) with ferries [*Magerholm ferjekai* (bottom) → *Blindheimsvika* (top)].

Figure A.21 illustrates the unweighted longest shortest path in the scenario without ferry operations. The trip spans the full extent of the network, from *Rørvik* on the island of Vigra to *Lerheimskaia* on Sula. As reported in Table A.17, this route requires 72 consecutive stops to complete. The route follows bus line 3 towards the central mobility hub *Kollektivknutepunkt*, continues on line 2 to *Porten*, and finally transfers to line 4 to reach *Lerheimskaia*.

Figure A.22 shows the unweighted longest shortest path in the scenario including ferry operations. As reported in Table A.18, this path covers 60 stops in total. The trip extends from *Magerholm ferjekai* on the mainland to *Blindheimsvika* on the island of Vigra. It follows bus line 2 towards the central mobility hub *Kollektivknutepunkt*, transfers to ferry line 1145 or 1149 to *Valderhaugstrand*, and finally continues on bus line 3 to reach *Blindheimsvika*.

Figure A.23: The longest shortest path (w.) without ferries [*Blindheim* (top) → *Lerheimskaia* (bottom)].

Figure A.24: The longest shortest path (w.) with ferries [*Roth* (top) → *Sulesund ferjekai* (bottom)].

Figure A.23 shows the corresponding weighted version, where travel times are taken into account. The longest shortest path in this case runs from *Blindheim* (Vigra) to *Lerheimskaia* (Sula) and takes approximately 115 minutes to complete. The route follows the same general structure as in the unweighted case, with transfers at *Kollektivknutepunkt* and *Porten*, highlighting central interchange points when no ferry connections are available.

Figure A.24 presents the weighted version, where in-vehicle travel times are considered. In this case, the longest shortest path runs from *Roth* on the island of Ellingsøya to *Sulesund ferjekai* on Sula, taking approximately 88 minutes to complete. The route involves taking bus line 31 to *Kollektivknutepunkt*, transferring to ferry line 1148 towards *Lerheimskaia*, continuing on bus line 4 to *Måseide skule*, and finally transferring to bus line 41 to reach *Sulesund ferjekai*.

Local network indicators

The comparison of local centrality measures with and without ferry connections (see Table A.19 and A.20) reveals that the inclusion of ferry links primarily affects accessibility and centrality within the L-space, while the P-space indicators remain (almost) unchanged. This confirms again that the ferry routes influence the physical connectivity between stops rather than the transfer structure between lines.

Table A.19: Local Network Indicators (both L- and P-space) without Ferry Links.

Centrality	Avg.	Std.	Min	Max	Centrality	Avg.	Std.	Min	Max
$k_{i,\mathrm{L}}$	0.01168	0.00424	0.00678	0.03390	$k_{i,\mathrm{P}}$	0.28983	0.21251	0.02712	1.50169
$c_{i,\mathrm{L,uw}}$	0.04354	0.01005	0.02269	0.06492	$c_{i,\mathrm{P,uw}}$	0.46276	0.07589	0.28420	0.79515
$c_{i,\mathrm{L,w}}$	0.00043	0.00008	0.00023	0.00063	$c_{i,\mathrm{P,w}}$	0.01152	0.00398	0.00270	0.01809
$b_{i,\mathrm{L,uw}}$	0.07944	0.10146	0.00000	0.55850	$b_{i,\mathrm{P,uw}}$	0.00418	0.02818	0.00000	0.46250
$b_{i,\mathrm{L,w}}$	0.08186	0.09555	0.00000	0.55798	$b_{i,\mathrm{P,w}}$	0.00528	0.03838	0.00000	0.54538

Table A.20: Local Network Indicators (both L- and P-space) with Ferry Links.

Centrality	Avg.	Std.	Min	Max	Centrality	Avg.	Std.	Min	Max
$k_{i,\text{L}}$	0.01177	0.00442	0.00678	0.03390	$k_{i,\text{P}}$	0.28985	0.21258	0.02712	1.50508
$c_{i,\text{L,uw}}$	0.04856	0.01056	0.02663	0.07268	$c_{i,\text{P,uw}}$	0.46306	0.07583	0.28420	0.79515
$c_{i,\text{L,w}}$	0.00047	0.00008	0.00031	0.00067	$c_{i,\text{P,w}}$	0.01153	0.00399	0.00270	0.01810
$b_{i,\text{L,uw}}$	0.07022	0.08536	0.00000	0.58826	$b_{i,\text{P,uw}}$	0.00417	0.02817	0.00000	0.46295
$b_{i,\text{L,w}}$	0.07373	0.07747	0.00000	0.50497	$b_{i,\text{P,w}}$	0.00528	0.03839	0.00000	0.54571

In the L-space, both the average unweighted and weighted closeness centrality values increase slightly when ferry links are included (from 0.04354 to 0.04856 and from 0.00043 to 0.00047, respectively). This indicates that, on average, each stop becomes more accessible to the rest of the network once the ferry connections are included, see Figure A.25 and A.26. The five stops with the highest weighted closeness centrality values in the case with the ferry connections considered are *Hoff vest* ($6.72 \cdot 10^{-4}$), *Hoff* ($6.55 \cdot 10^{-4}$), *Kvervesenteret* ($6.55 \cdot 10^{-4}$), *Kverve* ($6.49 \cdot 10^{-4}$), and *Klipra* ($6.33 \cdot 10^{-4}$).
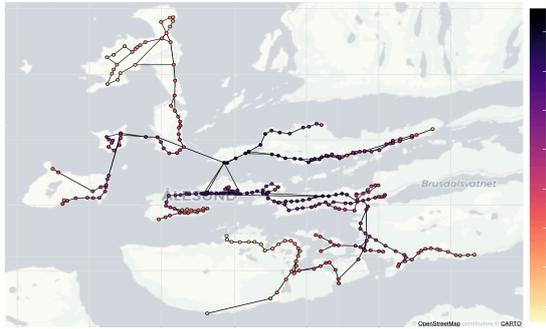
Figure A.25: The weighted closeness values visualised on each node in scenario without ferry connection.
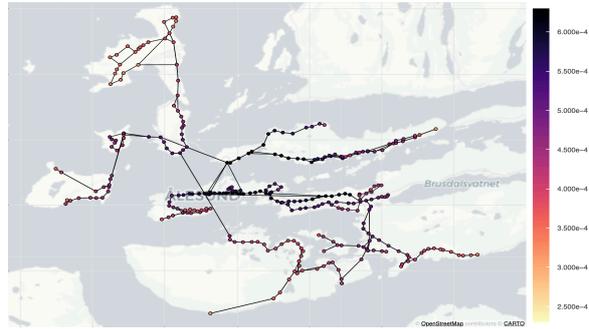
Figure A.26: The weighted closeness values visualised on each node in scenario with ferry connection.

The betweenness centrality values show a small decrease in both mean and standard deviation when ferries are included (from 0.07944 to 0.07022 and from 0.10146 to 0.08536 unweighted, respectively), suggesting a more even distribution of shortest paths across the network. In other words, the ferry routes relieve some of the load from key transfer nodes (like *Moa Trafikkterminal* and *Porten* in the east of the network) by providing alternative cross-island connections that reduce the need for detours through the whole region. See Figure A.27 and A.28. The five stops with the highest weighted betweenness centrality values in the case with the ferry connections considered are *Kollektivknutepunkt* (0.505), *Kverve* (0.337), *Gatestopp Moa* (0.335), *Spjekavikskiftet* (0.300), and *Martingjerdet* (0.294).

Figure A.27: The weighted betweenness values visualised on each node in scenario without ferry connection.

Figure A.28: The weighted betweenness values visualised on each node in scenario with ferry connection.

The degree centrality remains almost stable (it has a really small increase), reflecting that the number of directly connected stops per node does not change substantially, see Figure A.29 and A.30. The five stops with the highest degree centrality values in the case with the ferry connections considered are

Kollektivknutepunkt (3.39·10^{-2}), *Urdalen* (3.39·10^{-2}), *Kverve* (2.37·10^{-2}), *Gatestopp Moa* (2.37·10^{-2}), and *Hankanekrysset* (2.03·10^{-2}).

Figure A.29: The degree values visualised on each node in scenario without ferry connection.
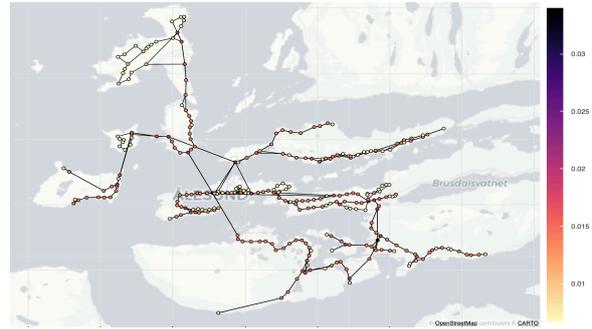
Figure A.30: The degree values visualised on each node in scenario with ferry connection.

In the P-space, all centrality measures remain nearly identical between the two versions, confirming that the transfer structure is not significantly affected. The ferry links thus improve how stops are connected in space, not how many transfer options are available between lines.

Passenger flow distribution
Figure A.31 shows the estimated number of passengers boarding per stop, based on the spatial popula-tion assignment described in Subsection A.3.2. The resulting distribution shows the population density and urban structure: the highest boarding volumes are concentrated at stop *Pensjonisten* (220 passen-gers, city centre), *Apotekertorget* (207 passengers, city centre), *Kirkekrysset* (172 passengers, Sula), *Klipra* (158 passengers, city centre), and *Løndalskiftet* (155 passengers, Spjelkavik). See Figure A.32.

Figure A.31: Passenger assignment per stop in network.
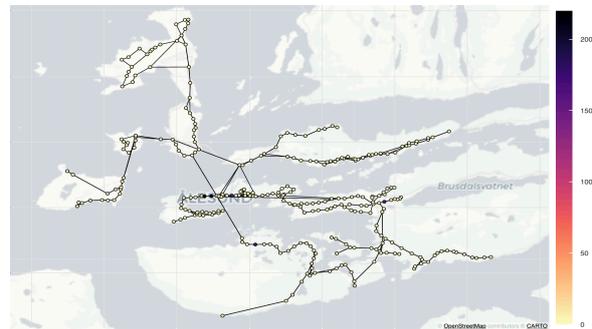
Figure A.32: Top 5 most passengers per stop.

In contrast, peripheral stops on, for example, the islands of Ellingsøya, Vigra, and Godøya show much lower boarding numbers, reflecting both lower residential densities and limited service frequencies.

The spatial distribution of passenger flows, shown in Figure A.33 and A.34, reveals a clear concentra-tion along the main west–east corridor. This corridor connects the dense urban core around *Kollek-tivknutepunkt* with the regional interchange at *Moa trafikkterminal* and further extends towards *Blind-heim* and *Langevåg*. The same corridor also carries the highest link loads (around 1,750 passengers per edge) in the opposite direction, illustrating strong bidirectional flows between the residential areas in the east and the employment and service centres in the city centre.
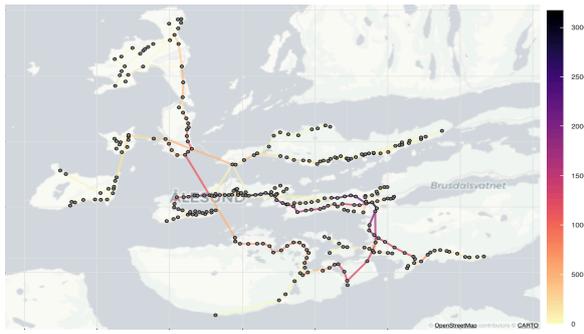
Figure A.33: Load on each link.
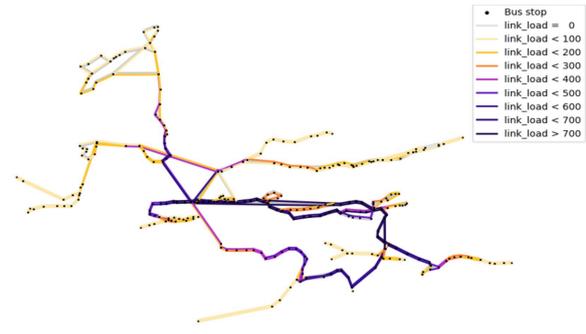
Figure A.34: Load on each edge.

Network saturation and capacity utilisation

The link load is divided by the number of vehicles on the corresponding edge, visualised in Figure A.35 and A.36.

Figure A.35: Number of vehicles on each link.
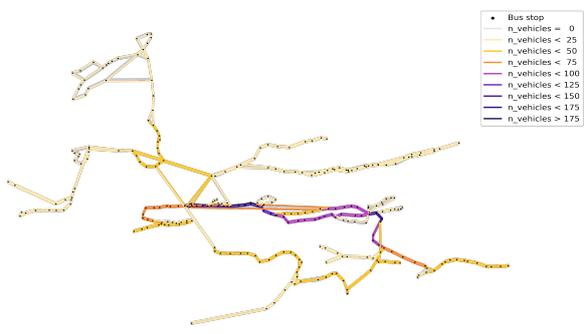
Figure A.36: Number of vehicles on each edge.

The calculated saturation levels, displayed in Figure A.37 and A.38, indicate that the network operates well below its nominal capacity. Across all links, the maximum saturation ratio remains below 1.0, meaning that no connection experiences vehicle overcrowding under the assumed demand conditions. This aligns with operational data for Ålesund's bus services, which report an average occupancy rate of around 32% (Statistisk Sentralbyrå, 2025a). The relatively low load factors suggest that the current service supply comfortably accommodates passenger demand, though it may also point to underutilised capacity on some peripheral routes. Overall, the network appears resilient and well-dimensioned, with spare capacity available to absorb future ridership growth or service integration with ferry and regional lines.
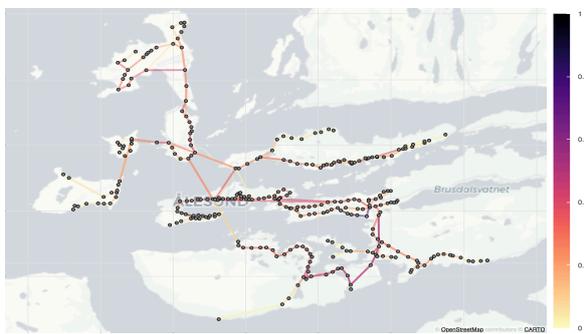
Figure A.37: Saturation on each link.
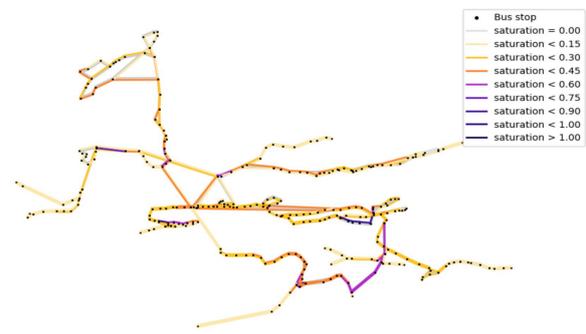
Figure A.38: Saturation on each edge.

A.3.4. Discussion

The bus network performance analysis provides insights into the structure and performance of Ålesund's public transport system. However, several factors should be considered when interpreting the results, as they influence the precision of the findings and their application to real-world operations.

- To make the Ålesund public transport network suitable for analysis, the raw GTFS data from Entur were pre-processed and simplified. This created a manageable model but required several assumptions. Service frequencies were assumed to be uniform across the day, which may cause minor deviations from actual operation patterns. Similarly, routes operated by only one vehicle per day were excluded from the dataset. While this slightly overestimates overall network performance, it avoids unrealistic shortcut connections and shows a more representative picture of regular service.

- The analysis relies on GTFS data from a typical weekday. Seasonal variations, holidays, and weekend schedules were not considered. Passenger assignment was determined using estimated travel times and transfer counts, rather than observed behaviour or occupancy data, as that was not available. As a result, the reported passenger loads should be seen as indicative rather than absolute.

- Travellers were assigned to the network based on the number of residents around each stop, normalised by total daily trips. However, this approach is supply-oriented and does not fully capture the demand side. Well-connected areas may attract relatively more travellers than their population would suggest, while less accessible areas might generate fewer trips. Factors such as travel motivation, comfort, and price were not included. For instance, while a single bus trip costs NOK 48 (∼€4) regardless of distance, ferry fares are higher. It would therefore be interesting to explore how travel costs influence route choice and willingness to transfer between modes.

- The inclusion of ferry services boosts regional accessibility by reducing travel times between islands. However, ferries are weather-dependent and can face disruptions, especially during the stormy winter months. This raises the question of whether ferries should be treated as fully integrated components of the public transport network or as complementary services that support, but do not replace, land-based connections.

Despite these limitations, the analysis provides a reliable indication of where its strengths and weaknesses lie. It serves as a foundation for future work that could integrate observed passenger data, dynamic demand modelling, or cost evaluation to further refine the understanding of public transport performance in the region.

A.3.5. Conclusion

An analysis of the bus network in Ålesund shows that the current public transport system is robust and well structured. The network is generously dimensioned in relation to current transport demand: no connection has reached saturation point and the average occupancy rate of buses is approximately 32%. The main passenger flows are concentrated along the west-east corridor between the city centre and *Moa trafikkterminal*, indicating a clear main structure within the network. Connections to the surrounding islands, such as Ellingsøya and Vigra, are, on the other hand, used less.

The ferry connections noticeably increase regional accessibility. Both the average and maximum travel times are reduced, mainly due to faster connections between the islands. The ferries primarily serve as efficient long-distance connections, thereby strengthening the cohesion of the public transport network without fundamentally changing the existing topology.

Overall, the analysis shows that the cause of low bus usage in Ålesund is unlikely to lie in the network structure itself. The system is technically good operating, well connected and has sufficient capacity for future growth. This suggests that other factors (such as travel habits, perception of travel time, comfort, or limited motivation to leave the car at home) play a more important role in the low use of public transport.

A.4. Overall conclusion traffic analyses

The OmniTRANS model showed that congestion in the city is currently at high levels during the evening peak. The main east-west corridor in the city cannot handle more car traffic than it does now. Public transport ridership is low, while it could potentially help solve the congestion problems. The bus could become essential in the modal split of the future, especially with an increasing population and new points of interest in the city centre (e.g. a new concert hall). The bus network analysis showed that the network itself is actually good, none of the stops has an extreme low value within one of the local indicators. Increasing the frequency of all bus lines by 50% does not lead to a substantially higher ridership in buses, as followed from the OmniTRANS model, and is therefore not advised.

The new bus hub in the centre performs well and efficiently connects the main lines in the network, facilitating accessibility across the city, which can be seen in, for example, the betweenness values.

The graph-based bus network performance analysis confirmed these findings. It showed that Ålesund's bus system is structurally strong and generously dimensioned in relation to current demand. No links in the network experience saturation, and the average bus occupancy is around 32%. The main passenger flows are concentrated along the west–east corridor. The inclusion of ferry services further enhances regional accessibility by shortening the longest and average travel paths.

Both analyses therefore indicate that the existing public transport network design is good, but passenger levels are low. This means that other policy measures have to be taken to increase public transport usage. This could involve discouraging car use by removing parking facilities or introducing additional taxes. Another option is to encourage public transport use by improving the design and experience of bus stops, for example, by providing shelters for bad weather, clear branding, and live information about bus schedules and locations.

Both analyses do not include costs, which could be an important factor. Lowering the fares of buses might also lead to increased ridership, but this has to be investigated.

Assessment of the Environmental Impact of the Devold Building

B.1. Introduction

B.1.1. Sørsida and Kulturhavna

The original plan for Sørsida, developed in 2015, does not mention the reuse of existing buildings (Amundsen et al., 2024). At the time, the intention was to demolish them to make room for new ones. However, in recent years, the idea of reusing existing buildings in Sørsida has grown in popularity, mainly due to social and environmental considerations (Amundsen et al., 2024). Not only does it help preserve the identity of the area by retaining the original architecture, but it also promotes more environmentally sustainable construction practices by reducing the amount of construction and demolition waste, as well as greenhouse gas (GHG) emissions. Although the reuse of buildings offers social and environmental benefits, it should be noted that it is generally a complicated process that leads to additional work in the areas of regulation and planning (Amundsen et al., 2024).

The shift in perspective has resulted in new functions for several existing buildings in Sørsida. Some examples are the Molobygget, or Molo building, where a bar/brewery/restaurant has been established and the old bus station, which now houses a concert hall/stage (Amundsen et al., 2024).

It has also led to more research initiatives on the role of reuse in urban development. One of these research initiatives is the previously mentioned Re-Value project. Although Re-Value's interest lies with the development of the entirety of Sørsida, it focuses in particular on Kulturhavna, a small part of Sørsida located on the seafront that functions as a pilot area for the project.

The pilot area is meant to show how co-creation, cooperation, and knowledge sharing can lead to sustainable urban development by bringing together and using the input of relevant stakeholders, such as future users of the area (Amundsen et al., 2024). For Sørsida Utvikling AS (SUAS), achieving sustainable urban development means striking a balance between economic, environmental, and social sustainability (Amundsen et al., 2024). In practice, this implies creating an area that is financially attractive to investors, has the smallest possible environmental footprint, and provides a place that people enjoy visiting and using.

B.1.2. Devold building

Within Re-Value, the terms *temporary Kulturhavna* and *permanent Kulturhavna* are used to distinguish between the area's current state and its long-term vision. The idea is that the input from the temporary Kulturhavna will be used to gradually transition the area into the permanent Kulturhavna.

At the moment, the temporary Kulturhavna consists of several temporary buildings, such as a library and a sauna, as well as the Devold building (Figure B.1), which was constructed in 1961 to serve as a warehouse close to the water. Today, the building is owned by SUAS and is used for various temporary measures.

Figure B.1: The Devold building.

If the original plan for Sørsida from 2015 were to be followed, the Devold building would be demolished and replaced with several smaller buildings intended for cultural and hospitality-related activities. More recent plans suggest that the area is still being considered for cultural activities, but now with the Devold building retained instead of demolished (A. Amundsen, personal communication, September 2025). It should be noted that these plans are still in their early stages and subject to change.

Reuse of the Devold building is only possible if the condition of the structure is good enough. That is why the Devold building was inspected and structurally assessed for future use as a concert hall in late 2023. The inspections were carried out visually, without sampling or testing, by Norconsult, a Nordic engineering consultancy firm.

In general, the superstructure was found to be in good condition (Norconsult, 2023). Some minor corrosion to the walls and wear of the roof were observed, but no serious damage was identified that would prevent the reuse of the existing structure. The repairs required to the roof and walls were estimated at 2-2.5 million NOK.

The reuse of the Devold building becomes more complicated when considering its foundation (Norconsult, 2023). The building is partly founded on a rubble fill and partly on rock, with the rubble fill dating from before 1929. This uneven foundation raises concerns about the long-term stability of the foundation, particularly if additional loads are introduced. Any increase in load may require reinforcement to the current foundation to ensure enough strength.

Furthermore, part of the quay structure beneath the Devold building is over 100 years old and in poor condition. Norconsult concluded that minimal repairs (estimated to cost 0.1-0.25 million NOK) would be sufficient if the building is only to be used for approximately three more years. However, long-term use would require a completely new floor that is independent of the quay (estimated to cost 22-27 million NOK) or waiting for the port authorities to renovate the quay construction before starting work on the Devold building (estimated to cost 6-9 million NOK). However, it is unknown whether the port authorities are planning on fixing the quay construction within the next few years.

Norconsult also states in their inspection report that the building was designed with three floors in mind, however, initially only one floor was constructed (Norconsult, 2023). It is not clear whether the existing foundation and roof were designed with additional floors in mind or whether they were designed for only a one story building. This must be further investigated to determine whether the elements meet current-day standards with respect to permitted loads.

The most recent development, after the inspection report of Norconsult, was the renovation of the Devold building in 2024 to repurpose it as a skate hall. The hall is also being used as an event space.

During this renovation, only the minimal required repairs to the floor, roof, and walls were conducted. If the building is to be reused for more years to come, then it's important that the floor is structurally assessed another time and that more information is gathered on the state of the quay and the plans for improving the quay. Without this information, it will be difficult to reuse the building, as it results in a very uncertain situation.

B.2. Problem Statement

At the time of writing, more is known about Sørsidas economic and social sustainability than about its environmental sustainability. This is because economic sustainability has been the dominant factor in traditional property development for a long time, which means that there is already a lot of experience and knowledge in this area. Furthermore, the inspection report of Norconsult gave clear values for the costs that would have to be made to make sure the Devold building could be reused. The social sustainability of Sørsida is actively being investigated through events and workshops of the Re-Value project. In contrast, not much is known about the environmental sustainability besides the fact the construction sector uses large amounts of energy and produces a lot of greenhouse gas emissions. Furthermore, most emissions from the construction sector are not being accounted for within the municipality's overall emissions since they are not considered direct emissions. This results in a situation where there is a lack of data on environmental sustainability.

The goal of this study is to bridge this gap by providing information on the implications of demolishing and rebuilding or reusing existing buildings. Not only will this create more balance between the three different aspects of sustainable urban development in future decision making, it also supports SUAS in their ongoing research on Kulturhavna and Sørsida as a whole. For this study, the Devold building is used as a case study as requested by the client.

B.3. LCA Methodology

This study uses the Life Cycle Assessment (LCA) methodology to quantify and compare the environmental impacts of various (re)development scenarios (demolition and new construction, and reuse) for the Devold building in Sørsida. An LCA evaluates the environmental impact of a building or product across its entire life cycle, from raw material extraction to End of Life waste management (Finnveden et al., 2009).

Standards are in place at international, European, and national level to guide the implementation of LCAs and to ensure consistent and comparable results (Bjørn et al., 2017). The aim of the international standards is to provide a general framework for conducting LCAs (Bjørn et al., 2017). The European standards build on this framework by providing more specifics on the calculation method, resulting in more consistent and comparable results (Standards Norway, 2012). An example of a European standard is EN 15978, which provides a calculation method for the environmental impact of buildings throughout their entire life cycle (Standards Norway, 2012). This standard is often used in combination with another European standard, EN 15804, which provides a calculation method for assessing the environmental impact of construction elements throughout their entire life cycle, as well as rules for developing Environmental Product Declarations (EPDs) (Standards Norway, 2023). EPDs are documents containing quantified data on the environmental impact of construction elements throughout their entire life cycle and are often used to compare products with similar functions (International Organization for Standardization, 2006). They also serve as data sources for other LCAs.

The national standards are adaptations of the European standards and provide more clarity on aspects that remain relatively vague in their European counterparts (Vandervaeren et al., 2022). In addition, they ensure that the LCA calculation method is in accordance with other rules and regulations, as well as national climate goals (Resch et al., 2022). In Norway, NS 3720 is an adaptation of the previously mentioned EN 15978 and provides a calculation method for GHG emissions of buildings (Standards Norway, 2024).

These standards not only provide calculation methods but also specify which environmental impacts should be considered and how they should be structured and reported. This is done through the selection of impact categories and modules used in the LCA. Impact categories represent the different types of environmental impacts that a building or product can cause. The European standards EN

15978 and EN 15804 describe 13 core impact categories and 6 additional ones, resulting in a total of 19 (Standards Norway, 2012) (Standards Norway, 2023). The Norwegian standard NS 3720 narrows this down and only includes categories 1-4, which relate to GHG emissions (Standards Norway, 2024). Table B.1 shows the different impact categories, as well as their corresponding indicator and unit.

Table B.1: Impact categories, their indicator and unit.

Impact category	Indicator	Unit
Climate change - total	GWP-total	kg CO_2 eq.
Climate change - fossil	GWP-fossil	kg CO_2 eq.
Climate change - biogenic	GWP-biogenic	kg CO_2 eq.
Climate change - land use and land use change	GWP-luluc	kg CO_2 eq.
Ozone depletion	ODP	kg CFC 11 eq.
Acidification	AP	mol H+ eq.
Eutrophication aquatic freshwater	EP-freshwater	kg PO4 eq.
Eutrophication aquatic marine	EP-marine	kg N eq.
Eutrophication terrestrial	EP-terrestrial	mol N eq.
Photochemical ozone formation	POCP	kg NMVOC eq.
Depletion of abiotic resources - minerals and metals	ADP-minerals&metals	kg Sb eq.
Depletion of abiotic resources - fossil fuels	ADP-fossil	MJ, net calorific value
Water use	WDP	m³ world eq. deprived
Particulate matter emissions	PM	disease incidence
Ionising radiation, human health	IRP	kBq U235 eq.
Ecotoxicity (freshwater)	ETP-fw	CTUe
Human toxicity, cancer effects	ETP-c	CTUh
Human toxicity, non-cancer effects	ETP-nc	CTUh
Land use related impacts / soil quality	SQP	dimensionless

Modules are used to distinguish between different life cycle stages of a building or product. The use of modules makes it possible to analyse how each life cycle stage contributes to the overall environmental impact of a building or product. Typically, LCA calculations following the European standards EN 15978 and EN 15804 include the following modules (Circular Ecology, 2023):

Product stage
- A1: Raw material supply and processing of secondary material
- A2: Transport of raw and secondary material
- A3: Manufacturing of construction products

Construction stage
- A4: Transport to the building site
- A5: Installation into the building

Use stage
- B1: Use or application of the installed product
- B2: Maintenance
- B3: Repair
- B4: Replacement
- B5: Refurbishment
- B6: Operational energy use
- B7: Operational water use

End of life stage
- C1: Deconstruction and demolition
- C2: Transport to waste processing facilities
- C3: Waste processing for reuse, recovery, and/or recycling

- C4: Waste disposal

Module D is also typically included in LCA calculations. This module represents potential environmental impacts, both positive and negative, associated with reuse, recycling, and energy recovery of a building or product beyond the system boundary. For example, recycling concrete can reduce the demand for natural aggregates, saving energy and avoiding emissions that would be required for their extraction. These benefits are reported as negative impacts in module D.

LCA calculations based on the Norwegian standard NS 3720 use a modified version of the previously stated list of modules (Standards Norway, 2024). These modifications consist of the exclusion of module B7 (operational water use) and the addition of the new module B8 (emissions due to transport in operation). This new module covers the environmental impacts of transporting people, goods, and services during the operation of the building. When performing LCA calculations, it is important to stay critical of these exclusions and additions. For instance, excluding an impact category or module with high environmental impacts can make a product or building appear more environmentally sustainable than it truly is, resulting in misleading conclusions and potentially greenwashing.

To ensure a transparent and consistent assessment, and avoid misleading conclusions as much as possible, two parallel LCAs are performed in this study. The first LCA is based on the Norwegian standard NS 3720 and therefore only considers GHG emissions. This approach ensures that the results are comparable with other projects in Norway that apply the same methodology. This assessment will from now on be referred to as the Norwegian LCA. The second LCA is based on the European standards EN 15978 and EN 15804 and considers all impact categories and modules, as far as possible. This approach serves as a sensitivity analyses to test whether the conclusions from the GHG-only LCA remain valid when considering additional impact categories. This assessment will from now on be referred to as the European LCA.

An LCA typically consists of the following phases (Latimer, 2023):

1. Goal and scope definition
2. Life Cycle Inventory (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation

In the following sections, these stages will be followed and developed first for the demolition and new construction scenario. After the interpretation of these results, assessments of the reuse scenario will be performed.

B.4. Goal and Scope Definition Phase

B.4.1. Goal
The goal of both LCAs is to evaluate the environmental impact of the Devold building in the event of demolition and new construction according to the original plan for Sørsida of 2015, as well as to explore more environmentally sustainable alternatives based on reuse of the existing building.

B.4.2. Functional unit
The functional unit of both LCAs is 1 m2 gross floor area (GFA) over a reference study period of 60 years. This functional unit is used to ensure comparability with other Norwegian LCAs, where this is a common functional unit.

B.4.3. System boundary
The system boundary depends on the standard on which the LCA is based. Based on what was discussed in Section B.3, the Norwegian LCA only considers GHG emissions (impact categories 1-4) and includes modules A1-A5, B1-B6, B8, C1-C4, and D. The module on operational water use (B7) is excluded. The European LCA considers all impact categories, as far as possible. For this study, it was sometimes not possible to find environmental data on all 19 impact categories. Therefore, only impact categories 1-13 are included.

In addition, it was sometimes not possible to find environmental data on all B modules (B1-B8). This is not uncommon in environmental databases, as manufacturers of construction elements find it difficult to predict what will happen to their product during the use stage. Therefore, only modules A1-A5, C1-C4, and D are considered for the initial LCA calculations. This applies both to the Norwegian and European LCA.

Table B.2 and Table B.3 show an overview of which impact categories and modules are included in the initial LCA calculations. An 'X' means that the impact category or module is included, while an 'N/A' means that the impact category of module is excluded.

Table B.2: Impact categories included in the Norwegian and European LCAs.

Impact category	LCA based on NS 3720	LCA based on EN 15978 and EN 15804
Climate change - total	X	X
Climate change - fossil	X	X
Climate change - biogenic	X	X
Climate change - land use and land use change	X	X
Ozone depletion	N/A	X
Acidification	N/A	X
Eutrophication aquatic freshwater	N/A	X
Eutrophication aquatic marine	N/A	X
Eutrophication terrestrial	N/A	X
Photochemical ozone formation	N/A	X
Depletion of abiotic resources - minerals and metals	N/A	X
Depletion of abiotic resources - fossil fuels	N/A	X
Water use	N/A	X
Particulate matter emissions	N/A	N/A
Ionising radiation, human health	N/A	N/A
Ecotoxicity (freshwater)	N/A	N/A
Human toxicity, cancer effects	N/A	N/A
Human toxicity, non-cancer effects	N/A	N/A
Land use related impacts / soil quality	N/A	N/A

Table B.3: Modules included in the Norwegian and European LCAs.

Module	LCA based on NS 3720	LCA based on EN 15978 and EN 15804
A1: Raw material supply and processing of secondary material	X	X
A2: Transport of raw and secondary material	X	X
A3: Manufacturing of construction products	X	X
A4: Transport to the building site	X	X
A5: Installation into the building	X	X
B1: Use or application of the installed product	N/A	N/A
B2: Maintenance	N/A	N/A
B3: Repair	N/A	N/A
B4: Replacement	N/A	N/A
B5: Refurbishment	N/A	N/A
B6: Operational energy use	N/A	N/A
B7: Operational water use	N/A	N/A
B8: Emissions due to transport in operation	N/A	N/A
C1: Deconstruction and demolition	X	X
C2: Transport to waste processing facilities	X	X
C3: Waste processing for reuse, recovery, and/or recycling	X	X
C4: Waste disposal	X	X
D: Future reuse, recycling or energy recovery potentials	X	X

Lastly, most of the sources used in this study present the environmental impacts of modules A1-A3 as a combined value. So instead of a separate A1, A2, and A3 module, this study will use a combined A1-A3 module.

B.4.4. Assumptions and limitations
Assumptions have been made because of a lack of data and various other uncertainties. These assumptions, as well as other limitations, and their implications for the LCA calculations are listed below.

Limitation: Dimensions of the Devold building
Accurate measurements of the dimensions of the Devold building are lacking. While some dimensions were given, the other dimensions have been measured from the original floor plans of 1961 and the updated floor plans from the renovations of 2024, which may lead to small measurement errors.

Assumption: Dimensions and materials of the new buildings
Information on the dimensions and materials of the new buildings that would replace the Devold building (according to the plan for Sørsida of 2015) is lacking. Therefore, this study assumes that the dimensions and materials are similar to the dimensions and materials of the Devold building. Thus, information on the dimensions and materials of the Devold building will also be used for the new buildings.

Assumption: In-situ vs. precast concrete
The original building notice states that the main structural elements of the Devold building are made of reinforced concrete (K.S. Knudsen, 1961). Based on visual inspections during visits to the Devold building, this study assumes that precast reinforced concrete elements were used. This applies to the columns, floor, foundation, roof, and walls.

Assumption: Density of reinforced concrete
This study assumes that all reinforced concrete elements have a density of approximately 2,500 kg/m3 (EurocodeApplied, n.d.).

Assumption: Future use of the area
The future function of the Devold building, or more precisely the area in which it is located, is still being investigated by the municipality. This study assumes that the building will keep its current function as skatehall and event space. Thus, no additional facilities are required, and that the operational energy use (B6) will remain similar.

Assumption: Reuse of existing foundation
The Norconsult report states that there is no risk of subsidence (and subsequent damage) if the pressure of the foundation on the underlaying soil does not change. If the building's function remains the same, it is expected that there will be no additional pressure. In that case, this study assumes that the existing foundation can be reused. Thus, no new foundation elements will have to be produced, which is why it is left out of the LCA calculations.

Assumption: Insulation panels
The Norconsult report states that it is uncertain whether the wood wool cement insulation panels are still present in the building. This is because it was not possible to detect them during the visual inspections as there was too much stuff in the way. This study assumes that the wood wool cement insulation panels are still present in the building. This means these construction elements will have to be demolished and processed accordingly during the demolition of the Devold building in the demolition and new construction scenario.

Limitation: Cut-off criteria
The cut-off criteria according to EN 15804 will be used for both the Norwegian and European LCAs to make the calculations more structured. Thus, the amount of material excluded does not exceed 1% of the total weight of the building (Standards Norway, 2023). For the LCA calculation, this limitation means that materials in low quantities can be removed from the LCA calculations as long as their combined weight percentage does not exceed 1%.

Limitation: Environmental Product Declarations
Finding EPDs that match the construction elements of the Devold building is difficult. This is because EPDs are a recent development, making it unlikely that an EPD of a construction element of 1961 exists. In addition, it is not known which specific construction elements were used during the construction of

the Devold building. For this reason, data from EPDs of similar construction elements are used. In addition, it is difficult to find EPDs for construction elements that are produced close to Ålesund or even in Norway. For this reason, EPDs are used from neighbouring countries like Denmark and Sweden, where Norwegian EPDs are lacking. Furthermore, some of the EPDs used in this study don't contain data on all impact categories and/or modules. This limits the inclusion of impact categories and/or modules to the ones for which environmental data is provided in the EPDs.

B.5. Inventory Analysis Phase

B.5.1. Bill of materials

Table B.4 shows an overview of the different materials that can be found in the Devold building, as well as their volume [m³], average density [kg/m³], weight [kg], and contribution to the total weight of the structure [%].

Table B.4: Bill of materials of the Devold building.

Material	Volume [m³]	Average density [%]	Weight [kg]	Weight percentage [%]
Glass	3.39	941.60	3,195.19	0.096
Icopal	11.54	1,428.57	16,482.14	0.50
Paint	0.10	1,300	129.07	0.004
Reinforced concrete	1,302.39	2,500	3,257,038.89	98.35
Steel	14.43	1,271.52	18,351.15	0.55
Wood	0.80	247.44	198.24	0.01
Wood wool cement	40.46	400	16,184.78	0.49

The following materials are excluded from further calculations according to the cut-off criteria of EN 15804: Glass, icopal, paint, and wood. These materials have a combined weight percentage of 0.60%. This leaves enough room for unintentional exclusion of materials that could not be identified on the basis of the provided floor plans and additional information.

Table B.4 shows that the Devold building consists mainly of reinforced concrete. Table B.5 shows the different elements of the building that consist of reinforced concrete, as well as their volume [m³] and their contribution to the total volume [%].

Table B.5: The reinforced concrete elements of the Devold building and their respective volumes and volume percentages.

Element	Volume [m³]	Volume percentage [%]
Columns	93.12	7.15
Floor	95.55	7.33
Foundation	211.73	16.25
Roof	727.19	55.82
Stairs	0.52	0.04
Walls	174.70	13.41

In addition to reinforced concrete, steel and wood wool cement are also still considered in the LCA calculations. These materials can be found in the garage doors and the insulation, respectively.

B.5.2. Data sources

To determine the environmental impact of the Devold building, EPDs are used as the main data source. These are documents that provide the environmental impact of each possible combination of impact category and module for a certain construction element. Most EPDs originate from the website of EPD-Norway, which is a Norwegian EPD programme operator (EPD-Norge, n.d.). Their goal is to help businesses communicate the environmental impact of their products by creating verified and understandable EPDs. Their website also contains EPDs from other countries, as they collaborate with EPD programme operators from neighbouring countries like Denmark and Sweden, as well as programme operators from more far away countries like China. The other EPDs originate from the website of the construction product's producer. Below, a list is provided of the EPDs that are used for the different elements of the Devold building.

Columns (reinforced concrete)
- EPD in accordance with ISO 14025 and EN 15804 + A2 Pelare XC4+XF1 (UBAB Ulricehamns Betong AB, 2024a)

- EPD in accordance with ISO 14025 and EN 15804 + A2 Pelare och Balk (Nybetong AB, 2024b)

- EPD in accordance with ISO 14025 and EN 15804 + A2 Pelare XC3-XF4, nivå 3 (Tranemo Prefab AB, 2024)

Floor and roof (reinforced concrete)
- EPD in accordance with ISO 14025 and EN 15804 + A2 Massivt bjälklag (UBAB Ulricehamns Betong AB, 2025b)

- EPD in accordance with ISO 14025 and EN 15804 + A2 Massivt förspänt bjälklag (UBAB Ulricehamns Betong AB, 2025c)

- EPD in accordance with ISO 14025 and EN 15804 + A2 Massiv bjälklagsplatta/RD-platta nivå 3 (Tranemo Prefab AB, 2025)

Foundation (reinforced concrete)
- EPD in accordance with ISO 14025 and EN 15804 + A2 1 meter steel reinforced fundation Pile in B3 45 x 45 type 20, with 20 rebar (Centrum Pæle A/S, 2025a)

- EPD in accordance with ISO 14025 and EN 15804 + A2 1 meter steel reinforced fundation Pile in B3 45 x 45 type 16, with 16 rebar (Centrum Pæle A/S, 2025b)

- EPD in accordance with ISO 14025 and EN 15804 + A2 1 meter steel reinforced fundation Pile in G3 45 x 45 type 20, with 20 rebar (Centrum Pæle A/S, 2025c)

Stairs (reinforced concrete)
- EPD in accordance with ISO 14025 and EN 15804 + A2 Svängda trappor (AB Strängbetong, 2025)

- EPD in accordance with ISO 14025 and EN 15804 + A2 Trappa svängd XC1 (UBAB Ulricehamns Betong AB, 2024b)

Walls (reinforced concrete)
- EPD in accordance with ISO 14025 and EN 15804 + A2 Massiv vägg (UBAB Ulricehamns Betong AB, 2025a)

- EPD in accordance with ISO 14025 and EN 15804 + A2 Massivvägg (Nybetong AB, 2024a)

- EPD in accordance with ISO 14025 and EN 15804 + A2 Massivvägg V (Skar Elements Hudiksvall AB, 2024)

Garage doors (steel)
- EPD Sectional doors (Lindab A/S, 2022)

Insulation (wood wool cement)
- EPD in accordance with ISO 14025 and EN 15804 + A2 Semullit Träullit Baux – Cement Grey wood wool cement panels and wall systems (Träullit AB, 2024a)

- EPD in accordance with ISO 14025 and EN 15804 + A2 Semullit Träullit Baux – Cement Grey-White Natural wood wool cement panels and wall A2 fire class (Träullit AB, 2024b)

- EPD in accordance with ISO 14025 and EN 15804 + A2 Semullit Träullit Baux – White Natural wood wool cement panels and wall systems (Träullit AB, 2024c)

B.6. Impact Assessment Phase

B.6.1. Impact calculation

The first step in the impact assessment phase involves creating a dataset containing environmental data of the Devold building's construction elements. Table B.6 shows an overview of these construction elements, as well as the functional unit used in their corresponding EPDs and the quantity of the elements expressed in the functional unit.

Table B.6: Construction elements of the Devold building and their quantities using the functional units of the EPDs.

Element	Functional unit	Quantity Devold building
Columns (reinforced concrete)	Weight [tonne]	232.80
Floor (reinforced concrete)	Weight [tonne]	238.87
Foundation (reinforced concrete)	Length [m]	164.86
Roof (reinforced concrete)	Weight [tonne]	1,817.99
Stairs (reinforced concrete)	Weight [tonne]	1.30
Walls (reinforced concrete)	Weight [tonne]	436.75
Garage doors (steel)	Surface [m²]	96.22
Insulation (wood wool cement)	Weight [tonne]	16.18

For several construction elements, multiple EPDs were used. For these elements, the mean environmental impact of all EPDs was calculated for each combination of impact category and module. This resulted in a single representative value for every impact category-module pair for every construction element. These values were then multiplied by the respective quantities, which are shown in the third column of Table B.6. This resulted in a data set that contains the environmental impact of every impact category-module pair for the different construction elements of the Devold building. These values were then divided by the GFA, which is equal to 1273.98 m², to ensure that the environmental data is presented in the functional unit as described in Subsection B.4.2. In addition, the values were multiplied by the respective ecocosts, as shown in Table B.7, to monetize the environmental impact (Nationale Milieudatabase, n.d.). However, the ecocosts are in euros and were therefore multiplied by 11.66 to convert them to the Norwegian krone.

Table B.7: Ecocosts per impact category.

Impact category	Ecocosts [€]
Climate change - total	0.116
Climate change - fossil	0.116
Climate change - biogenic	0.116
Climate change - land use and land use change	0.116
Ozone depletion	32
Acidification	0.39
Eutrophication aquatic freshwater	1.96
Eutrophication aquatic marine	3.28
Eutrophication terrestrial	0.36
Photochemical ozone formation	1.22
Depletion of abiotic resources - minerals and metals	0.3
Depletion of abiotic resources - fossil fuels	0.00033
Water use	0.00506
Particulate matter emissions	549750
Ionising radiation, human health	0.049
Ecotoxicity (freshwater)	0.00013
Human toxicity, cancer effects	1,096,368
Human toxicity, non-cancer effects	147,588
Land use related impacts / soil quality	0.000087

Various adjustments to this data set have been made to ensure more accurate environmental impacts. These adjustments are listed below.

Cross section of the foundation
The EPDs of the foundation consider a cross section that is smaller than the cross section of the foundation piles of the Devold building. Therefore, the environmental impacts have been scaled accordingly. This has been done by first dividing the values by the cross section mentioned in the EPDs and then multiplying them by the cross section of the foundation piles of the Devold building, which is approximately 1.04m² when measured from the provided technical drawings (K.S. Knudsen, 1961).

Scaling of module A4
The environmental data of module A4 was recalculated to ensure that it more accurately reflects the distance that the product has to travel from the production facility to the construction site. This was

done by dividing the values by the distance mentioned in the EPDs and then multiplying that value by the distance between the production facility and the Devold building.

Modules C2-C4 for reinforced concrete construction elements

All EPDs of the reinforced concrete construction elements, except those of the foundation, assume a recycling rate of 100%. The EPDs of the foundation assume that the construction elements remain in the ground after the building has been demolished, which is common practice. However, recent data shows that only 59.8% of Norwegian construction and demolition waste is prepared for reuse and recycling (European Environment Agency, 2025). Therefore, the assumed recycling rate is considered unrealistic, which resulted in the alteration of modules C2-C4 for the relevant EPDs.

For each impact category, the environmental data of module C2 was recalculated using the following equation:

$$C_2^* = C_{2,EPD} \cdot \frac{d_R}{d_{EPD}} \cdot p_R + C_{2,EPD} \cdot \frac{d_L}{d_{EPD}} \cdot p_L \tag{B.1}$$

Where C_2^* is the recalculated environmental impact in the respective functional unit, $C_{2,EPD}$ is the environmental impact in the EPD in the respective functional unit, d_R is the distance between the Devold building and the closest recycling facility [km], d_{EPD} is the distance mentioned in the EPD [km], p_R is the waste fraction that gets recycled [-], d_L is the distance between the Devold building and the closest landfill [km], and p_L is the waste fraction that gets landfilled [-]. The closest landfill is approximately 150 km from the Devold building (Bergmesteren Raudsand AS, n.d.) and the closest recycling facility is approximately 14 km from the Devold building (Attvin, n.d.).

For each impact category, the environmental data of module C3 was recalculated by multiplying them by 0.598.

As the EPDs assume a recycling rate of 100%, they do not contain data on the environmental impact of reinforced concrete being landfilled. That is, there is no environmental data for module C4. This gap in the dataset was filled in by two additional EPDs of reinforced concrete construction elements that are partially landfilled. The additional EPDs assume that 67% of the construction product is landfilled, while 33% is recycled (Skonto Prefab, 2022b)(Skonto Prefab, 2022a). Thus, the environmental data of module C4 has to be scaled to represent 40.2% instead of 67%. This was achieved by dividing the environmental data by 67% and subsequently multiplying it by 40.2%. The additional EPDs use a functional unit of 1 tonne, so to get the environmental impact of one of the reinforced concrete construction elements, the environmental data was multiplied by the quantities as shown in the third column of Table B.6.

Module C2 for steel garage doors

The EPD of the steel garage door assumes a recycling rate of 98%, which is based on the market situation of 2022 (Lindab A/S, 2022). Therefore, the assumed recycling rate is considered realistic, resulting in only an alteration to module C2.

For each impact category, the environmental data of module C2 was recalculated using the following equation:

$$C_2^* = C_{2,EPD} \cdot \frac{d_R}{d_{EPD}} \tag{B.2}$$

Where C_2^* is the recalculated environmental impact in the respective functional unit, $C_{2,EPD}$ is the environmental impact in the EPD in the respective functional unit, and d_R is the distance between the Devold building and the closest recycling facility [km]. The closest recycling facility is approximately 14 km from the Devold building (Vartdal Gjenvinning AS, n.d.).

Module C2 for wood wool cement insulation

The EPDs of the wood wool cement insulation assume that the material is transported to a waste incineration facility for energy recovery. This is considered a realistic scenario for the construction product, resulting in only an alteration to module C2.

For each impact category, the environmental data of module C2 was recalculated using the following equation:

$$C_2^* = C_{2,EPD} \cdot \frac{d_I}{d_{EPD}} \tag{B.3}$$

Where C_2^* is the recalculated environmental impact in the respective functional unit, $C_{2,EPD}$ is the environmental impact in the EPD in the respective functional unit, and d_I is the distance between the Devold building and the closest waste incineration facility [km]. The closest waste incineration facility is approximately 286 km from the Devold building (Statkraft Varme AS, n.d.).

Recalculation of module D

For most construction elements, such as the columns, floor, roof, stairs, walls, and garage doors, the estimated service life is 50 years. However, this study uses a reference study period of 60 years. Thus, for these elements, double the amount is needed as they are demolished and replaced after 50 years have expired. That is, the production and placement (modules A1-A5) of these elements occur twice within the reference study period. However, it would not be accurate to fully include the environmental impact of modules A1-A5, as the new element will retain its function for another 40 years after the reference study period has ended. Similarly, it would not be fair to fully exclude the environmental impact of modules C1-C4, as demolition and processing of the new element is bound to happen at some point. This is accounted for by making adjustments to module D. A fraction of modules A1-A5 are subtracted from module D to represent the remaining functionality of the new element after the reference study period. A fraction of modules C1-C4 is added to module D to represent the demolition and processing of the new element after the reference study period. For construction elements with a service life of 50 years, thus, the new element retains its function for 40 of its 50 years after the reference study period. Therefore, 0.8 (40/50) times the sum of modules A1-A5 is subtracted from module D. In addition, the new element is in use for 10 of its 0 years during the reference study period. Therefore, 0.2 (10/50) times the sum of modules C1-C4 is added to module D. Lastly, for the reinforced concrete elements, the environmental data of module D was recalculated by multiplying it by 0.598 before subtraction and addition of the other modules.

B.6.2. Results demolition and new construction scenario

Table B.8 and Table B.9 show the results of the Norwegian LCA for the demolition of the Devold building using the functional unit of 1 m² GFA over a reference study period of 60 years with and without monetization, respectively.

Table B.8: Monetized results, in Norwegian Kroner (NOK), of the Norwegian LCA for the demolition of the Devold building.

Element	C1	C2	C3	C4	D	Total
Columns	0.52	0.84	0.04	1.40	-0.15	2.66
Floor	0.50	0.90	0.02	1.43	-3.08	-0.22
Foundation	0.00	0.00	0.00	0.00	-0.03	-0.03
Roof	3.84	6.82	0.17	10.92	-23.44	-1.69
Stairs	0.01	0.01	0.00	0.01	-0.01	0.01
Walls	0.87	1.55	0.05	2.62	-1.24	3.85
Garage doors	0.00	0.00	0.60	0.00	-3.91	-3.30
Insulation	0.00	0.65	8.49	0.09	-0.38	8.84
Total	**5.74**	**10.76**	**9.37**	**16.47**	**-32.20**	**10.15**

Table B.9: Results, in kg CO_2, of the Norwegian LCA for the demolition of the Devold building without monetization.

Element	C1	C2	C3	C4	D	Total
Columns	0.38	0.62	0.03	1.03	-0.11	1.96
Floor	0.37	0.66	0.02	1.06	-2.28	-0.16
Foundation	0.00	0.00	0.00	0.00	-0.02	-0.02
Roof	2.84	5.04	0.13	8.07	-17.33	-1.25
Stairs	0.00	0.01	0.00	0.01	-0.01	0.01
Walls	0.64	1.14	0.04	1.94	-0.91	2.85
Garage doors	0.00	0.00	0.44	0.00	-2.89	-2.44
Insulation	0.00	0.48	6.27	0.06	-0.28	6.53
Total	**4.24**	**7.96**	**6.93**	**12.18**	**-23.81**	**7.50**

Table B.10 and Table B.11 show the results of the Norwegian LCA for the construction of the new building(s) using the functional unit of 1 m² GFA over a reference study period of 60 years with and without monetization, respectively.

Table B.10: Monetized results, in Norwegian Kroner (NOK), of the Norwegian LCA for the construction of the new building(s).

Element	A1-A3	A4	A5	B1-B8	C1	C2	C3	C4	D	Total
Columns	55.27	17.79	0.57	N/A	0.52	0.84	0.04	1.40	-29.31	47.12
Floor	33.11	28.25	1.02	N/A	0.50	0.90	0.02	1.43	-27.74	37.49
Foundation	0.00	0.00	0.00	N/A	0.00	0.00	0.00	0.00	-0.04	-0.04
Roof	251.96	215.00	7.77	N/A	3.84	6.82	0.17	10.92	-211.14	285.35
Stairs	0.47	0.07	0.01	N/A	0.01	0.01	0.00	0.01	-0.23	0.35
Walls	65.31	45.55	3.29	N/A	0.87	1.55	0.05	2.62	-46.40	72.84
Garage doors	10.89	0.35	1.89	N/A	0.00	0.00	0.60	0.00	-9.04	4.69
Insulation	0.13	5.48	1.15	N/A	0.00	0.65	8.49	0.09	-0.38	15.60
Total	**417.15**	**312.49**	**15.69**	**N/A**	**5.74**	**10.76**	**9.37**	**16.47**	**-324.28**	**463.40**

Table B.11: Results, in kg CO_2, of the Norwegian LCA for the construction of the new building(s) without monetization.

Element	A1-A3	A4	A5	B1-B8	C1	C2	C3	C4	D	Total
Columns	40.86	13.15	0.42	N/A	0.38	0.62	0.03	1.03	-21.67	34.84
Floor	24.48	20.89	0.75	N/A	0.37	0.66	0.02	1.06	-20.51	27.72
Foundation	0.00	0.00	0.00	N/A	0.00	0.00	0.00	0.00	-0.03	-0.03
Roof	186.29	158.96	5.74	N/A	2.84	5.04	0.13	8.07	-156.10	210.97
Stairs	0.35	0.05	0.00	N/A	0.00	0.01	0.00	0.01	-0.17	0.26
Walls	48.29	33.68	2.43	N/A	0.64	1.14	0.04	1.94	-34.30	53.86
Garage doors	8.05	0.26	1.40	N/A	0.00	0.00	0.44	0.00	-6.68	3.47
Insulation	0.10	4.05	0.85	N/A	0.00	0.48	6.27	0.06	-0.28	11.53
Total	**308.41**	**231.03**	**11.60**	**N/A**	**4.24**	**7.96**	**6.93**	**12.18**	**-239.76**	**342.61**

Combining the environmental impact of the demolition of the Devold building and the construction of the new building(s) results in a total environmental impact of NOK 473.54 per m² GFA over a reference study period of 60 years or 350 kg CO_2 per m² GFA over a reference study period of 60 years.

The modules contribute to the total environmental impact to varying degrees. To gain more insight into this, the contribution of each module was calculated by dividing the absolute environmental impact of a module by the sum of the absolute environmental impact of all modules. The contribution of each module can be seen in Figure B.2.
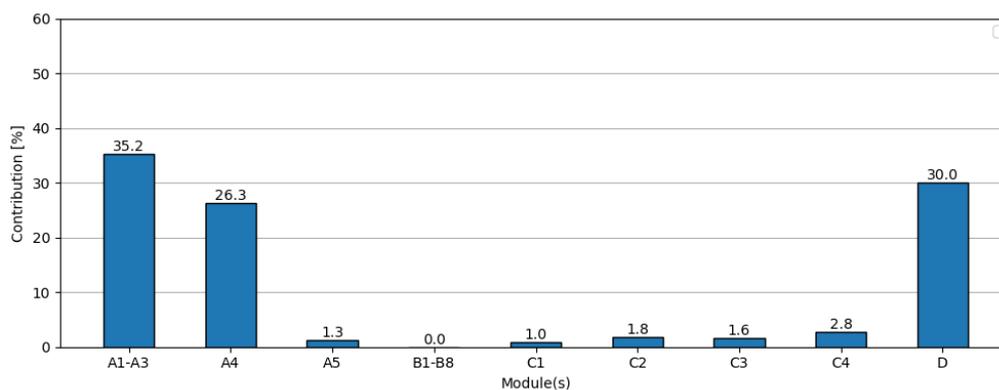
Figure B.2: Contribution of each life cycle stage to the total environmental impact for the Norwegian LCA.

Table B.12 and Table B.13 show the monetized results of the European LCA for the demolition of the Devold building and the construction of the new building(s) respectively using the functional unit of 1 m² GFA over a reference study period of 60 years.

Table B.12: Monetized results, in Norwegian Kroner (NOK), of the European LCA for the demolition of the Devold building.

Element	C1	C2	C3	C4	D	Total
Columns	1.09	2.13	0.10	2.02	-0.34	5.00
Floor	1.27	2.26	0.06	2.07	-5.94	-0.27
Foundation	0.00	0.00	0.00	0.00	-0.05	-0.05
Roof	9.68	17.19	0.45	15.79	-45.20	-2.08
Stairs	0.01	0.01	0.00	0.01	-0.01	0.02
Walls	2.39	4.25	0.16	3.79	-2.25	8.35
Garage doors	0.00	0.05	5.79	0.13	-124.38	-118.41
Insulation	0.02	1.23	8.64	0.29	-10.50	-0.33
Total	**14.46**	**27.12**	**15.21**	**24.10**	**-188.62**	**-107.73**

Table B.13: Monetized results, in Norwegian Kroner (NOK), of the European LCA for the construction of the new building(s).

Element	A1-A3	A4	A5	B1-B8	C1	C2	C3	C4	D	Total
Columns	174.72	92.91	1.13	N/A	1.09	2.13	0.10	2.02	-107.17	166.93
Floor	235.66	71.16	2.58	N/A	1.27	2.26	0.06	2.07	-128.97	186.09
Foundation	0.00	0.00	0.00	N/A	0.00	0.00	0.00	0.00	-0.05	-0.05
Roof	1,793.53	541.60	19.63	N/A	9.68	17.19	0.45	15.79	-981.57	1,416.30
Stairs	0.55	0.45	0.01	N/A	0.01	0.01	0.00	0.01	-0.41	0.63
Walls	573.34	123.49	7.65	N/A	2.39	4.25	0.16	3.79	-282.66	432.42
Garage doors	420.53	12.23	13.67	N/A	0.00	0.05	5.79	0.13	-301.76	150.64
Insulation	48.82	9.27	3.64	N/A	0.02	1.23	8.64	0.29	-10.50	61.40
Total	**3,247.14**	**851.12**	**48.31**	**N/A**	**14.46**	**27.12**	**15.21**	**24.10**	**-1,813.09**	**2,414.36**

Combining the environmental impact of the demolition of the Devold building and the construction of the new building(s) results in a total environmental impact of NOK 2,306.63 per m² GFA over a reference study period of 60 years.

Similarly to the Norwegian LCA, the modules contribute to the total environmental impact to varying degrees. The contribution of each module can be seen in Figure B.3.
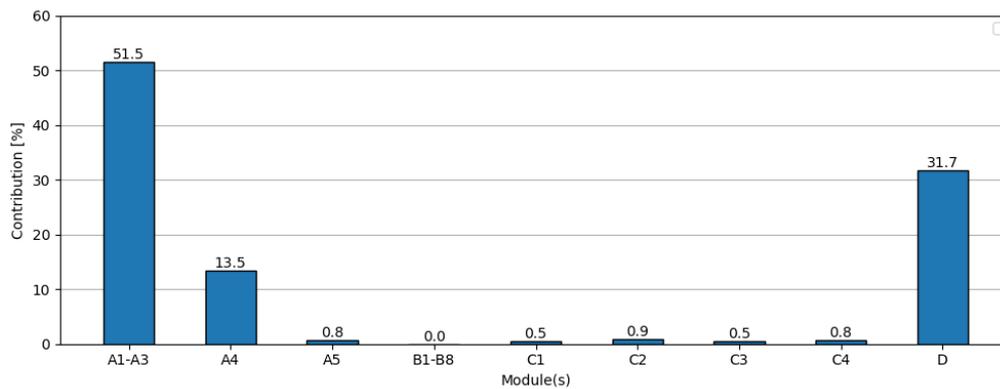
Figure B.3: Contribution of each life cycle stage to the total environmental impact for the European LCA.

B.7. Interpretation Phase

B.7.1. Interpretation of the demolition and new construction scenario

This section will only discuss the results of Subsection B.6.2. Interpretations of further calculations and a general discussion will be discussed later in the appendix.

The assumption that the foundation can be reused in combination with the fact that the foundation remains in the ground at the end of its service life has resulted in an insignificant contribution of this element to the total environmental impact. The foundation only contributes to module D with a relatively small environmental benefit. However, this environmental benefit is so small that its inclusion does not significantly affect the total environmental impact.

The environmental impact for module D of every construction element is a negative value. Thus, instead of negatively influencing the environment, it is actually beneficial to the environment. This is likely because most elements are recycled at the end of their service life and therefore produce secondary building materials. For the insulation, which is not recycled, it is likely due to the fact that incineration of the wood wool cement insulation panels leads to energy generation.

Table B.8 and Table B.9 show that, for the Norwegian LCA, the insulation is the biggest contributor to the environmental impact of the demolition of the Devold building. This is likely because the energy generation through incineration is outweighed by the GHG emissions that occur during the dismantling of this construction element. In addition, the tables show that the floor, roof, and garage doors have a negative environmental impact. Thus, demolition of these elements actually results in an environmental benefit. For the floor and roof, This is likely because the environmental benefit of the fraction that is recycled outweighs the environmental impact of the fraction that is landfilled. For the garage doors, This is likely because 98% of the steel is recycled, resulting in an environmental benefit.

Table B.12 shows that, for the European LCA, the walls are the biggest contributor to the environmental impact of the demolition of the Devold building. This is more difficult to explain as the walls are not the largest element of the Devold building. It likely has something to do with he fact that the benefit of the demolition of the walls is outweighed by the impact of demolition and landfilling. In addition, the tables show that the floor, roof, and garage doors have a negative environmental impact, which is similar to the Norwegian LCA.

The demolition of the Devold building for the European LCA results in a negative environmental impact. Thus, if the materials are recycled and processed according to the assumed recycling rates, the demolition of the Devold building on its own will actually result in an environmental benefit.

Table B.10 and Table B.11 show that, for the Norwegian LCA, the roof is the biggest contributor to the environmental impact of the construction of the new building(s). This is likely because the roof is made up of reinforced concrete, which is generally a construction material with high GHG emissions. In addition, Table B.5 shows that the roof is the largest element consisting of reinforced concrete (approximately 55.82%). The tables also show that the stairs have the smallest contribution (not taking the foundation

into account) to the environmental impact. This is likely because the stairs are the smallest element consisting of reinforced concrete (approximately 0.04%). Table B.13 and shows similar results.

Figure B.2 shows that module A1-A3 has the highest contribution to the total environmental impact. This module is likely the biggest as 98.35% of the building consists of reinforced concrete, which is a building material with a relatively high environmental impact. The second highest contribution is due to module D. This module is likely a big contributor as the majority of the construction elements are recycled at the end of their service life. The third highest contribution is due to module A4. This is likely due to the big distance between the area where the construction elements are produced and the construction site, which is caused by the use of EPDs from neighbouring countries.

Figure B.3 shows that the modules with the highest contribution to the environmental impact for the Norwegian LCA are also the biggest contributors to the environmental impact of the European LCA. However, there is a bigger difference between their contributions than before. This is likely because the European LCA includes more impact categories. These impact categories probably play a bigger role in the processes of modules A1-A3 and D, than in the processes of module A4, which would explain why there is a bigger difference between the contribution of the modules compared to the Norwegian LCA.

B.7.2. Reuse scenario

Instead of demolition and new construction, it is also possible to reuse the current structure. In the reuse scenario, it is likely that the building will have to undergo maintenance, repair, and overhaul (MRO). Thus, various processes that have been left out in previous assessments will have to be investigated. That is why the scope of the Norwegian and European LCAs is expanded to now also include maintenance (B2), repair (B3), replacement (B4), and operational energy use (B6). Use or application of the installed product (B1) is left out, because it was not possible to find environmental data for this module for all construction elements. Refurbishment (B5) is left out because all processes that would fall under refurbishment are already accounted for in maintenance (B2), repair (B3) and replacement (B4). Operational water use (B7) is left out by default in LCAs based on NS 3720 and is therefore also not included in this study. Transport to and from the building (B8) is left out because it was not possible to find data for this module. Table B.14 shows an overview of the expanded scope.

Table B.14: Expanded scope for the Norwegian and European LCAs.

Module	LCA based on NS 3720	LCA based on EN 15978 and EN 15804
A1: Raw material supply and processing of secondary material	X	X
A2: Transport of raw and secondary material	X	X
A3: Manufacturing of construction products	X	X
A4: Transport to the building site	X	X
A5: Installation into the building	X	X
B1: Use or application of the installed product	N/A	N/A
B2: Maintenance	X	X
B3: Repair	X	X
B4: Replacement	X	X
B5: Refurbishment	N/A	N/A
B6: Operational energy use	X	X
B7: Operational water use	N/A	N/A
B8: Emissions due to transport in operation	N/A	N/A
C1: Deconstruction and demolition	X	X
C2: Transport to waste processing facilities	X	X
C3: Waste processing for reuse, recovery, and/or recycling	X	X
C4: Waste disposal	X	X
D: Future reuse, recycling or energy recovery potentials	X	X

It is difficult to predict where and when the building will require MRO, as this depends on uncertain factors such as the weather conditions to which the building will be exposed and the state of the construction element over time. Therefore, assumptions will have to be made, which are listed below.

Assumption: Maintenance and repair
The EPDs of the reinforced concrete construction elements do not contain environmental data on modules B2 and B3. Therefore, this study assumes that these elements do not require any form of MRO if they are within their estimated service life. Thus, modules B2 and B3 of the reinforced concrete construction elements will be equal to 0 in the demolition and new construction scenario. This also applies to the foundation even though they are not within their estimated service life.

Assumption: Damage to the Devold building
The Norconsult report states that the damage to the Devold building consisted mainly of corrosion damage to the exterior, as well as damage to the floor (Norconsult, 2023). Based on this information, this study assumes that similar damage will occur within the study period. Patch repair is considered the most suitable solution for such damage. This is a commonly used repair technique for (reinforced) concrete structures where parts of the surface layer have crumbled away (Årskog & Fossdal, 2004). Patch repair slows the corrosion of the reinforcement steel that might have become exposed due to the absence of the concrete surface layer. It is also assumed that the application of patch repair does not influence the dismantling or demolition process of the repaired construction elements at the end of their service life. Lastly, this study assumes that only the construction elements that were repaired during the renovations of 2024 will require patch repair. This includes the floor, as well as the roof and walls. For the floor, the entire GFA is considered (1273.98 m²). For the roof, only the underside and the side of the roof are considered (497.72 m²), as the top of the roof received a new protective layer during the 2024 renovations. This layer is expected to be able to protect the roof from any damage during the study period. For the walls, the entire area of the exterior walls is considered (817.16 m²).

To account for MRO, adjustments were made to the Norwegian and European LCAs. First, adjustments were made to previous assessments of the demolition and new construction scenario to ensure fair comparison between that scenario and the new reuse scenario. Then adjustments were made for the reuse scenario. All adjustments are based on the Norconsult report and are listed below (Norconsult, 2023).

Adjustments to the demolition and new construction scenario
The environmental impact of modules B2 and B3 for the reinforced concrete construction elements is equal to 0, as this study assumes that these construction elements do not require maintenance and repair when they are within their estimated service life. This is also true for the foundation even though it is not within its estimated service life. The environmental impact of modules B2 and B3 for the garage doors and the insulation was derived from its corresponding EPD. The value for the garage doors was multiplied by 1.2 to scale the value from 50 to 60 years. The production and instalment of the new construction elements in year 50 of the reference study period is no longer included in modules A1-A5, but was moved to module B4. This applies to the reinforced concrete construction elements (except the foundation) and the garage doors. The foundation is not replaced, as it is expected that the foundation can be reused for the entire study period. Therefore, the environmental impact of module B4 for the foundation is equal to 0. The estimated service life of the insulation is equal to the reference study period. Therefore, the insulation will not have to be replaced and the environmental impact of module B4 for the insulation is equal to 0.

Addition of operational energy use (B6)
This applies both to the demolition and new construction and reuse scenarios. Data on the operational energy use (B6) of the Devold building was provided by SUAS. The building has two electricity meters, which together measure the total electricity consumption of the building in kilowatt-hours (kWh). Table B.15 and Table B.16 show the electricity consumption of the Devold building of 2024 and 2025 respectively.

Table B.15: Electricity consumption of the Devold building in 2024.

Month	Meter 1 [kWh]	Meter 2 [kWh]	Total [kWh]
January	593	-	593
February	556	-	556
March	595	-	595
April	575	-	575
May	594	-	594
June	576	1,190	1,766
July	1,019	1,663	2,682
August	718	1,919	2,637
September	575	1,341	1,916
October	589	3,041	3,630
November	571	3,122	3,693
December	588	5,404	5,992
Total 2024	**7,549**	**17,680**	**25,229**

Table B.16: Electricity consumption of the Devold building in 2025.

Month	Meter 1 [kWh]	Meter 2 [kWh]	Total [kWh]
January	581	11,502	12,083
February	520	14,416	14,936
March	575	15,167	15,742
April	561	11,816	12,377
May	580	8,126	8,706
June	564	4,259	4,823
July	593	2,502	3,095
August	371	3,221	3,592
September	-	-	-
October	-	-	-
November	-	-	-
December	-	-	-
Total 2025	**4,345**	**71,009**	**75,354**

The second electricity meter was under external management until May 2024. Therefore, data on the electricity consumption of this month and the months before is missing. In addition, a heat pump was installed in the building and connected to the second electricity meter in January 2025, which explains the sudden jump in electricity consumption. The missing data and the introduction of the heat pump make it difficult to directly calculate the annual operational energy use, which is why additional information is needed.

As the heat pump is in place to regulate the temperature in the building, the electricity consumption of the heat pump will be affected mainly by the change in outside temperature, where more extreme changes in outside temperature will result in a higher electricity consumption. In addition, a heat pump uses more energy when it is heating a building compared to when it is cooling a building (Raleigh Heating Home Services, n.d.). This can also be seen in the data provided by SUAS.

Data from the weather station at Ålesund Airport shows that the average temperature in the area is at its lowest from December to March, which matches the relatively high electricity consumption measured by meter 2 from January to March (Cedar Lake Ventures, n.d.). The same data shows that the average temperature is at its highest from June to September, which matches the relatively low electricity consumption measured by meter 2 from June to August.

Rough estimates of the electricity consumption for the months without data are based on the average outside temperatures throughout the year. The average temperatures of September and June are the same, therefore, it is estimated that the electricity consumption in these months is also the same. If there is not a month that perfectly matches with another month regarding the average temperature, then the electricity of the month with the closest average temperature is used. Table B.17 shows an overview of the monthly average temperature, the electricity consumption of the Devold building, and the estimates for the September, October, November, and December.

Table B.17: Updated electricity consumption of the Devold building in 2025.

Month	Average temperature [°C]	Total electricity consumption [kWh]
January	2.22	12,083
February	2.22	14,936
March	3.33	15,742
April	5.56	12,377
May	8.89	8,706
June	11.67	4,823
July	13.89	3,095
August	13.89	3,592
September	11.67	4,259
October	8.33	8,126
November	5	11,816
December	3.33	15,167
Total 2025	**-**	**114,722**

This brings the estimated annual electricity consumption of the Devold building to 114,722 kWh. The average environmental impact of 1 kWh in Norway is equal to 20 g CO_2 eq (Nowtricity, n.d.). Thus, the electricity consumption results in an environmental impact of 2,294 kg CO_2 eq. per year.

Adjustments for the reuse scenario
The environmental impact of modules A1-A5 for all construction elements is equal to 0, as the building is being reused. The environmental impact of module B2 for the reinforced concrete construction elements is equal to 0, as maintenance of these elements is not considered in this study. The environmental impact of module B3 for the reinforced concrete construction elements depends on the amount of patch repair required. This study assumes that most do not require any patch repair, therefore, the environmental impact of module B3 for these construction elements is equal to 0. A separate EPD was used for the production and application of patch repair for the floor, roof, and walls, which do require patch repair (Saint-Gobain, 2022). The environmental impact of module B3 of these construction elements is equal to the sum of the environmental impact of modules A1-A5 of the patch repair EPD multiplied by the area of the element that requires patch repair. This value is also multiplied by the degree of patch repair, a variable that is added to account for the uncertainty of not knowing where and when patch repair will be required. The environmental impact of modules B2 and B3 for the garage doors and the insulation was derived from the respective EPD. The value for the garage doors was multiplied by 1.2 to scale the value from 50 to 60 years. The environmental impact of module B4 for all construction elements (except the foundation) is equal to the sum of the environmental impact of modules A1-A5, C1-C4 and D, as the original element has to be removed first (hence C1-C4 and D) before being replaced by a new element (hence A1-A5). This value is also multiplied by the degree of replacement, a variable that is added to account for the uncertainty of not knowing where and when a construction element will have to be replaced. The environmental impact of module B4 for the foundation is equal to 0, as the construction element is not replaced during the reference study period.

If the Devold building is demolished within the reference study period, then the environmental impact of the modules from stage C will be allocated to the respective modules. However, if the Devold building is demolished outside of the reference study period, then the environmental impact of the modules from stage C will be allocated to module D. This is similar to the calculations that were performed earlier to account for this process in the demolition and new construction scenario.

The recalculation of module D also applies to the reuse scenario, but in the reuse scenario it is uncertain in which year the construction elements are replaced or if they are replaced at all. However, the subtraction of stage A and addition of stage C are done in a similar way. For stage A, the time between the end of the reference study period and the year in which the Devold building is demolished is determined and stage A is scaled accordingly. For stage C, the time between the placement of the construction element and the end of the reference study period is determined and stage C is scaled accordingly.

Addition of insulation and cover floor layers
According to the Norconsult report, the floor of the Devold building will have to be improved to allow long-term reuse (Norconsult, 2023). However, there is no detailed information on the composition of the additional floor layers, only that their combined thickness is approximately 35-45 cm and that at least an insulation layer and cover layer are added. Therefore, estimates on the dimensions of these additional floor layers were made. The total thickness of the combined floor layers is estimated to be 40 cm, with a 15 cm thick insulation layer (Kerr, 2024) and a 25 cm thick cover layer. For the area of the additional floor layers, the GFA is used, which is equal to 1,273.98 m². Two new EPDs were used for the addition of these floor layers to the LCAs (BEWI ASA, Insulation and Construction, 2024)(Lister Ferdigbetong AS, 2025).

The EPD of the cover layer does not contain environmental data for module B5. However, Figure B.2 and Figure B.3 show that the contribution of this module to the total environmental impact is very low. Therefore, this study assumes that the exclusion of this module for this element will not significantly alter the results of the assessments.

Modules A4 and C2 of the insulation layer have undergone similar adjustments as the insulation panels. These adjustments were discussed in Subsection B.6.1.

B.7.3. Updated results demolition and new construction scenario
Table B.18 and Table B.19 show the results of the Norwegian LCA for the demolition of the Devold building using the functional unit of 1 m² GFA over a reference study period of 60 years with and without monetization, respectively.

Table B.18: Updated monetized results, in Norwegian Kroner (NOK), of the Norwegian LCA for the demolition of the Devold building.

Element	C1	C2	C3	C4	D	Total
Columns	0.52	0.84	0.04	1.40	-0.15	2.66
Floor	0.50	0.90	0.02	1.43	-3.08	-0.22
Foundation	0.00	0.00	0.00	0.00	-0.03	-0.03
Roof	3.84	6.82	0.17	10.92	-23.44	-1.69
Stairs	0.01	0.01	0.00	0.01	-0.01	0.01
Walls	0.87	1.55	0.05	2.62	-1.24	3.85
Garage doors	0.00	0.00	0.60	0.00	-3.91	-3.30
Insulation	0.00	0.65	8.49	0.09	-0.38	8.84
Operational energy (B6)	0.00	0.00	0.00	0.00	0.00	0.00
Total	**5.74**	**10.76**	**9.37**	**16.47**	**-32.20**	**10.15**

Table B.19: Updated results, in kg CO_2, of the Norwegian LCA for the demolition of the Devold building without monetization.

Element	C1	C2	C3	C4	D	Total
Columns	0.38	0.62	0.03	1.03	-0.11	1.96
Floor	0.37	0.66	0.02	1.06	-2.28	-0.16
Foundation	0.00	0.00	0.00	0.00	-0.02	-0.02
Roof	2.84	5.04	0.13	8.07	-17.33	-1.25
Stairs	0.00	0.01	0.00	0.01	-0.01	0.01
Walls	0.64	1.14	0.04	1.94	-0.91	2.85
Garage doors	0.00	0.00	0.44	0.00	-2.89	-2.44
Insulation	0.00	0.48	6.27	0.06	-0.28	6.53
Operational energy (B6)	0.00	0.00	0.00	0.00	0.00	0.00
Total	**4.24**	**7.96**	**6.93**	**12.18**	**-23.81**	**7.50**

Table B.20 and Table B.21 show the results of the Norwegian LCA for the construction of the new building(s) using the functional unit of 1 m² GFA over a reference study period of 60 years with monetization. Table B.22 and Table B.23 show the results without monetization.

Table B.20: Updated monetized results, in Norwegian Kroner (NOK), for modules A1-A5 and B1-B5 of the Norwegian LCA for the construction of the new building(s).

Element	A1-A3	A4	A5	B1	B2	B3	B4	B5
Columns	27.63	8.89	0.29	N/A	0.00	0.00	36.81	N/A
Floor	16.55	14.13	0.51	N/A	0.00	0.00	31.19	N/A
Foundation	0.00	0.00	0.00	N/A	0.00	0.00	0.00	N/A
Roof	125.98	107.50	3.88	N/A	0.00	0.00	237.37	N/A
Stairs	0.24	0.04	0.00	N/A	0.00	0.00	0.27	N/A
Walls	32.66	22.78	1.64	N/A	0.00	0.00	57.08	N/A
Garage doors	5.44	0.17	0.95	N/A	0.03	2.08	6.56	N/A
Insulation	0.13	5.48	1.15	N/A	0.00	0.00	-	N/A
Operational energy (B6)	0.00	0.00	0.00	N/A	0.00	0.00	0.00	N/A
Total	**208.64**	**158.98**	**8.42**	**N/A**	**0.03**	**2.08**	**369.28**	**N/A**

Table B.21: Updated monetized results, in Norwegian Kroner (NOK), for modules B6-B8, C1-C4 and D of the Norwegian LCA for the construction of the new building(s).

Element	B6	B7	B8	C1	C2	C3	C4	D	Total
Columns	-	N/A	N/A	0.52	0.84	0.04	1.40	-29.31	47.12
Floor	-	N/A	N/A	0.50	0.90	0.02	1.43	-27.74	37.49
Foundation	-	N/A	N/A	0.00	0.00	0.00	0.00	-0.04	-0.04
Roof	-	N/A	N/A	3.84	6.82	0.17	10.92	-211.14	285.35
Stairs	-	N/A	N/A	0.01	0.01	0.00	0.01	-0.23	0.35
Walls	-	N/A	N/A	0.87	1.55	0.05	2.62	-46.40	72.84
Garage doors	0.00	N/A	N/A	0.00	0.00	0.60	0.00	-9.04	6.80
Insulation	-	N/A	N/A	0.00	0.65	8.49	0.09	-0.38	15.60
Operational energy (B6)	146.16	N/A	N/A	0.00	0.00	0.00	0.00	0.00	146.16
Total	**146.16**	**N/A**	**N/A**	**5.74**	**10.76**	**9.37**	**16.47**	**-324.28**	**611.66**

Table B.22: Updated results, in kg CO_2, for modules A1-A5 and B1-B5 of the Norwegian LCA for the construction of the new building(s) without monetization.

Element	A1-A3	A4	A5	B1	B2	B3	B4	B5
Columns	20.43	6.58	0.21	N/A	0.00	0.00	27.22	N/A
Floor	12.24	10.44	0.38	N/A	0.00	0.00	23.06	N/A
Foundation	0.00	0.00	0.00	N/A	0.00	0.00	0.00	N/A
Roof	93.14	79.48	2.87	N/A	0.00	0.00	175.50	N/A
Stairs	0.17	0.03	0.00	N/A	0.00	0.00	0.20	N/A
Walls	24.14	16.84	1.21	N/A	0.00	0.00	42.20	N/A
Garage doors	4.02	0.13	0.70	N/A	0.02	1.53	4.85	N/A
Insulation	0.10	4.05	0.85	N/A	0.00	0.00	0.00	N/A
Operational energy (B6)	0.00	0.00	0.00	N/A	0.00	0.00	0.00	N/A
Total	**154.26**	**117.54**	**6.23**	**N/A**	**0.02**	**1.53**	**273.02**	**N/A**

Table B.23: Updated results, in kg CO_2, for modules B6-B8, C1-C4 and D of the Norwegian LCA for the construction of the new building(s) without monetization.

Element	B6	B7	B8	C1	C2	C3	C4	D	Total
Columns	0.00	N/A	N/A	0.38	0.62	0.03	1.03	-21.67	34.84
Floor	0.00	N/A	N/A	0.37	0.66	0.02	1.06	-20.51	27.72
Foundation	0.00	N/A	N/A	0.00	0.00	0.00	0.00	-0.03	-0.03
Roof	0.00	N/A	N/A	2.84	5.04	0.13	8.07	-156.10	210.97
Stairs	0.00	N/A	N/A	0.00	0.01	0.00	0.01	-0.17	0.26
Walls	0.00	N/A	N/A	0.64	1.14	0.04	1.94	-34.30	53.86
Garage doors	0.00	N/A	N/A	0.00	0.00	0.44	0.00	-6.68	5.02
Insulation	0.00	N/A	N/A	0.00	0.48	6.27	0.06	-0.28	11.53
Operational energy (B6)	108.06	N/A	N/A	0.00	0.00	0.00	0.00	0.00	108.06
Total	**108.06**	**N/A**	**N/A**	**4.24**	**7.96**	**6.93**	**12.18**	**-239.76**	**452.22**

Combining the environmental impact of the demolition of the Devold building and the construction of the new building(s) results in a total environmental impact of NOK 621.80 per m² GFA over a reference study period of 60 years or 460 kg CO_2 per m² GFA over a reference study period of 60 years.

The updated contribution of each module for the Norwegian LCA can be seen in Figure B.4.

Figure B.4: Updated contribution of each life cycle stage to the total environmental impact for the Norwegian LCA.

Table B.18 shows the results of the European LCA for the demolition of the Devold building using the functional unit of 1 m² GFA over a reference study period of 60 years with monetization.

Table B.24: Updated monetized results, in Norwegian Kroner (NOK), of the European LCA for the demolition of the Devold building.

Element	C1	C2	C3	C4	D	Total
Columns	1.09	2.13	0.10	2.02	-0.34	5.00
Floor	1.27	2.26	0.06	2.07	-5.94	-0.27
Foundation	0.00	0.00	0.00	0.00	-0.05	-0.05
Roof	9.68	17.19	0.45	15.79	-45.20	-2.08
Stairs	0.01	0.01	0.00	0.01	-0.01	0.02
Walls	2.39	4.25	0.16	3.79	-2.25	8.35
Garage doors	0.00	0.05	5.79	0.13	-124.38	-118.41
Insulation	0.02	1.23	8.64	0.29	-10.50	-0.33
Operational energy (B6)	0.00	0.00	0.00	0.00	0.00	0.00
Total	**14.46**	**27.12**	**15.21**	**24.10**	**-188.62**	**-107.73**

Table B.25 and Table B.26 show the results of the European LCA for the construction of the new building(s) using the functional unit of 1 m² GFA over a reference study period of 60 years with monetization.

Table B.25: Updated monetized results, in Norwegian Kroner (NOK), for modules A1-A5 and B1-B5 of the European LCA for the construction of the new building(s).

Element	A1-A3	A4	A5	B1	B2	B3	B4	B5
Columns	87.36	46.46	0.57	N/A	0.00	0.00	134.38	N/A
Floor	117.83	35.58	1.29	N/A	0.00	0.00	154.70	N/A
Foundation	0.00	0.00	0.00	N/A	0.00	0.00	0.00	N/A
Roof	896.76	270.80	9.82	N/A	0.00	0.00	1,177.38	N/A
Stairs	0.27	0.23	0.00	N/A	0.00	0.00	0.50	N/A
Walls	286.67	61.74	3.83	N/A	0.00	0.00	352.24	N/A
Garage doors	210.26	6.12	6.83	N/A	3.55	86.24	223.21	N/A
Insulation	48.82	9.27	3.64	N/A	0.00	0.00	0.00	N/A
Operational energy (B6)	0.00	0.00	0.00	N/A	0.00	0.00	0.00	N/A
Total	**1,647.98**	**430.19**	**25.97**	**N/A**	**3.55**	**86.24**	**2,042.42**	**N/A**

Table B.26: Updated monetized results, in Norwegian Kroner (NOK), for modules B6-B8, C1-C4 and D of the European LCA for the construction of the new building(s).

Element	B6	B7	B8	C1	C2	C3	C4	D	Total
Columns	0.00	N/A	N/A	1.09	2.13	0.10	2.02	-107.17	166.93
Floor	0.00	N/A	N/A	1.27	2.26	0.06	2.07	-128.97	186.09
Foundation	0.00	N/A	N/A	0.00	0.00	0.00	0.00	-0.05	-0.05
Roof	0.00	N/A	N/A	9.68	17.19	0.45	15.79	-981.57	1,416.30
Stairs	0.00	N/A	N/A	0.01	0.01	0.00	0.01	-0.41	0.63
Walls	0.00	N/A	N/A	2.39	4.25	0.16	3.79	-282.66	432.42
Garage doors	0.00	N/A	N/A	0.00	0.05	5.79	0.13	-301.76	240.43
Insulation	0.00	N/A	N/A	0.02	1.23	8.64	0.29	-10.50	61.40
Operational energy (B6)	146.16	N/A	N/A	0.00	0.00	0.00	0.00	0.00	146.16
Total	**146.16**	**N/A**	**N/A**	**14.46**	**27.12**	**15.21**	**24.10**	**-1,813.09**	**2,650.31**

Combining the environmental impact of the demolition of the Devold building and the construction of the new building(s) results in a total environmental impact of NOK 2,542.58 per m² GFA over a reference study period of 60 years.

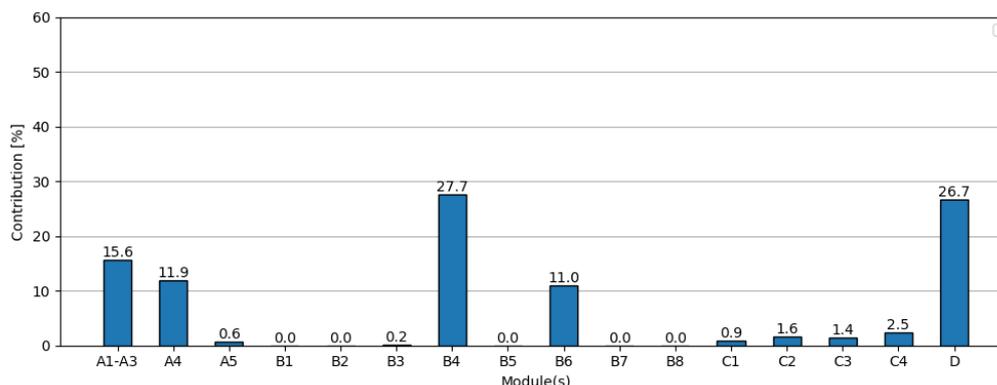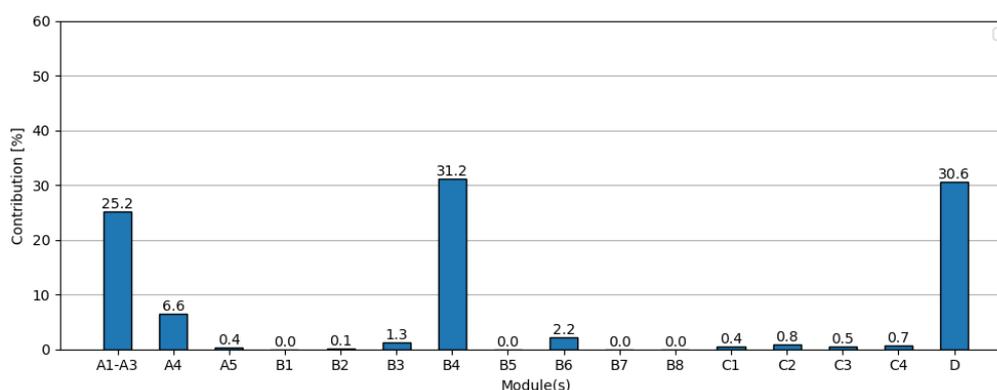The updated contribution of each module for the European LCA can be seen in Figure B.5.

Figure B.5: Updated contribution of each life cycle stage to the total environmental impact for the European LCA.

B.7.4. Interpretation of updated results demolition and new construction scenario

This section will only discuss the results of Subsection B.7.3. Interpretations of further calculations and a general discussion will be discussed later in the appendix.

The updated results of the demolition and new construction scenario can mostly be interpreted in the same way as the original results. This was to be expected, as only minor changes were made. The biggest difference is in the contribution of the different modules to the environmental impact. Module B4 is now the biggest contributor instead of module A1-A3. This is due to the fact that module B4 encompasses modules A1-A5 of the new construction elements that are produced and installed in year 50 of the reference study period. So in essence, the reason as to why this module is the biggest contributor is still the same as before, as the production and placement of construction elements comes paired with a high environmental impact. Another difference is that module B6 delivers a significant contribution to the environmental impact of the building. Thus, the way in which the building is used has a big influence on the environmental impact of the building due to a change in operational energy use. Module B6 delivers a less significant contribution to the total environmental impact for the European LCA, because only data on the GHG emissions of energy use in Norway was found.

B.7.5. Results reuse scenario

The following results assume a degree of patch repair of 10%, a degree of replacement of 10% and replacement in year 10 of the reference study period. Table B.27 and Table B.28 show the results of

the Norwegian LCA for the reuse of the Devold building using the functional unit of 1 m² GFA over a reference study period of 60 years with monetization. Table B.29 and Table B.30 show the results without monetization.

Table B.27: Monetized results, in Norwegian Kroner (NOK), for modules A1-A5 and B1-B5 of the Norwegian LCA for the reuse of the Devold.

Element	A1-A3	A4	A5	B1	B2	B3	B4	B5
Columns	0.00	0.00	0.00	0.00	0.00	0.00	3.80	0.00
Floor	0.00	0.00	0.00	0.00	0.00	0.01	2.75	0.00
Foundation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Roof	0.00	0.00	0.00	0.00	0.00	0.00	20.91	0.00
Stairs	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00
Walls	0.00	0.00	0.00	0.00	0.00	0.01	5.75	0.00
Garage doors	0.00	0.00	0.00	0.00	0.03	2.08	0.33	0.00
Insulation	0.00	0.00	0.00	0.00	0.00	0.00	1.56	0.00
Insulation layer floor	7.70	0.55	0.03	0.00	0.00	0.00	0.00	0.00
Cover layer floor	71.38	121.90	0.00	0.00	0.00	0.00	0.00	0.00
Operational energy (B6)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	**79.09**	**122.45**	**0.03**	**0.00**	**0.03**	**2.10**	**35.12**	**0.00**

Table B.28: Monetized results, in Norwegian Kroner (NOK), for modules B6-B8, C1-C4 and D of the Norwegian LCA for the reuse of the Devold.

Element	B6	B7	B8	C1	C2	C3	C4	D	Total
Columns	0.00	0.00	0.00	0.52	0.84	0.04	1.40	-0.15	6.46
Floor	0.00	0.00	0.00	0.50	0.90	0.02	1.43	-3.08	2.54
Foundation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.03	-0.03
Roof	0.00	0.00	0.00	3.84	6.82	0.17	10.92	-23.44	19.23
Stairs	0.00	0.00	0.00	0.01	0.01	0.00	0.01	-0.01	0.04
Walls	0.00	0.00	0.00	0.87	1.55	0.05	2.62	-1.24	9.61
Garage doors	0.00	0.00	0.00	0.00	0.00	0.60	0.00	-3.91	-0.87
Insulation	0.00	0.00	0.00	0.00	0.65	8.49	0.09	-0.38	10.40
Insulation layer floor	0.00	0.00	0.00	0.00	0.13	14.47	0.00	16.30	39.18
Cover layer floor	0.00	0.00	0.00	3.14	4.70	0.23	4.03	-0.75	204.64
Operational energy (B6)	146.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	146.16
Total	**146.16**	**0.00**	**0.00**	**8.87**	**15.59**	**24.08**	**20.51**	**-16.67**	**437.36**

Table B.29: Results, in kg CO_2, for modules A1-A5 and B1-B5 of the Norwegian LCA for the reuse of the Devold.

Element	A1-A3	A4	A5	B1	B2	B3	B4	B5
Columns	0.00	0.00	0.00	0.00	0.00	0.00	2.81	0.00
Floor	0.00	0.00	0.00	0.00	0.00	0.00	2.03	0.00
Foundation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Roof	0.00	0.00	0.00	0.00	0.00	0.00	15.46	0.00
Stairs	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00
Walls	0.00	0.00	0.00	0.00	0.00	0.00	4.25	0.00
Garage doors	0.00	0.00	0.00	0.00	0.02	1.53	0.24	0.00
Insulation	0.00	0.00	0.00	0.00	0.00	0.00	1.15	0.00
Insulation layer floor	5.69	0.41	0.02	0.00	0.00	0.00	0.00	0.00
Cover layer floor	52.78	90.13	0.00	0.00	0.00	0.00	0.00	0.00
Operational energy (B6)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	**58.47**	**90.53**	**0.02**	**0.00**	**0.02**	**1.54**	**25.97**	**0.00**

Table B.30: Results, in kg CO_2, for modules B6-B8, C1-C4 and D of the Norwegian LCA for the reuse of the Devold.

Element	B6	B7	B8	C1	C2	C3	C4	D	Total
Columns	0.00	0.00	0.00	0.38	0.62	0.03	1.03	-0.11	4.77
Floor	0.00	0.00	0.00	0.37	0.66	0.02	1.06	-2.28	1.87
Foundation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.02	-0.02
Roof	0.00	0.00	0.00	2.84	5.04	0.13	8.07	-17.33	14.22
Stairs	0.00	0.00	0.00	0.00	0.01	0.00	0.01	-0.01	0.03
Walls	0.00	0.00	0.00	0.64	1.14	0.04	1.94	-0.91	7.10
Garage doors	0.00	0.00	0.00	0.00	0.00	0.44	0.00	-2.89	-0.65
Insulation	0.00	0.00	0.00	0.00	0.48	6.27	0.06	-0.28	7.69
Insulation layer floor	0.00	0.00	0.00	0.00	0.09	10.70	0.00	12.05	28.97
Cover layer floor	0.00	0.00	0.00	2.32	3.48	0.17	2.98	-0.55	151.30
Operational energy (B6)	108.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	108.06
Total	**108.06**	**0.00**	**0.00**	**6.56**	**11.53**	**17.80**	**15.16**	**-12.33**	**323.34**

The reuse of the Devold building results in a total environmental impact of NOK 437.36 per m² GFA over a reference study period of 60 years or 323 kg CO_2 per m² GFA over a reference study period of 60 years.

The contribution of each module in the reuse scenario for the Norwegian LCA can be seen in Figure B.6.
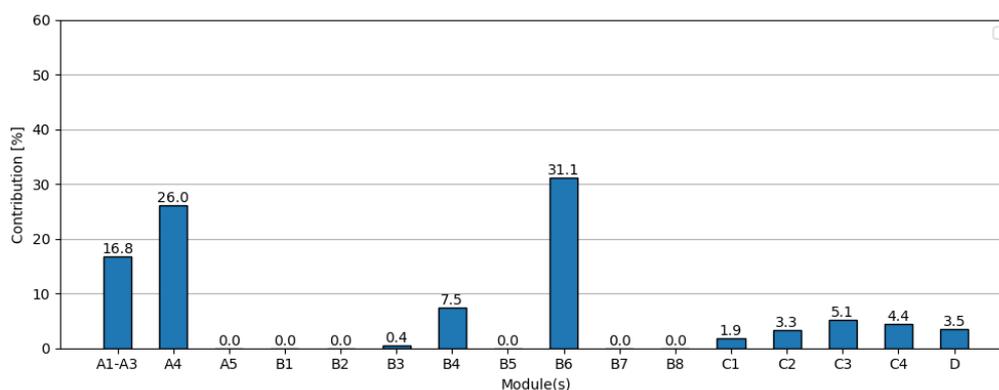
Figure B.6: Contribution of each life cycle stage in the reuse scenario to the total environmental impact for the Norwegian LCA.

Table B.31 and Table B.32 show the results of the European LCA for the reuse of the Devold building using the functional unit of 1 m² GFA over a reference study period of 60 years with monetization.

Table B.31: Monetized results, in Norwegian Kroner (NOK), for modules A1-A5 and B1-B5 of the European LCA for the reuse of the Devold.

Element	A1-A3	A4	A5	B1	B2	B3	B4	B5
Columns	0.00	0.00	0.00	N/A	0.00	0.00	13.72	N/A
Floor	0.00	0.00	0.00	N/A	0.00	0.00	14.84	N/A
Foundation	0.00	0.00	0.00	N/A	0.00	0.00	0.00	N/A
Roof	0.00	0.00	0.00	N/A	0.00	0.00	112.94	N/A
Stairs	0.00	0.00	0.00	N/A	0.00	0.00	0.05	N/A
Walls	0.00	0.00	0.00	N/A	0.00	0.00	35.54	N/A
Garage doors	0.00	0.00	0.00	N/A	3.55	86.24	10.48	N/A
Insulation	0.00	0.00	0.00	N/A	0.00	0.00	6.14	N/A
Insulation layer floor	17.69	0.96	0.05	N/A	0.00	0.00	0.00	N/A
Cover layer floor	182.97	213.26	0.00	N/A	0.00	0.00	0.00	N/A
Operational energy (B6)	0.00	0.00	0.00	N/A	0.00	0.00	0.00	N/A
Total	**200.66**	**214.22**	**0.05**	**N/A**	**3.55**	**86.25**	**193.71**	**N/A**

Table B.32: Monetized results, in Norwegian Kroner (NOK), for modules B6-B8, C1-C4 and D of the European LCA for the reuse of the Devold.

Element	B6	B7	B8	C1	C2	C3	C4	D	Total
Columns	0.00	N/A	N/A	1.09	2.13	0.10	7.02	-0.34	23.71
Floor	0.00	N/A	N/A	1.27	2.26	0.06	7.20	-5.94	19.70
Foundation	0.00	N/A	N/A	0.00	0.00	0.00	0.00	-0.05	-0.05
Roof	0.00	N/A	N/A	9.68	17.19	0.45	54.82	-45.20	149.90
Stairs	0.00	N/A	N/A	0.01	0.01	0.00	0.04	-0.01	0.10
Walls	0.00	N/A	N/A	2.39	4.25	0.16	13.17	-2.25	53.27
Garage doors	0.00	N/A	N/A	0.00	0.05	5.79	0.13	-74.38	31.86
Insulation	0.00	N/A	N/A	0.02	1.23	8.64	0.29	-6.28	10.03
Insulation layer floor	0.00	N/A	N/A	0.00	0.21	14.64	0.00	0.30	33.86
Cover layer floor	0.00	N/A	N/A	5.12	7.88	34.18	5.83	-26.25	422.99
Operational energy (B6)	146.16	N/A	N/A	0.00	0.00	0.00	0.00	0.00	146.16
Total	**146.16**	**N/A**	**N/A**	**19.59**	**35.21**	**64.03**	**88.50**	**-160.39**	**891.53**

The reuse of the Devold building results in a total environmental impact of NOK 891.53 per m² GFA over a reference study period of 60 years.

The contribution of each module in the reuse scenario for the European LCA can be seen in Figure B.7.
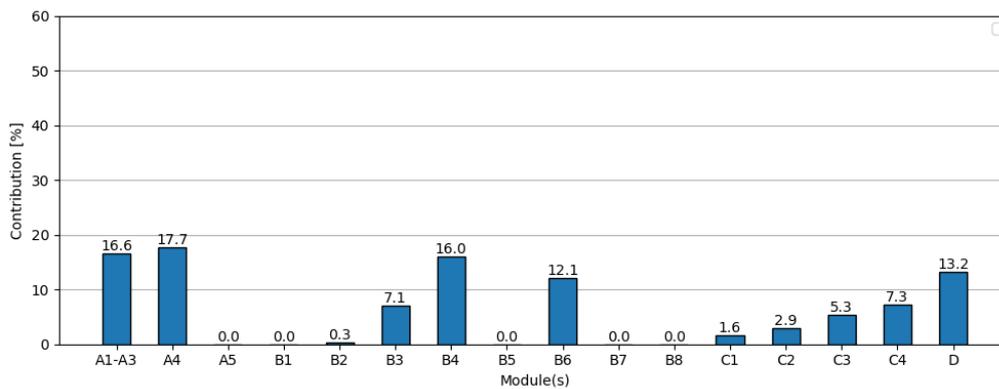
Figure B.7: Contribution of each life cycle stage in the reuse scenario to the total environmental impact for the European LCA.

B.7.6. Comparison

Figure B.8 shows the environmental impact, expressed in NOK per m² GFA over a reference study period of 60 years, for the Norwegian LCA of the reuse scenario for different degrees of patch repair in blue, as well as the environmental impact of the demolition and new construction scenario in red. Figure B.9 shows the same, but for the European LCA.

Figure B.8: Environmental impact of the Devold building for varying degrees of patch repair for the Norwegian LCA.
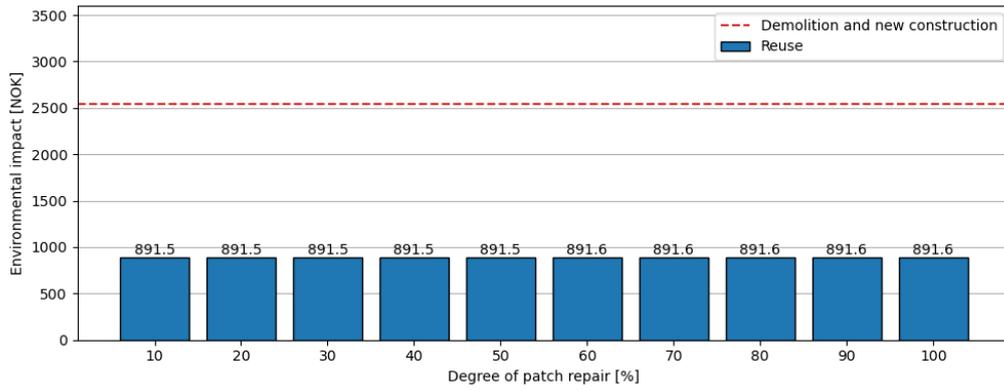
Figure B.9: Environmental impact of the Devold building for varying degrees of patch repair for the European LCA.

Figure B.10 shows the environmental impact, expressed in NOK per m² GFA over a reference study period of 60 years, for the Norwegian LCA of the reuse scenario for different degrees of replacement in blue, as well as the environmental impact of the demolition and new construction scenario in red. Figure B.11 shows the same, but for the European LCA.

Figure B.10: Environmental impact of the Devold building for varying degrees of replacement for the Norwegian LCA.
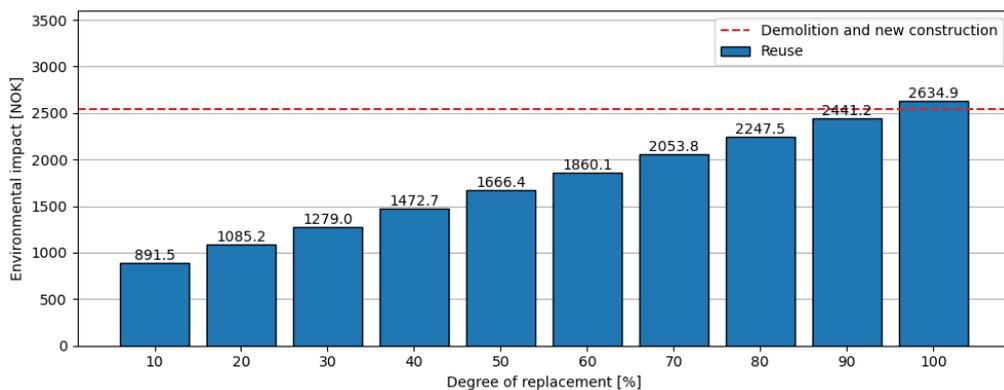
Figure B.11: Environmental impact of the Devold building for varying degrees of replacement for the European LCA.

Figure B.10 shows the environmental impact, expressed in NOK per m² GFA over a reference study period of 60 years, for the Norwegian LCA of the reuse scenario for different years in which the construction elements are replaced in blue, as well as the environmental impact of the demolition and new construction scenario in red. Figure B.11 shows the same, but for the European LCA.
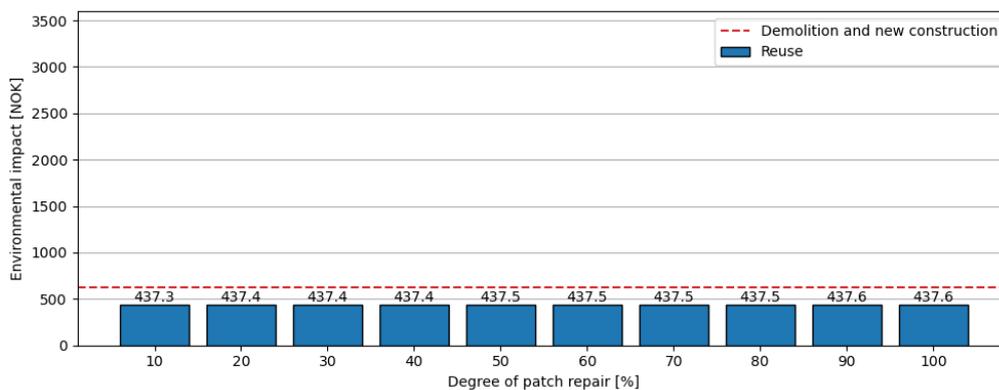
Figure B.12: Environmental impact of the Devold building for varying years in which the construction elements are replaced for the Norwegian LCA.
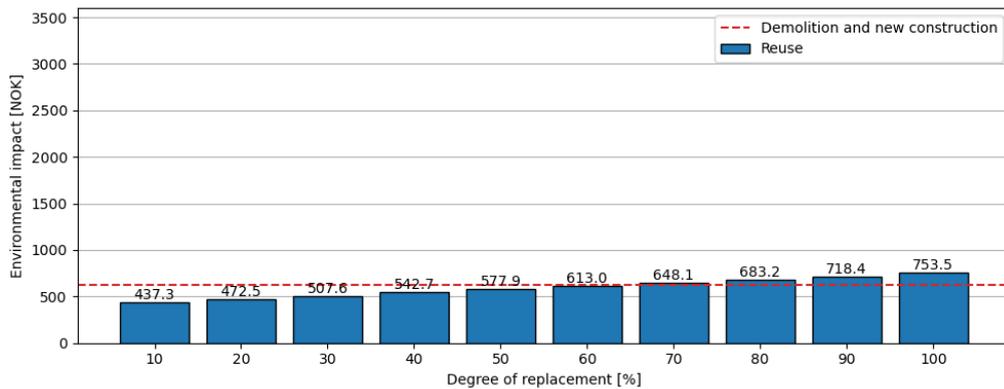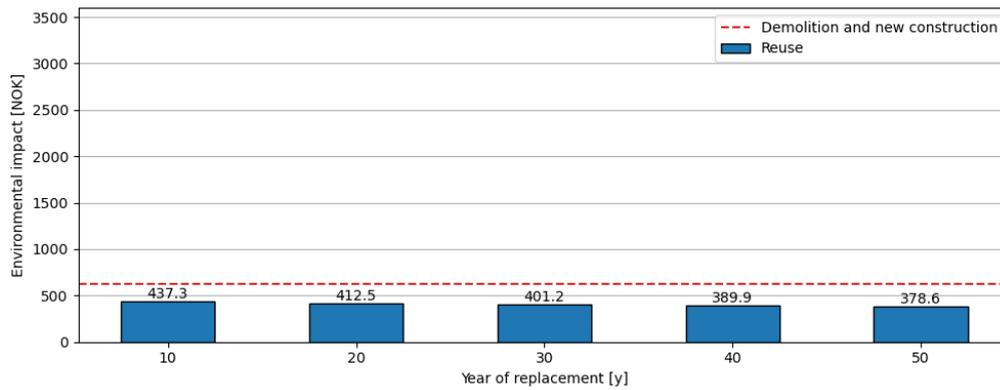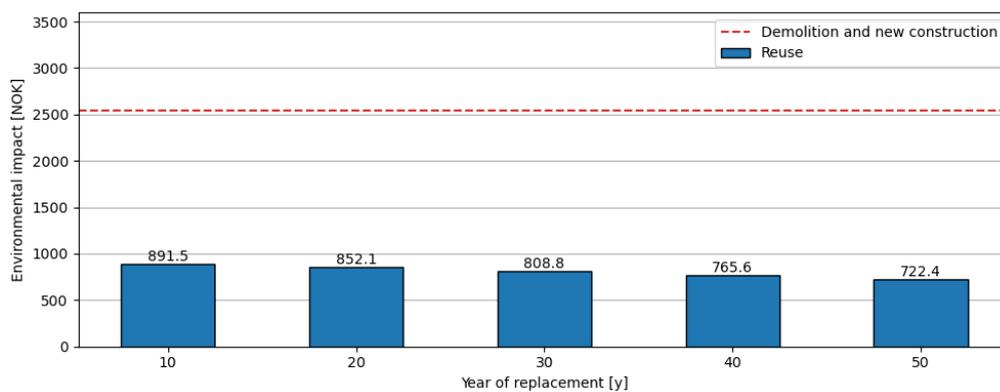

Figure B.13: Environmental impact of the Devold building for varying years in which the construction elements are replaced for the European LCA.

B.7.7. Interpretation of results reuse scenario and comparison

This section will only discuss the results of Subsection B.7.5 and Subsection B.7.6. Interpretations of further calculations are discussed earlier in the appendix. A general discussion can be found later in the appendix.

For the Norwegian LCA of the reuse scenario, it can be seen that the cover floor layer and operational energy (B6) are the biggest contributors to the environmental impact of the Devold building. The high contribution of the cover floor layer is likely due to the fact that this is a relatively large concrete element, which is a material that is known to have a significant environmental impact. The contribution of the operational energy use shows again that the function of the building and the corresponding energy use have a significant impact on the total environmental impact of the building. The garage doors have a negative environmental impact and thus an environmental benefit. This is likely due to the high recycling rates of the construction elements, as was seen in previous results.

The contribution of the different modules of the reuse scenario has seen some changes compared to the contributions of the demolition and new construction scenario. The results show that the operational energy use of the building delivers the biggest contribution to the total environmental impact. The second and third biggest contributions are delivered by modules A4 and A1-A3 respectively. This is different from what could be seen in pervious results. Now, the transport of the construction elements (A4) has a higher contribution than the production and instalment. This is likely because in this scenario it will not be necessary to produce a lot of new construction elements. However, the construction elements still have to be transported from the place where they are produced to the construction site. Due to the lower amount of construction elements, the trucks are likely less efficiently loaded, which causes a shift in the mutual relationship between the two modules.

Figure B.8 and Figure B.9 show that varying degrees of patch repair do not have a significant influence on the environmental impact in the reuse scenario. A higher degree of patch repair does result in a higher environmental impact by a little. For all degrees of patch repair, the environmental impact of the reuse scenario stays below that of the demolition and new construction scenario. Thus, patch repair is an environmentally sustainable method of repairing damage to a reinforced concrete building. The main difference between the Norwegian and European LCAs is the difference between the environmental impact of both scenarios. The difference for the European LCA is much bigger than the difference for the Norwegian LCA.

Figure B.10 and Figure B.11 show that the amount of construction elements that have to be replaced has a significant influence on the environmental impact. This was to be expected, as previous results have shown that the production and placement of new construction elements is one of the main contributors to the environmental impact. In addition, a 100% degree of replacement is, in essence, the same as the demolition and new construction scenario. However, the reuse scenario also includes two new elements (the insulation layer and the cover layer of the floor) and therefore exceeds the environmental impact of the demolition and new construction scenario for a degree of replacement of 100%. In addition, the difference between both scenarios is bigger for the European LCA than for the Norwegian LCA. This also results in the fact that for the Norwegian LCA, only about 60% of the construction elements can be replaced before the environmental impact of the reuse scenario exceeds the environmental impact of the demolition and new construction scenario, while a degree of replacement of about 90% is possible for the European LCA.

Figure B.12 and Figure B.13 show that the year in which the construction element are replaced does not have a significant influence on the environmental impact of the reuse scenario. The graphs do shows that the longer the original construction elements are preserved, the lower the total environmental impact will be, which can be seen by the decreasing trend in the graphs. For all considered years in which the construction elements could be replaced, the environmental impact of the reuse scenario stays below the one of the demolition and new construction scenario. Again the main difference between the Norwegian and European LCAs is the difference between the environmental impact of both scenarios. This difference is much bigger for the European LCA.

B.8. General Discussion

The previous chapters have already discussed the interpretation of the results. This section therefore focuses on the limitations of this study, as well as suggestions for future research.

The study includes various assumptions related to the data and the methodology. It is important to note that most of these assumptions affect both the demolition and new construction scenario and the reuse scenario in a similar way. In addition, while the absolute environmental impacts may vary, the comparison between the scenarios, which is the main focus of this study, remains valid.

The lack of accurate dimensional data has likely caused minor differences between measured and actual building dimensions. This is mainly due to measurement errors, as various dimensions had to be measured from the floor plans by hand. However, these errors are expected to be minor since the measurements were conducted with high precision. Also, because the same dimensions are used for all LCA calculations, it is not likely that this will have had a significant effect on the comparison of both scenarios. Some construction elements could not be identified in the floor plans and were thus unintentionally excluded from the LCAs Including these construction elements in the LCAs would result in a slight increase of the total environmental impact. However, as this applies to both scenarios, this is not expected to have a significant influence on the results of the comparison.

It is very unlikely that the new building(s) will have the same dimensions and materials as the Devold building. Using fewer construction elements will reduce the environmental impact, while the use of more construction elements will increase the environmental impact. Similarly, using more environmentally sustainable construction materials will reduce the environmental impact, while the use of less environmentally sustainable construction materials will increase the environmental impact. The assessments also assume that the Devold building was constructed with precast reinforced concrete elements. If the building consists of in-situ elements, then all LCA calculations would need to be done again using appropriate EPDs. However, as this applies to both scenarios, this is not expected to have a significant

influence on the results of the comparison. Also, if the density of the elements deviates from the ones that have been used in this study, then the quantities of the construction elements of the Devold building will be different. Again, while this may alter absolute values, it does not affect the relative comparison.

The future use of the Devold building is uncertain. The study assumes that it will retain its current function as skate hall and event space. However, if the function were to change, for example to a concert hall, additional facilities and equipment would be needed. This would lead to an increase of the total environmental impact of the Devold building. Again, this applies to both scenarios, and is therefore not expected to result in a different comparison of the LCAs. A change in use could also result in a different load on the foundation. If it turns out that these loads are higher than before, then it might be necessary to install additional reinforcement for the foundation. This would increase the total environmental impact of the Devold building but is unlikely to change the relative comparison between scenarios.

The use of EPDs from neighbouring countries has likely resulted in a higher environmental impact than the actual impact of the Devold building. This mainly applies to module A4, as the actual transport distances will be much shorter than the distances that are currently used in the study. Using EPDs from Norwegian producers will significantly lower the contribution of this module to the total environmental impact. This affects both scenarios equally, and therefore is not expected to result in a significant difference in the comparison of both scenarios. This will have a significant impact on the interpretation of the contribution of each module to the total environmental impact, as the contribution of module A4 will now be much lower and will likely no longer be one of the main contributors. Similarly, the construction elements of the Devold building are not identical to the construction elements described in the EPDs. This results in the fact that the environmental impact of this study will not be identical to the actual impact of the Devold building. Again, this affects both scenarios, and thus, will not result in a significant change to the comparison of the scenarios.

Currently, repairs are only included in the reuse scenario. Including similar repairs in the demolition and new construction scenario would likely reduce its environmental impact and could therefore lead to a different outcome of the comparison of both scenarios. If damage occurs to other construction elements, additional repairs may be necessary in the reuse scenario. However, this is considered unlikely, as these elements are not exposed to severe weather conditions or heavy loads. Furthermore, no signs of damage to other construction elements were found during Norconsult's inspection, indicating that future damage is unlikely.

it has been assumed that the operational energy use of the Devold building will remain constant over the reference study period. However, this is very unlikely and it is expected that this value will fluctuate throughout the years. As this module has a significant contribution to the total environmental impact of the Devold building, any change will lead to noticeably different results. Again, this would apply to both scenarios equally. Therefore, it is not expected that this will alter the comparison of both scenarios. It will significantly alter the interpretation of the contribution of the different modules to the total environmental impact, similarly to module A4.

All of these limitations and assumptions indicate that additional research is needed to create a more complete and accurate overview of the environmental impact of the Devold building. Relevant research includes the creation of a detailed overview of the construction elements of the Devold building to be able to compute a more accurate value for the environmental impact. It would also be good to get more information from the port authorities on their future plans for the quay construction, as this plays a big role in the future of Kulturhavna. Lastly, this study has shown that the production and placement of construction elements is the biggest contributor to the environmental impact of a building. Therefore, it would be valuable to investigate different repair and maintenance methods to try to reduce the environmental impact as much as possible.

B.9. Conclusion

The study concludes that reusing the Devold building results in a lower environmental impact than demolishing and constructing a new structure. The largest contribution to the environmental impact stems from the production and installation of construction elements (modules A1–A5). Therefore, this should be avoided as much as possible by finding ways to prolong the service life of the current construction

elements.

Although this study only examined patch repair, the results indicate that maintenance and repair contribute minimally to the total environmental impact, confirming that they are environmentally sustainable practices.

Lastly, comparing different LCA methodologies shows that a GHG-only assessment cannot fully capture a building's environmental impact and may lead to incorrect conclusions.

C

Redesign Steinvåg Bridge

To make the city of Ålesund future-proof, it is important that the traffic system and its structural components are able to meet its future needs. Since the city consists of islands, bridges play a crucial role in this system. One of these bridges, the Steinvåg bridge, is nearing the end of its service life and must thus be replaced. In this appendix, a preliminary design of the bridge is made.

C.1. Introduction

The Steinvåg bridge was opened 1953 on August 30th and connects the islands Aspøya and Hessa. It is 144.4 meters long, 9 meters wide and has a total height of 25 meters. It consists of a concrete arch and a bridge deck, which is 17 meters above the water level (Kartverket, 2025). It consists of two traffic lanes, one in each direction, and a narrow sidewalk is present on both sides of the road. Currently, the bridge is planned to be demolished for two reasons.

Firstly, the bridge is an uncomfortable crossing for pedestrians since the sidewalks are quite narrow. Furthermore, there is little to no room for cyclists to use the bridge. A possible solution for this problem could be hanging a sidewalk or cycling passage on the sides of the bridge, but studies have shown that the bridge design doesn't have sufficient capacity for such an addition (NRK, 2025).

The second reason why demolition is planned is the state of the bridge and its reinforcement. In 2017, studies have shown high concentrations of chloride in the concrete (Gundersen, 2017). Maintenance for the reinforcement was needed and performed around the time of these chloride measurements. This maintenance only extends the service life of the bridge by 20 years, so in 12 years, the bridge will reach its service life and needs to be demolished. Due to the presence of the chloride, the reuse of parts of the bridge might be difficult and costly. In Section 2.5 it is investigated whether parts might still be useful for new purposes or whether the bridge should be downcycled for less critical uses.

The realisation of the new connection must consider various boundaries and conditions. This Program of Requirements (PoR) lists these conditions in a structured manner, regarding structural, social and sustainable demands.

- The construction should connect both islands;
- There can be almost no disconnection (less than one week), should always be reachable for emergency services;
- The project has to be CO_2 neutral/low emissions;
- Connection should maintain sufficient vertical clearance, above and below the water surface;
- The design should be suitable for different modalities;
- The new service life should be at least 100 years;
- The new design should not have a negative impact on the skyline;
- All elements should be assessed for reuse;

- It should be designed within the regulations of Håndbøker Statens Vegvesen and NS-EN;
- The new connection should allow for future traffic intensity scenarios.

As can be seen in this list, the bridge will be designed for a service life of 100 years. The future traffic intensity for this period in time needs to be estimated. Based on estimations and calculations, it is expected that the current dimensions of the bridge are sufficient. Section 3.1 even shows that increasing the population with 5,000, will not result in a bottleneck on the bridge. It is thus sufficient to design a bridge with cycling lanes and a wider pedestrian crossing without adding an additional lane for car traffic.

The next step is the selection of a suitable bridge type. In principle, a wide range of materials could be used, but within the scope of this study the analysis is limited to concrete bridge solutions. Five design concepts were initially explored, of which four proved feasible once the required span was taken into account. An overview of these alternatives, including their advantages and limitations, is provided in Section 3.1.

The decision for the type of bridge that will be designed is based on conversations with authorities and preferences of local citizens. These conversations show that in Norway it is a common practice to replace a structure with a similar type. For this reason, an arch bridge has been chosen, more specifically a tied-arch bridge. The location of the bridge and its columns is shown in Figure C.1.

Figure C.1: Location bridge and columns.

The next step is to determine the global dimensions of the bridge. The span follows from the new placement of the bridge and its supporting columns and is set at 90 metres. The vertical clearance remains 17 metres, matching the existing situation. This is necessary to ensure that the same water traffic can still pass underneath and because the surrounding road infrastructure is already designed for this clearance. The overall width of the bridge is derived from its intended use and the requirements set by the Norwegian design codes.

The expected traffic volume remains below 6,000 vehicles per day, which classifies the road as type Hø1. This requires a minimum carriageway width of 7.5 metres, consisting of two 3-metre traffic lanes and a 0.75-metre hard shoulder on each side. The dimensions of the pedestrian and cycling facilities follow the existing plans for the island of Hessa. In these plans, the bicycle lanes are 1.5 metres wide, while the sidewalks measure 2 metres on one side of the road and 2.5 metres on the other, as shown in Figure C.2.
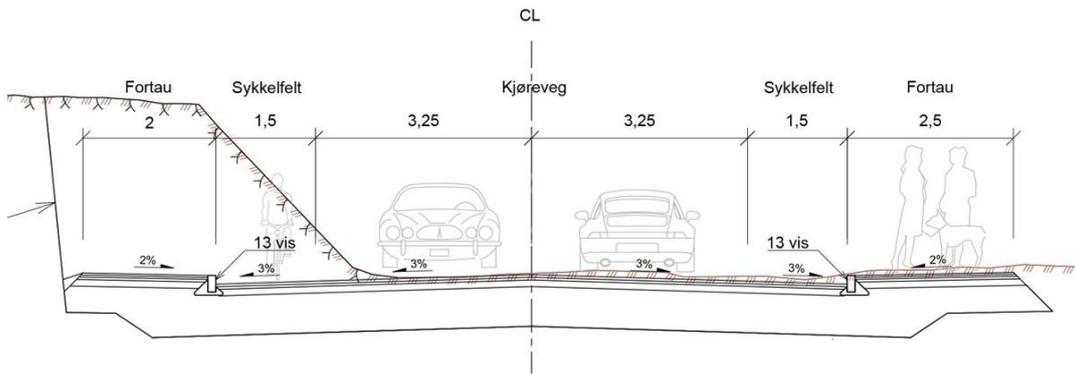
Figure C.2: Plans bicycle lane Hessa (Bypakke Ålesund, 2025e).
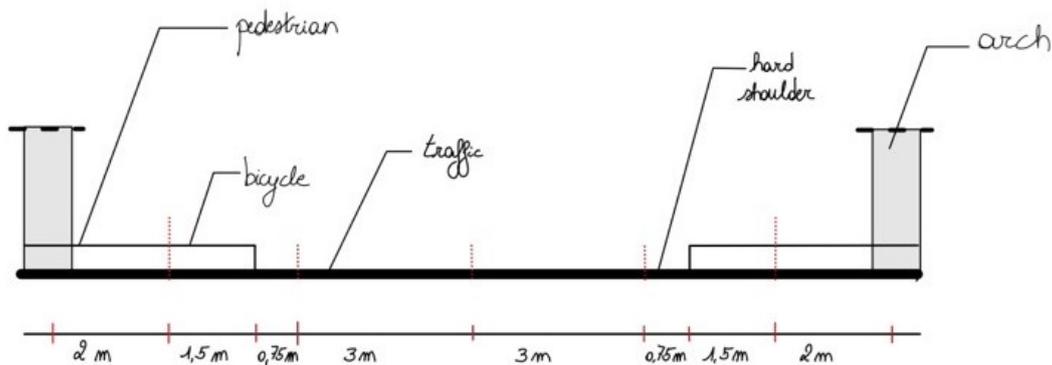
Figure C.3: Width of bridge.

The bicycle lanes on the bridge will match the ones of the plans, the sidewalks will be as wide as the smallest one from the plans. This brings the width of the bridge to 14.5 meters, excluding the width of the arch.

C.2. Loads

Now that the basic dimensions have been defined, the next step is to determine the loads acting on the structure. A distinction is made between permanent and variable loads:

- Permanent loads consist of the self-weight of the structural elements as well as superimposed dead loads, including the road surface, parapets and safety barriers;
- Variable loads include traffic loads, environmental effects (such as wind and temperature), and temporary loads during construction.

In addition, accidental loads should be considered, such as the potential impact of a vessel collision. However, this is out of the scope of this report.

Because these loads may occur under different conditions and with varying levels of uncertainty, partial safety factors and combination factors are applied. The governing expressions for the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) situations are given in Equation C.1 and C.2.

ULS:

$$E_d = \sum_{j \geq 1} \gamma_{G,j}\, G_{k,j} + \gamma_p\, P + \gamma_{Q,1}\, Q_{k,1} + \sum_{i>1} \gamma_{Q,i}\, \psi_{0,i}\, Q_{k,i} \tag{C.1}$$

SLS:

$$E_d = \sum_{j \geq 1} G_{k,j} + P + Q_{k,1} + \sum_{i > 1} \psi_{0,i}\, Q_{k,i} \tag{C.2}$$

These formulas take various γ and ψ factors as input, as well as the design loads. First the design loads are shown in Table C.1 with the derivation or explanation in the most right column. Note that these values are given for the forces that will be applied on one arch. All forces are multiplied by the relevant effective width. Only the non-self-evident loads will be elaborated below.

Table C.1: Characteristic Loads for Bridge Design.

Load	Value	Explanation
Permanent Loads [kN/m]		
Self-weight deck	57.02	See Subsection C.2.1
Self-weight arch	12.02	See Subsection C.2.1
Superimposed dead loads trafficlane	9.38	Statens Vegvesen, 2025a, § 5.2.2-2
Superimposed dead loads bicycle lane/sidewalk	9.00	Statens Vegvesen, 2025a, § 5.2.2-1
Variable Loads [kN/m]		
Traffic load LM1	27.45	Standards Norway, 2010, § 4.3.2
Tandem System LM1	2x 300 kN + 2x 200 kN	Standards Norway, 2010, § 4.3.2
Traffic load Norwegian standard	67.14	Statens Vegvesen, 2014, Most critical of loads
Traffic load Norwegian standard	24.00	Statens Vegvesen, 2014, Most critical of loads
Snow	23.25	Standards Norway, 2018
Construction work	19.38	Conservative load of 2.5 kN/m²

C.2.1. Permanent

The permanent load is calculated by multiplying the density by the effective volume. In this case this means $0.3 \cdot 7.75 \cdot 2,500 = 57.02$ kN/m.

C.2.2. Traffic

There are two different approaches that need to be tested. The first one is Load Model 1 (LM1) defined by the Eurocode. This places a uniformly distributed load on traffic lanes, with corresponding tandem systems. These TS's need to be placed in different positions throughout the system to identify the determining load combination for different elements. This procedure is shown in Figure C.4.

Figure C.4: Load Model 1 (Standards Norway, 2010).

The second approach is the load model defined by Statens Vegvesen, 2014. The load is also distributed over the bridgedeck area, with certain additional loading situations. These loading situations can be seen in Figure C.5.
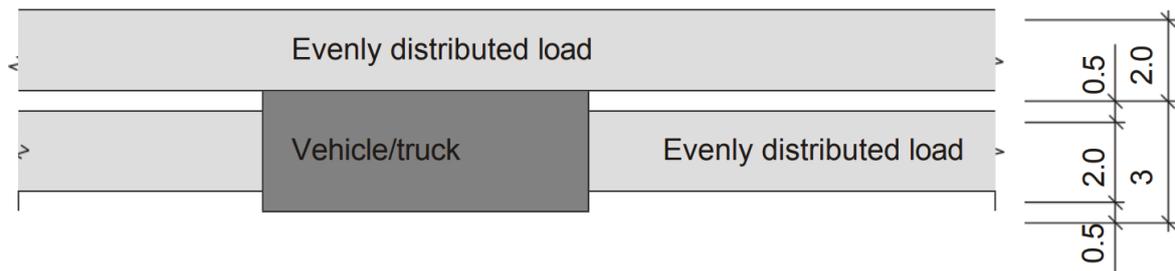
Figure C.5: Load placement (Statens Vegvesen, 2014).

The safety and combination factors differ per type of load and are stated in Table C.2.

Table C.2: ULS & SLS Partial Factors and Combination Factors for Bridge Design.

Load Type	γ (ULS/SLS)	ψ_0	ψ_1	ψ_2	Reference
Permanent Loads					
Self-weight	1.35 / 1.0	-	-	-	Standards Norway, 2016
Superimposed dead loads	1.35 / 1.0	-	-	-	Standards Norway, 2016
Variable Loads					
Traffic / live load	1.35 / 1.0	0.7	0.7	0.2	Standards Norway, 2016
Snow	1.6 / 1.0	0.7	0.5	0.2	Standards Norway, 2018
Construction stage loads	1.5 / 1.0	1.0	0	1.0	Standards Norway, 2016

These load combinations will be applied in the longitudinal direction of the bridge. In this orientation, the arch, the cables and the deck can be evaluated. The structural assessment will be carried out in two steps: first through simplified hand calculations, and then through a finite element model.

C.3. Calculations by Hand

The first step in determining the dimensions of the bridge is to carry out a set of hand calculations. These results will later be used to verify the numerical models and to check whether the outcomes fall within the expected range. The input parameters are defined parametrically so that they match the values used in the FEM models.

The quantities of interest are:

- the support reactions;
- the maximum tensile force in the deck (tie);
- the maximum compressive force in the arch;
- the maximum tensile force in the hangers;
- the maximum bending moment in both the arch and the deck.

The arch geometry is defined by the following parabolic equation:

$$z(x) = 20 \left(1 - \frac{x^2}{2025} \right) \qquad\qquad \text{(C.3)}$$

The calculation starts with the support reactions. Since there are no external horizontal forces, the horizontal reaction at the supports is zero. For the simplest symmetrical loading case, the vertical reaction at each support is equal to half of the total vertical load.

Next, the internal forces are evaluated. This is done by determining all internal forces for each of the elements and simplifying the structure into a large truss system. This approach provides a good indication of the correct order of magnitude, although a number of simplifications have been applied. The complete calculation procedure is presented in Section G.3 in Appendix G.

The internal moments were based on a slight simplification. The tie-beam is assumed as an infinitely long continuous beam with the following 'forget-me-nots':

$$M_{\text{at support}} = -\frac{qL^2}{12},$$
$$M_{\text{in span}} = \frac{qL^2}{24} \tag{C.4}$$

The parametric formulas are then filled in with the loads determined in Table C.1.

C.4. FEM analysis

The 2D DIANA model is constructed with the help of the DIANAIE function. Therefore, small changes are easily adaptable. In this chapter, each property of the model will be given and all assumptions will be explained in further depth.

Table C.3 shows the shape properties of the different shapes in the model. All shapes are modelled as wires.

Table C.3: Shapes properties.

	Element Class	Material	Geometry
Deck	Class-III Beams 2D	Concrete	0.5 m x 7.75 m (y,z)
Arch	Class-III Beams 2D	Concrete	1.2 m x 0.7 m (y,z)
Cables	Regular Truss	Steel	0.00785 m² (circular cross section)

The concrete is modelled after the Eurocode 2 EN1992-1-1 and includes a total strain crack model. For the tensile behaviour, a linear-ultimate crack strain tensile curve is chosen with an ultimate strain of 0.0015. The compressive behaviour is according to the compression curve in EN1992-1-1 and no reduction model is used. The material properties that correspond to the concrete class C45/55 in DIANA are listed in Table C.4.

Table C.4: Concrete properties.

Property	Value	Unit
Young's modulus (E_{cm})	$3.62832 \cdot 10^7$	kN/m²
Poisson ratio (ν_c)	0.2	-
Thermal expansion coefficient (α_t)	$1 \cdot 10^{-5}$	-
Density (ρ)	2.4	T/m³
Mean uniaxial tensile strength (f_{ctm})	3,795.45	kN/m²
Mean compressive strength (f_{cm})	53,000	kN/m²

For the steel of the cables, a simple stress model is used with no compression as the stress dependency. The Young's modulus is $1.95 \cdot 10^8$ kN/m² and a Poisson ratio of 0.3.

A structural linear static analysis is performed with the loads listed in Table C.1.

C.5. Determining Dimensions

In the model, various load combinations were applied to determine the internal forces within the structure. These internal forces were then used to design and verify the dimensions of the main components of the bridge. The detailed calculations from these analyses are presented in Section G.3 in Appendix G. The following sections outline the key assumptions made during the analysis and provide corresponding explanations.

To begin, the dimensions that are evaluated include the arch, which has a thickness of 0.7 m and a height of 1.2 m. The same dimensions are applied to the tie beam that connects the two arch bases. In the calculations, each tie is designed to carry the forces corresponding to half the bridge width, while in practice additional prestressing strands in the deck contribute to the total capacity.

For the arch, deck, and prestressing system, several load cases were analysed to assess the structure's resilience under various combinations. These analyses indicate both the structural performance under different loading scenarios and the appropriate prestressing level to apply at each construction stage.

The first analysis focuses on the deck and prestressing system 28 days after casting, when the concrete has reached its design strength. The maximum prestress is governed by the concrete's compressive capacity. For concrete class C45/55, the design compressive strength f_{cd} is 30 MPa, and the maximum permissible tensile stress is 1.77 MPa.

At this initial stage, when the deck has just been cast and no external loads are applied, the maximum allowable prestress force is 25,200 kN to prevent concrete crushing. To ensure adequate compression throughout the structure and to account for construction uncertainties, it was decided to apply 50% of the final prestress at this stage.

In the next construction stage, when the self-weight of the arch induces a horizontal reaction at the beam connection, a minimum prestress force is calculated. The analysis shows that the prestress should exceed 1,116 kN to prevent tensile stresses under Serviceability Limit State (SLS) conditions.

The transportation phase is also assessed. During transport, no additional external loads are considered, but a safety margin is included to cover potential uncertainties. Prior to lifting, the final prestress is applied to ensure that both Ultimate Limit State (ULS) and SLS conditions are satisfied.

Under ULS, the complete design is verified for all components. In the final configuration, using four prestressing strands of 31x150 mm² within the tension tie results in a unity check value of 0.46, indicating that the design has sufficient reserve capacity to accommodate neglected effects such as wind and accidental loads.

The cables are assumed to have an effective area equivalent to a strand with a diameter of 100 mm. At the ultimate limit state, the stress in the steel is 105 N/mm², which is well below the yield strength of any steel component. This suggests that the cross-section could be optimized further if the same force distribution pattern is maintained.

The overall dimensions are summarized in Table C.5.

Table C.5: Typical Dimensions of Tied-Arch Bridge Elements.

Element	Dimensions [m]
Arch	1.2 x 0.7 m
Tie beam	1.2 x 0.7 m
Deck	0.3 m (containing longitudinal and crossbeams)
Cables	Diameter of 0.1 m
Pre-stress	4 x 31 x 150 per tie beam

C.6. Joints and Bearing

The approach bridge is designed using a slightly more simplified approach than was used for the main arch structure of the bridge. The tandem axle loads from LM1 were, for example, neglected in the design, since the most critical situation has the TS on the deck of the arch. The structure needs two approach bridges. On the East side of the bridge, on Aspøya, the approach bridge is required to span 45 m and to overcome a vertical height difference of 2 m between the two ends. It connects the existing road to the arch structure. On the west side of the bridge, on Hessa, the structure should span 90 meters to connect the arch structure to the road on the island. It also needs to overcome the height difference, and it should incorporate a curve, as can be seen in Figure C.6. The total elevation difference to be overcome by the approach is 11 metres. The elevation change along the trajectory of the bridge can be seen in Figure C.7.
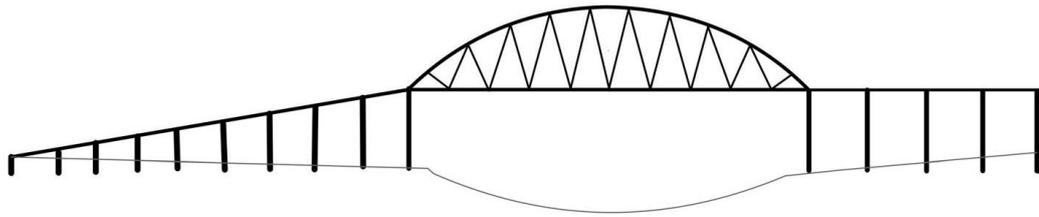
Figure C.6: Side view trajectory bridge.

Figure C.7: Height profile of ground (Statistik Sentralbryå, n.d.).

Both approach bridges have a dilation joint at one side. The one on Hessa has the joint at the connection between the abutment (land) and the approach bridge. The other dilation joint is placed between the arch structure and the approach bridge toward Aspøya. This is visualised in Figure C.8. The dilation joints are chosen based on the expected expansion of the bridge deck. The formula for this expansion is:

$$\Delta L_{\text{total}} = \Delta L_T + \Delta L_M + \Delta L_S + \Delta L_C \tag{C.5}$$

where:

- ΔL_T = thermal movement (temperature effects) [mm];
- ΔL_M = mechanical movement (imposed loads, settlements, etc.) [mm];
- ΔL_S = shrinkage movement (concrete drying shrinkage) [mm];
- ΔL_C = creep movement (time-dependent deformation under sustained stress) [mm].

In this report, only the thermal movement and the movement due to creep will be considered. It is assumed that the movement to shrinkage is dealt with during the casting process. The movement due to creep will be estimated based on a rule of thumb.

The thermal movement is based on the length, alpha, and temperature differences. The temperature difference in this case is 50 degrees, assuming that the temperature in Norway varies between +30 °C and -20 °C, and the thermal coefficient alpha is 10^{-5} (Table C.4). The dilation joint on Hessa has to accommodate the movement of 130 meters of the bridge and the one on the side of the arch structure has to accommodate the movement of 90 meters. It is assumed that the deck will shorten 0.4% due to creep. Table C.6 shows the movement per dilation joint and the total movement both have to accommodate.

Table C.6: Movements.

Movement	Joint Hessa [m]	Joint arch structure [m]
Thermal	0.065	0.045
Creep	0.520	0.360
Total	0.585	0.405

These results mean that modular expansion joints need to be used since the movements are larger than 250 mm.

The new trajectory of the bridge allows for multiple columns to be placed under this structure, reducing the span of the bridge elements. On Aspøya, four sets of columns will be placed and on Hessa nine and the end of both approach bridges will rest on an abutment, bringing the span of each bridge element to 10 meters. This allows the bridge to be made using slab decks, just like in the arch structure. The height of the deck is 0.3 meters and the loads on the deck are the same as on the arch structure, except for the tandem axle loads.

In Table C.7 and C.8, the reaction forces on the columns and the abutments are listed for both approach bridges. The values correspond to the forces that will work on a single column, on the abutments, the double of the force in the table will work.

Table C.7: Values approach bridge Aspøya.

Column	Force [kN]
Abutment	710.3
Column 1	2,066.4
Column 2	1,679.0
Column 3	2,066.4
Column with arch	710.3

Table C.8: Values approach bridge Hessa.

Column with arch	Force [kN]
Abutment	713.0
Column 1	2,050.3
Column 2	1,743.3
Column 3	1,825.2
Column 4	1,804.7
Column 5	1,804.7
Column 6	1,825.2
Column 7	1,742.3
Column 8	2,050.3
Abutment	713.0

The support reaction from the arch structure is equal to 10,658.9 kN. The type of bearing that will be used in this case is a pot bearing. For the other supports, elastomeric bearings can be used since the highest load here is 2,066.4 kN. The dimensions of the bearings will be found using NEN-EN 1337. The Dutch code was used due to the unavailability of the Norwegian annex of the Eurocode. Pot bearings can carry loads up to 40 MPa (Y. Yang, 2025). The minimal area of the rubber then becomes 266,473 mm², which is used to find the required diameter. This can be rounded to 600 mm (European Committee for Standardization, 2004b), bringing the stress to 37.7 MPa. Four pot bearings will be used in the structure: two on each side of the arch structure. Where the dilation joint is placed, the bearing should be able to move, whilst on the other side one of the bearings should be pinned in all directions. Where the dilation joints will be placed and how each of the bearing can move is shown in Figure C.8. The pot bearing can be made to move in any wanted direction by adding a teflon sheet between the top of the pot and the bottom of the steel plate connected to the deck. Movement in a direction can be locked by adding a steel pin.
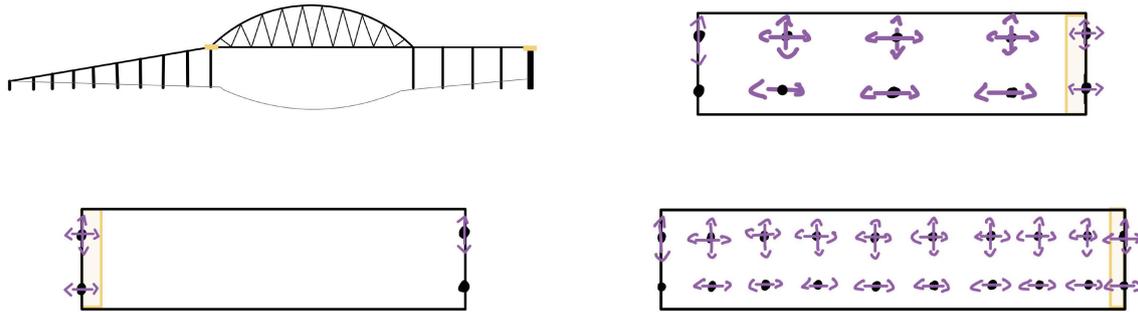
Figure C.8: Location of dilation joints and movement of bearings.

Reinforced elastomeric bearings can carry loads up to 15 MPa. All bearings in the structure will be the same and thus designed for a load of 2,066.4 kN. This brings the required area to 137760 mm². The dimension from the table 3 "Standard sizes for bearings type B" in the code that meets this requirement is a pad of 300 mm by 500 mm (European Committee for Standardization, 2004b), bringing the stress to 13.8 MPa. The elastomeric bearings can also be adjusted such that they are free to move in the required directions by adding steel pins.

Bearings help transfer the loads from the main structure to the substructure, which is the following step in the design. The substructure consists of columns and abutments. In this design, three different types will be present: the abutments at the ends of the approach bridges, the columns under the approach bridges and the columns on the edges of the arch structure.

The columns at the sides of the arch structure will carry the largest load. The bearing transfers two loads of 10,658.9 kN and two loads of 713 kN. The column is 800 mm wide and 1,300 mm long. The dimension of the column has to do with the dimensions of the bearings. The column should be at least 600 mm wide to accommodate the pot bearing and 900 mm long so both bearings can be placed. Spacing is needed on the outside of the bearings as well as in between, which brings the cross section to 800 x 1300 mm. It has to be checked whether this cross-section is sufficient for the compression that is imposed upon it. The minimum required cross-section for the column is equal to:

$$A_{c,\min} = \frac{N_{Ed}}{f_{cd}} = \frac{11,371.9 \text{ kN}}{30,000 \text{ kN/m}^2} = 0.253 \text{ m}^2 \tag{C.6}$$

The cross section of the column is thus large enough, since its cross section is equal to 1.04 m². As can be observed, the column is larger than needed to sustain the load from the structure. The choice is made to keep the cross section of the column larger than needed since some loads were not considered in the design and might have an impact on the column. An example of this is the wind load, which can cause large moments in the column.

The minimal longitudinal reinforcement needed in the column is determined by the Eurocode through the formula (European Committee for Standardization, 2004a):

$$A_{s,\min} = \frac{0.10 \cdot N_{Ed}}{f_{yd}} \tag{C.7}$$

This brings the minimal required longitudinal reinforcement to 2,614.23 mm². The chosen diameter is 12 mm and in total 26 rebars are placed in the cross-section of the column. On the short side of the column, seven rebars are placed, spaced at 100 mm from heart to heart and a cover of 94 mm. On the long side of the column, the heart-to-heart distance is 150 mm and the cover 119 mm. The total amount of longitudinal reinforcement in the cross section is now equal to 2,940.6 mm². Figure C.9 shows the layout of the reinforcement.
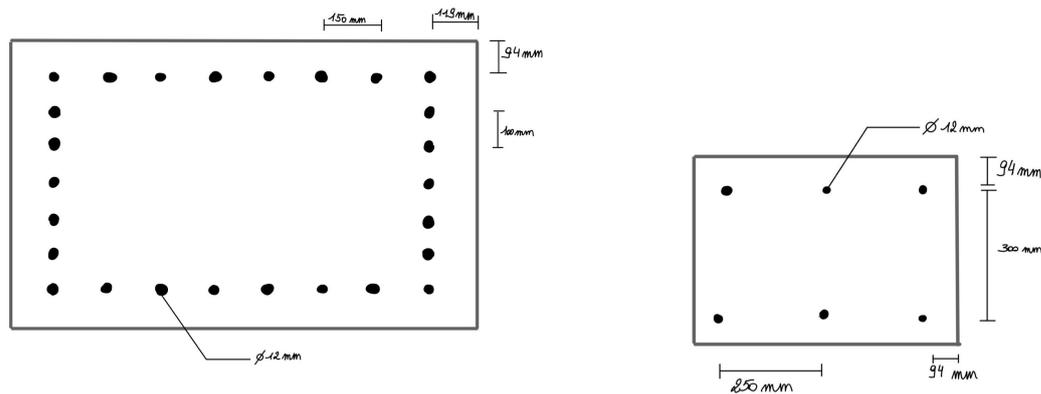
Figure C.9: Cross-section columns with reinforcement.

The transversal reinforcement also needs to be determined according to EN1992-1-1 (European Committee for Standardization, 2004a). The diameter should be larger than 6 mm and the spacing has a maximum of 160 mm. This is what will be used in this design. The horizontal loads are out of the scope of this report, therefore the columns can not be designed according to the shear force. For now it is assumed that this transversal reinforcement would be sufficient. In real life however, this should be calculated on shear and designed accordingly.

The columns under the approach bridges will have the same dimensions on both side of the bridge even though the loads are slightly different. This simplifies the production process and creates a more aesthetically pleasing view. The load that the columns must sustain is 2066.4 kN. With the concrete class C45/55, the minimum area should be 0.069 m². This is smaller than the cross section of the bearing, which is 0.15 m². With 100 mm on each side of the bearing, the cross section of the column becomes 0.35 m². The minimum longitudinal reinforcement is calculated according to Equation C.7 475.03 mm². Six rebars are placed in the cross section with a diameter of 12 mm. On the long side of the column there is a cover of 94 mm and a heart-to-heart spacing of 250 mm. On the short side of the column, the cover is the same but the heart-to-heart spacing between the rebars is 300 mm. This brings the total longitudinal reinforcement to 678.58 mm². Figure C.9 shows the layout of the longitudinal reinforcement. Just as with the columns on the side of the arch structure, the maximum spacing is 160 mm and the diameter that is used is 6 mm.

The abutment on the ends of the approach bridges should withstand a vertical force of 1,426 kN on Hessa and 1,402.6 kN on Aspøya. The type of soil at these locations is gneiss (Norges Geologiske Undersokelse, n.d.). This is also the material that will be used in the abutments. This choice is made since it seems as if the abutments that are currently present are made out of gneiss and it is an easily acquirable material. The material has a unit weight between 2,590 kg/m³ and 2,840 kg/m³, in the calculations, 2,700 kg/m³ will be used. The abutment has to be checked on tipping. For this calculation, a different force is used that the 1,426 kN and 1,402.6 kN. For the tipping calculation, only the self-weight of the bridge is considered. This brings the force on the bridge to 920.7 kN. The forces working on the abutment can be seen in Figure C.10.
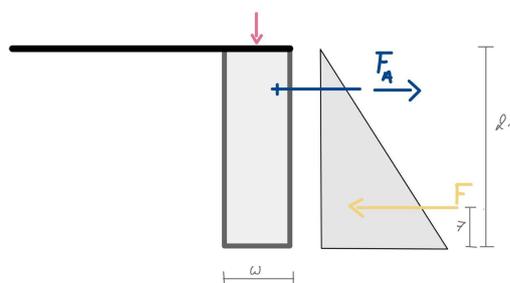
Figure C.10: Forces on abutment Aspøya.

The earth pressure is calculated using the formula (Editor Engineeringtoolbox, 2025):

$$F = 0.5 \cdot K \cdot \gamma \cdot h^2 = 0.5 \cdot 0.832 \cdot 27 \cdot 21^2 = 4,953.3 \text{ kN/m}' \qquad \text{(C.8)}$$

With $K = \frac{\mu}{1-\mu}$ and μ is the Poisson's ratio, which is 0.454 (Ji et al., 2009).

The moment that the self-weight and the force on the abutment should withstand then becomes:

$$4953.5 \cdot \frac{21}{3} = 34,674.5 \text{ kNm/m}'$$

The needed width of the abutment is determined by taking the moment around the lower left point of the abutment. This gives:

$$920.7 \cdot \frac{w}{2} + 21 \cdot 27 \cdot w \cdot \frac{w}{2} \geq 34,674.5 \Rightarrow w \geq 9.891 \text{ m}$$

This is however way too wide for the surroundings, so an anchor should be placed. The capacity of the anchor is estimated by a simplified calculation. The minimum width of the abutment can be determined by the following formula where the width of the abutment is assumed to be 2 meters and the anchor is placed at 14 meters height:

$$920.7 \cdot \frac{2}{2} + 21 \cdot 27 \cdot 2 \cdot \frac{2}{2} + F_A \cdot 14 \geq 34,674.5 \Rightarrow F_A \geq 2,329.9 \text{ kN}$$

For the abutment on Hessa, the load is 1,426 kN and only the self weight is equal to 924.16 kN. On Hessa, the abutment has a triangular shape unlike the wall-like rectangular shape on Aspøya. This shape is needed since both the land and the bridge deck are under an inclination at this location. Since these angles are not precisely known, too much assumptions would have to be made to check this abutment, making the results very unreliable. It is therefore considered outside the scope of this project. In Figure C.11, a side view of the abutment is drawn. The same type of calculations should be made so that tipping of the abutment is prevented.
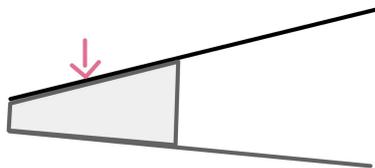
Figure C.11: Forces on abutment Hessa.

Both abutments should also be checked on crushing. The compressive strength of gneiss is 160 MPa (L. Yang et al., 2023). On Aspøya, the abutment is at least 15.5 meters wide, bringing the minimum required width to 0.57 mm, so the structure is more than safe for crushing. On Hessa this will also be the case.

Finally, the foundation should be designed. Since the soil in the surrounding area consists of gneiss, it is assumed that a spread foundation will be sufficient enough (European Committee for Standardization, 2004b). This has to be reinforced accordingly and will be anchored into the ground. The foundations have to withstand the load from the columns, which is the sum of the loads on the columns and the self-weight of the columns. With a bridge height of 17 meters, the highest loads that the foundations should be able to carry are:

$$0.8 \cdot 1.3 \cdot 17 \cdot 25 + 713 + 10,659.9 = 11,814.9 \text{ kN}$$

$$0.5 \cdot 0.7 \cdot 17 \cdot 25 + 2,066.4 = 2,215.15 \text{ kN}$$

The design of the foundation blocks and the anchorage is outside of the scope of this report. It should both be dimensioned to withstand the horizontal forces that occur due to the wind and acceleration and braking forces on the deck of the bridge. All of these forces have been neglected in this report and therefore only a suggestion for the kind of foundation is given.

C.7. Logistics

In order to construct the new bridge, intensive and accurate planning is required to make sure that each phase can be completed smoothly. So, before any of the construction can start, the surrounding area must be cleared for construction. This means that (a part of) the building on the east side should be demolished, the clearance on both sides of the water should be created and the locations of the foundation have to be prepared. [1]

The foundation needs to be built for the main piers for the superstructure and for the smaller piers and abutments of the approach bridges. The piers themselves can be cast in situ, since this does not disrupt any travel flow and needs to be hardened enough before the superstructure can be placed on top. This means that these elements will probably be cast early to allow full hardening. [2]

Then, a suitable location needs to be found near the new location of the bridge. This will most probably be at one of the harbour areas between Hessa and the city centre. There are a few locations, depending on the future use of the sites, where the construction could be built. At this location, a controlled environment can be created to ensure high quality-management. In Figure C.12, a possible location is scouted. [3] In a future scenario where this space will be used for other purposes, one of the other adjacent open harbour areas in the south might be used.

Most of the materials can be transported over the water due to the surrounding harbour areas. When not directly used it can be stored in one of the many port areas at the north side of the island. The concrete can be used from (Ultstein Betong Industri, n.d.) and the reinforcement can be used from (Norkstaal, n.d.). These companies have local branches that are easily reachable by water and road. [4]

When the right materials have all arrived, first of all the scaffolding should be built for the bridge deck and provide a safe working space. On top of this scaffolding of the two arches will be constructed. Inside the large amount of reinforcement should be tied and accurately placed within the scaffolding. The connecting elements for the cables should also be put into place for the connection between the arch and the deck.

The scaffolding will conform to the design of the deck, containing the grid pattern for the beams in both directions. Lateral and longitudinal reinforcements need to be tied together, the prestress ducts need to be set in place for both directions and the connections to the cables need to be put in place for later. The deck will be constructed with prestressing ducts in both directions to create compression in the deck and prevent it from buckling out of plane. After 28 days, when the concrete has achieved its desired compressive strength, part of the prestress will be applied. The process should be monitored accurately since it should be done in a symmetrical order to prevent undesired stresses. These values are only tested for the longitudinal direction, since that is the deciding direction.

After the deck has been stressed for half of the final load, the arches will be cast. Since they are cast upright, there is no need for extra dimensioning for rotations in the transportation process. The scaffolding will be used to support the arch before it reaches its design strength. It also contains the anchors for the transversal beams between the two arches. The casting will take place in phases, starting symmetrically on both sides of the arches. This measure prevents unwanted unbalanced loads and the zones that will endure the highest loads, will reach the necessary strength in time.

Once the arch is hardened enough, the additional post-tensioning can start. Starting with the longitudinal tendons in a symmetrical order and incrementally. This will continue until the desired compression is achieved and the tendons will be anchored at both ends of the deck. This procedure is repeated for all tendons. Afterwards the transverse prestressing will follow. These tendons are smaller and will cause a stiffer deck and limit the cracks. Finally, the concrete transversal beams can also be cast and this will follow the same procedure of formwork, reinforcement, casting and removing scaffolding. To ensure long-term durability, the prestressing ducts will be injected with grout. This protects the prestress from corrosion and enhances the structural integrity of the bridge.

Now that all the concrete elements are in place, it is time to connect the arch with the deck through the cables. These cables are going to be installed symmetrically, starting with the inward-leaning cables, from the outside to the inside. In this way, the load will be spread in the most desired manner. These cables are tensioned afterwards to perform the best when all the long-term effects are considered. After

these cables are all in place, the scaffolding between the arches and under the deck can be completely removed. When this has taken place, the final prestressing can be applied.

In the meantime, the bearings have been installed on the piers and abutments. The approach bridge can be cast in situ on those bearings. These approach bridges are simple slab elements with the same dimensions as the main deck, but contain less pre-stress. These approach bridges already have anchor plates or the right connection for the expansion joint that will eventually be placed there. Since the approach bridges are already installed, it will be easier to assist the placement of the arch construction.

Eventually, when the cables are installed, the deck is ready for transport. The structure will be pushed in the length direction onto a pontoon that is on the side of the harbour. This has to be done accurately and slowly using teflon sheets and a good anchorage of the pontoon. Once the pontoon completely supports the arch, it will be escorted to the right position in the water. The structure will be lifted incrementally and carefully placed on top of the piers. This method is based on the method used at the Portal North Bridge in New Jersey (NJ Transit, 2025). [5]

After placing everything securely in place, the finishing elements will be added. The roads on both sides will be connected, the asphalt and protective layers will be applied, the parapets and railing will be set in place and eventually the traffic will be redirected onto the new bridge. Eventually the old bridge can be demolished and down-cycled for a new purpose.
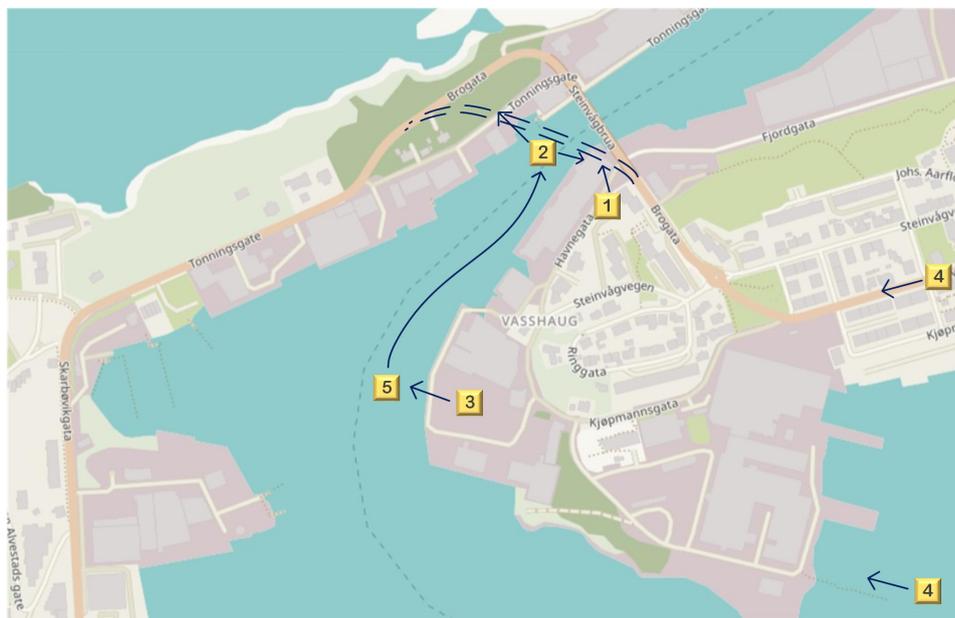
Figure C.12: Logistical map.

C.8. Discussion

Due to the limited time available for this project, several aspects of the tied-arch bridge design have not been fully developed or verified. The most significant limitations and exclusions are summarized below.

First, there was considerable freedom in determining the design direction. Although an initial meeting with the county was held regarding the replacement of the existing bridge, no specific design preferences or requirements were provided during the subsequent phases. As a result, it is uncertain whether the proposed design aligns with future planning objectives, local development strategies, or other influencing factors that may affect the final implementation.

Furthermore, the effects of accidental and wind loads have been neglected in the current analysis. These actions were not taken into consideration to simplify the design process, but they are critical for

a complete structural assessment. In a detailed design phase, the bridge must be verified for stability and safety under such load cases, including wind-induced vibrations, collision impacts, and potential fatigue effects.

A finite element model (FEM) was developed to evaluate the structural performance. However, due to modelling complications and time constraints, the model was simplified. The subsequent calculations were therefore performed using simplified, constant cross-sections. In reality, the geometry of the arch and tie members would vary along their length, which would significantly influence stiffness distribution, internal force flow, and dynamic response. A refined FEM with variable cross-sections would provide more accurate insight into the overall structural behaviour.

Overall, this design can be used as a guideline for the future connection, however a lot of details need to be checked.

D

Extra info Structural

Load type	Load configuration		Service classes			
			Bk10	BkT8	Bk8	Bk6
Wheel load		H	80	56	56	42
Axle load		A	160	112	112	84
Bogie load		A_1	65	40	40	30
		A_2	160	112	112	84
		a	1.3	1.2	1.2	1.2
Triple bogie load		A_1	70	60	50	40
		A_2	140	84	84	56
	The order of the axle loads is arbitrary.	a	1.3	1.2	1.2	1.2
Vehicle load		A	40	32	32	24
		V	300	280	220	180
	The axle load is placed in the most unfavorable position					
Truck load		A	40	32	32	24
		V	500	400	320	280
	The axle load is placed in the most unfavorable position	p	6	6	6	6

(*) For light bridge decks (steel decks, gratings, etc.), regardless of usage class, a wheel load of 35 kN distributed over a 20x20 cm area randomly placed on the roadway shall be checked.

Figure D.1: Use classes (Statens Vegvesen, 2014)
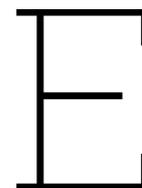
Traffic Estimation Aspøya-Hessa

This appendix documents the calculation behind the two directional traffic intensities on the Steinvåg bridge that are reported in Section 3.2. Two complementary estimation methods are applied: (1) using the population and employment, and (2) extrapolation from historical traffic counts. These methods require many assumptions, therefore the outcomes needs to be checked once the OmniTRANS model is finalised. In both methods, the traffic intensity for the evening peak (15:00-17:00) is estimated.

E.1. Method 1 - Population-Employment approach

This method assumes that evening-peak traffic mainly consists of commuting trips. The calculation relies on demographic and behavioural assumptions regarding the share of employed residents, work locations, departure patterns, and the modal split in Ålesund. The resulting steps and outcomes are summarised below:

- Hessa has 3852 inhabitants (Statistisk Sentralbyrå, 2025e);
- It is assumed that all people aged 20-70 years old are employee. This is 64% of the population (Statistisk Sentralbyrå, 2025c), corresponding to 2,465 employed residents;
- Hessa is mostly residential area, 80% of the employed residents (approx. 1,972 people) are assumed to work outside Hessa and thus return home via the bridge;
- 50% of these commuters (approx. 986 people) are assumed to travel during the 15:00-17:00 period, reflecting Norwegian working culture where employees can leave work flexibly after 15:00;
- The current model split (see Figure A.5) of Ålesund is used; 71% car driver, 7% car passenger, 6% public transport, 14% bicycle, and 2% pedestrian.

Based on these values, the estimated one-directional traffic load towards Hessa during the evening peak is equal to: 700 cars, 59 public transport users, 20 cyclists, and 138 pedestrians.

On the island of Hessa itself, there are 791 jobs (Statistisk Sentralbyrå, 2025e). Following the previous calculations and assumptions, 298 employees work on Hessa but live elsewhere ($791 - (2,465 - 1,972) = 298$). Applying the same modal split and the same 50% evening-peak assumption gives the estimated flow towards Aspøya during the same period: 106 cars, 9 public transport users, 3 cyclists, and 21 pedestrians.

E.2. Method 2 - Extrapolation from historical traffic counts

A traffic counter near the Steinvåg bridge (*Stenvågsund*) was active between March 2022 and September 2024 (period A) but is currently out of service (Statens Vegvesen, 2025b). To estimate recent trends, data from the nearby *Skutvika* counting point (see Figure A.12) from period A and between January and September 2025 (period B) were used, see Table E.1. The percentage change in total daily traffic between these two periods (calculated per weekday and per direction) was applied to the historical *Stenvågsund* weekday data.

Table E.1: Average number of vehicles per counting point and period.

	Average number of vehicles at *Stenvågsund* in period A		Average number of vehicles at *Skutvika* in period A		Average number of vehicles at *Skutvika* in period B			
	→ **Aspøya**	→ **Hessa**	→ **Aspøya**	→ **Hessa**	→ **Aspøya**	%	→ **Hessa**	%
Mo	3,861.1	3,873.2	5,140.4	5,020.8	5,165.0	+0.5	5,035.6	+0.3
Tu	3,994.1	3,989.8	5,277.1	5,166.1	5,327.0	+0.9	5,180.6	+0.3
We	4,009.8	4,005.8	5,243.2	5,138.5	5,309.1	+1.3	5,133.1	-0.1
Th	3,959.2	3,960.8	5,197.3	5,103.9	5,115.7	-1.6	4,989.6	-2.2
Fr	3,875.3	3,940.9	5,211.2	5,183.8	5,222.3	+0.2	5,165.4	-0.4

The average number of vehicles at *Stenvågsund* during period A was extrapolated using the observed growth in average vehicle counts at *Skutvika* between periods A and B. This yields the estimated average number of vehicles at *Stenvågsund* for period B (see Table E.2).

The share of vehicles travelling during the evening peak was derived from the hourly distribution at *Skutvika*. Between 15:00 and 16:00, 8.5% of daily traffic occurs towards Hessa, and 6.9% between 16:00 and 17:00, giving a combined evening-peak share of 15.4%. In the opposite direction (towards Aspøya), 9.1% and 9.2% of daily traffic occur during these hours, respectively. These percentages were applied to the extrapolated average daily totals at *Stenvågsund* to obtain the estimated evening-peak traffic volumes, as presented in Table E.2.

Table E.2: Average number of vehicles per counting point and period.

	Average number of vehicles at *Stenvågsund* in period B		Average number of vehicles at *Stenvågsund* in peak-hour	
	→ **Aspøya**	→ **Hessa**	→ **Aspøya**	→ **Hessa**
Mo	3,879.5	3,884.6	710.0	598.9
Tu	4,031.9	4,001.0	737.9	616.8
We	4,060.1	4,001.6	743.0	616.9
Th	3,897.0	3,872.2	713.2	596.9
Fr	3,883.5	3,926.9	710.7	605.4
Average	3,950.4	3,937.3	**723.0**	**607.0**

E.3. Conclusion

The first method estimates 700 passenger cars crossing the bridge towards Hessa during the evening peak, while the second method yields an average of 606 cars on weekdays (Monday–Friday). These values are relatively consistent, supporting the reliability of the estimation. In the opposite direction, however, the results diverge more strongly: 106 cars according to Method 1 versus 723 according to Method 2. Since the first method only accounts for commuter traffic, the higher estimate from Method 2 likely reflects additional trip purposes such as leisure, cultural activities, or social visits.

For the current situation, the results from Method 2 are used, as real traffic counts are considered more accurate and capture all trip motives.

<div align="right">

F

</div>

Stakeholder Analysis

As the project area mainly focuses the central area of Ålesund, various stakeholder groups in and around the city centre are directly or indirectly affected by the proposed interventions. Stakeholders are evaluated using two key parameters. The first is power, representing the degree of influence a stakeholder can exert over the project or its outcomes. The second is interest, reflecting how strongly the project affects or concerns the stakeholder. Together, these dimensions provide a structured framework for understanding the role and involvement of each actor, as visualised in the power-interest diagram in Figure F.1.
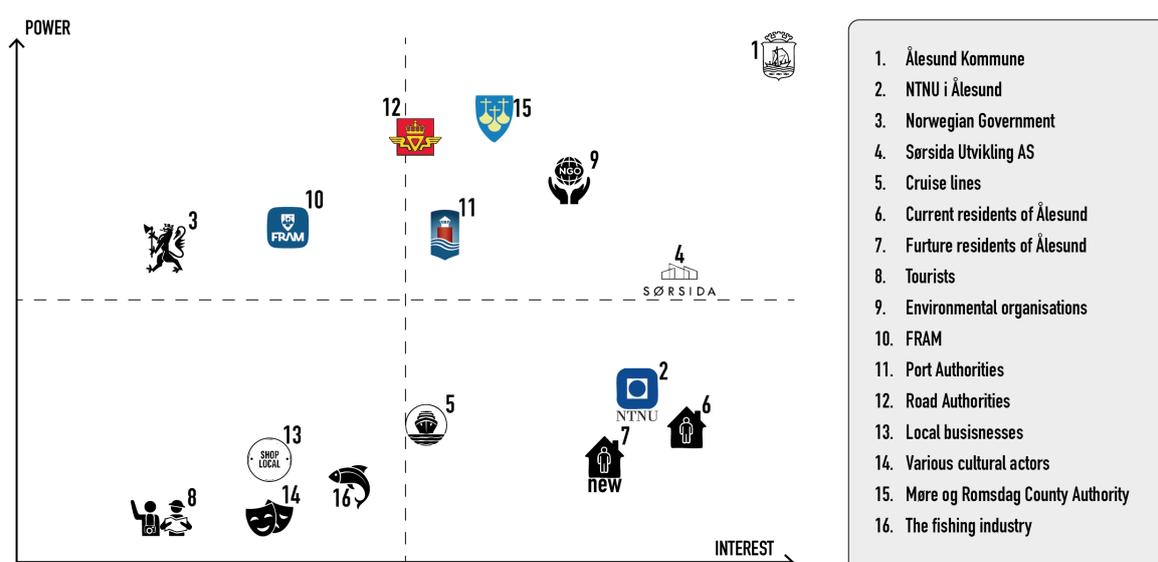
Figure F.1: Power-interest diagram.

1. Ålesund Kommune

Ålesund Kommune is the main client and leading authority for this project, as it holds responsibility for all developments within the municipality. The organisation consists of multiple departments, each with its own perspective and priorities. The municipality's best interest is to make Ålesund more sustainable, accessible, and future-proof.

Key municipal goals include maintaining reliable accessibility between the islands, ensuring the structural condition of key bridges, and increasing public transport use to reduce congestion and emissions. Furthermore, the municipality aims to revitalise the Sørsida area, where many buildings are currently

unoccupied. Repurposing these spaces aligns with Ålesund's sustainability objectives and contributes to creating a more 'vibrant urban atmosphere' (Re-Value, 2025).

Given its frontrunner position, Ålesund Kommune is expected to lead the overall process. Both its power and interest in the project are high, as it issues permits, allocates funding, and ensures that all project outcomes align with municipal policy goals.

2. NTNU i Ålesund

The Norwegian University of Science and Technology (NTNU) has multiple campuses all over Norway, one of which is located in Ålesund. This campus hosts around 000 students living both in the city centre and in nearby residential areas (NTNU, 2025).

NTNU plays an active role in the city's (sustainable) transformation through its involvement in the Re-Value project, which focuses on achieving climate-neutral cities while paying close attention to urban development (Re-Value, n.d.). Through this collaboration, the university contributes academic expertise to practical urban challenges, linking education, research, and real-world implementation.

NTNU's main interest lies in applying its knowledge to support sustainable development in Ålesund and strengthening its position as a university engaged in real-world innovation. Its power primarily stems from its partnership in the Re-Value project, where strategic decisions are made regarding the future of Ålesund's city centre. The university therefore holds a moderate level of power but a high level of interest.

3. Norwegian Government

The Norwegian government's main interest in this project lies in its contribution to national climate and sustainability goals. Norway has signed the Paris Agreement and aims to reduce greenhouse gas emissions by at least 50% by 2030 compared to 1990 levels (Norwegian Ministry of Climate and Environment, 2022; Regjeringen.no, 2025). Measures such as the reuse of (materials of) existing buildings and materials, as well as encouraging a modal shift from private cars to more sustainable modes of transport, directly support these national objectives.

The government's power is moderate, as most planning and implementation decisions are made at the municipal or county level. Its interest in this specific project is relatively low, given the local scale of Ålesund compared to national priorities.

4. Sørsida Utvikling AS

Sørsida Utvikling AS was established in 2019 as the development company responsible for managing the transformation of Ålesund's southern waterfront (Ålesund Kommune, n.d.). The company is part of Ålesund Kommune and coordinates both the strategic planning and day-to-day management of the area. Its primary objective is to turn Sørsida into a showcase for sustainable urban development, combining economic growth, environmental responsibility, and new housing opportunities. The project will provide approximately 13,000 m^2 of new development area and improve public access to the waterfront (Ålesund Kommune, 2025b).

The company's main interest lies in shaping Sørsida into a vibrant and attractive part of the city while ensuring that the development aligns with Ålesund's long-term sustainability goals and public needs. Temporary interventions in the area must therefore be designed to complement, rather than conflict with, the future development vision. As both a facilitator of private investment and a representative of municipal ambitions, Sørsida Utvikling AS holds high power and high interest in the project. Its decisions will play a decisive role in shaping how the southern waterfront contributes to Ålesund's resilience, liveability, and reputation as a forward-looking city.

5. Cruise Lines

Several international cruise lines make short stops at Ålesund harbour, with ships arriving and departing on a daily basis. An important factor influencing the main source of income for cruise lines is the possibility of visiting multiple coastal cities.

The power of the cruise lines is relatively low, as they do not have a direct contract with the municipality

that gives them the right to visit the harbour. However, since Ålesund's local economy partly depends on tourism revenue generated by cruise visitors, the municipality seeks to maintain good relations with these companies, which gives them a limited degree of indirect power. Their interest in this project is low, as it does not directly affect cruise operations or port access.

6. Current residents of Ålesund

Ålesund has a population of approximately 4000 residents spread across about 29 km² (Stokkan et al., 2025). It used to be one of the most densely populated areas in Norway and still has a high population density. The city has been developed with a strong car-oriented layout. As a result, public transport, cycling, and walking are used less frequently than private vehicles.

Residents generally want Ålesund to remain a liveable and vibrant city, offering a variety of activities and services, while still providing a quiet and comfortable living environment. They value accessibility and short travel times, and therefore expect an urban structure that limits congestion and supports efficient mobility.

Citizens can share their input and opinion on the development of Sørsida through the Re-Value project's surveys and workshops (Amundsen et al., 2024). These activities are intended to result in at least one concrete measure based on public input. Although final decisions rest with Ålesund Kommune and Sørsida Utvikling AS, residents also influence local policy indirectly through municipal elections. Overall, residents have moderate power but high interest, as the project's outcomes will directly affect their daily lives and the quality of their urban environment.

7. Future residents of Ålesund

The new plans include additional housing opportunities, making it essential to consider the demographic profile and facility needs of Ålesund's future residents. Depending on the municipality's priorities, these new neighbourhoods could attract different target groups, ranging from students to elderly residents. Each of these groups has distinct needs in terms of housing type, accessibility, and the design of public spaces. A cautionary example can be found in the Bijlmer district in Amsterdam (Humanity in Action, 2019), which was initially planned as an inclusive and forward-looking urban area but later became the Netherlands' first and only so-called ghetto.

Future residents have a high interest in the project, as it directly concerns their potential living environment. However, their individual influence is low, since they are not yet represented in the current decision-making processes.

8. Tourists

Ålesund is a very popular tourist destination in Norway, attracting approximately 70,000 visitors per year, making it the busiest port city in the country (Nikel, 2025). Tourism plays an important role in Ålesund's local economy.

The planned development of new cultural hotspots and public spaces along the waterfront is expected to further enhance Ålesund's appeal, creating a more vibrant and accessible environment for visitors. However, tourists have a low level of interest in the project itself, as they already perceive the city positively. Their influence is likewise low, though maintaining a welcoming and attractive cityscape indirectly benefits this group.

9. Environmental organisations

Sustainability is a central theme within urban development, and environmental organisations play an important role in ensuring that projects align with national and international climate goals. These groups advocate for low-emission or carbon-neutral construction, the preservation of natural areas, and the promotion of sustainable mobility. If environmental standards are not met, such organisations can raise public awareness or initiate actions that delay or even halt construction.

Given that this project directly contributes to Ålesund's sustainability objectives, environmental organisations have a high interest in its progress and outcomes. Their power is moderate, as they can influence public opinion and policy decisions, even though they are not directly involved in the implementation process.

10. FRAM

FRAM is responsible for the public transport in the county of Møre og Romsdal, which includes Ålesund (FRAM, n.d.). FRAM organises the planning and operating of regional bus and ferry services and plays a key role in achieving the municipality's transport-related goals. To encourage a shift from private car use to public transport, service improvements will depend on FRAM's ability and willingness to expand and adapt its network, even if such measures are not immediately financially profitable.

FRAM's interest in the broader urban development project is limited, as its main focus lies in transport operations. However, its power is moderate to high, since the municipality's ambitions for sustainable mobility and reduced congestion can only be realised through FRAM's active participation and collaboration.

11. Port Authorities

The Ålesundregionens Havnevesen, the port authority responsible for the Ålesund region, manages the city's port infrastructure. The harbour serves multiple functions, including cargo shipping, fisheries, passenger transport, and cruise operations (Ålesundregionens Havnevesen, n.d.).

With the redevelopment of the city's southern waterfront (Sørsida), some of the port industrial activities will be relocated to other locations, while cruise operations will continue to use the existing facilities. This relocation process makes the Port Authority a important stakeholder with high power, as its approval and operational planning are essential for ensuring that port functions remain efficient and compatible with the new urban development.

12. Road Authorities

The Norwegian Public Roads Administration (Statens Vegvesen) is responsible for managing the E136 highway, which runs through Ålesund (Statens Vegvesen, n.d.). Any proposed modification to this road must receive their approval, giving the agency significant decision-making power. In addition to ownership, Statens Vegvesen is also responsible for ensuring traffic safety, meaning that it will only approve changes if they meet the required safety and design standards.

Their interest in the project is moderate, as their primary concern lies with the national road network rather than the broader local redevelopment plans. However, their cooperation is essential for any infrastructure changes involving the E136 corridor.

13. Local businesses

The transformation of Ålesund's city centre offers new opportunities for local economic development. Reusing existing, underutilised buildings can attract new businesses and allow existing enterprises to expand within a revitalised urban environment.

Local businesses have a moderate interest in the project's outcomes, as these will directly influence customer access and business visibility. However, their power is limited, since they depend on decisions made by the municipality and development agencies.

14. Various cultural actors

The redevelopment of Sørsida offers opportunities for the reuse of existing buildings, which could benefit cultural organisations and artists. Empty or underutilised buildings could be transformed into creative spaces for art production, exhibitions, and events. An example of a key cultural actor already located in the area is *Terminalen Byscene*, a venue for concerts and cultural gatherings situated near the cruise docks (Amundsen et al., 2024). The building it occupies does not currently meet modern structural standards, so future redevelopment plans must take its relocation or renovation into account.

Cultural actors have a moderate interest in the reuse and development of the area. However, their power is limited, as they generally depend on municipal funding and decisions made by development companies.

15. Møre og Romsdal County Authority

The Møre og Romsdal County Authority is responsible for regional governance, overseeing various departments including infrastructure, education, and transport (Møre og Romsdal fylkeskommune, n.d.). Any significant change to Ålesund's roads or public buildings must be approved by the county council.

Its power is moderate to high, given its authority to approve infrastructure investments and its ownership of regional transport assets. The interest of the county is also high, as the project aligns with regional goals for sustainable mobility, accessibility, and economic development.

16. The fishing industry

Ålesund has a long-standing history as one of Norway's most flourishing fishing cities, gaining its reputation in the 19th century before much of the city was destroyed in the fire of 1904 (Adventures.com, n.d.). Although the industry never regained its former scale, fisheries and related businesses remain an important part of Ålesund's identity and local economy.

Today, many residents still depend on the fishing industry. Their interest in the project is moderate, as redevelopment could influence access to the harbour. Their power, however, is low, as they hold limited formal influence over urban planning processes but may still affect public opinion if their interests are overlooked.

G
Code of all Analyses

This appendix includes all the code that is used for the different analyses.

G.1. Codes of OmniTRANS Model

Code G.1: Trip generation.

```
1 tripEnds.combinations = [[11, 511]]
  # Generate dimension P11 for production and dimension A511 for attraction, results are stored in these
      dimensions
  tripEnds.time = 10
  # time 10 indicates the evening peak
5 tripEnds.functionSpec = ["(1.0*non_island+1.5*island)*0.447*jobs+0.025*residents",
                           "0.230*residents+(1.0*non_island_non_centre+0.15*island+1.3*centre)*
                           (0.0015*sports_area+0.001*culture_area)"]
  tripEnds.balance = ATTRACTIONS
  tripEnds.execute
```

Code G.2: Skim matrices for car, bike and walk.

```
1 #  mode 10, 20 and 40 are car, cycling and walking
  [10, 20, 40].each do |m|
      sk = OtTraffic.new
      sk.network = [m, 10]
5     # [mode, time]
      sk.skimMatrix = [1, m, 10, 1, [0, 0, 13], 1]
      # [purpose, mode, time, user, [results], iteration]
      # results are only stored for travel time, in dimension 13
      sk.skimFactors = [0, 0, 1]
10    # no additional factor over the travel time
      sk.execute

      # intrazonal travel time is set to half of the travel time to the closest neighbour.
      sc  = OtSkimCube.open
15    mat = sc[1, m, 10, 1, 13, 1]
      ok  = mat.fillIntra(1)
      # intrazonal travel time for zone 10 (external zone) is set to 99999.
      mat[10, 10] = 99999
      sc[1, m, 10, 1, 13, 1] = mat
20 end
```

Code G.3: Skim matrix public transport.

```
1 makeSkim = OtTransit.new
  makeSkim.network = [30, 10]
  # [mode, time], mode 30 is the bus
  makeSkim.modes = [[40, 40]]
5 # use as access and egress mode 40, walking
  makeSkim.routeFactors=[[0, 0.0, 1.0, 1.2, 10.0, 0.0]]
  # in computing generalised costs, 1 min of waiting time is considered as 1.2 min in-vehicle time.
  # a transfer is considered as 10 minutes in-vehicle time.
  makeSkim.minFind = [[40, 1]]
10 # find at least 1 bus stop for access/egress mode 40 in each zone
  makeSkim.skimMatrix = [1, 30, 10, 1, [18, 0, 13, 14, 0, 0, 17], 1]
  # [purpose, mode, time, user, [results], iteration]
  # only store generalised costs, in-vehicle time, waiting time and number of transfers in dimension 18, 13,
      14 and 17 respectively.
```

```
     makeSkim.skimFactors = [1, 0, 1, 1, 0, 0, 1]
15
     makeSkim.execute

     # intrazonal in-vehicle time:
     sc  = OtSkimCube.open
20   mat = sc[1, 30, 10, 1, 13, 1]
     ok  = mat.fillIntra(1)
     mat[10, 10] = 9999
     sc[1, 30, 10, 1, 13, 1] = mat

25   # intrazonal generalised costs:
     sc  = OtSkimCube.open
     mat = sc[1, 30, 10, 1, 18, 1]
     ok  = mat.fillIntra(1)
     mat[10, 10] = 9999
30   sc[1, 30, 10, 1, 18, 1] = mat
```

Code G.4: Simultaneous trip distribution and mode choice.

```
1    makeOd = OtGravity.new
     makeOd.skimMatrix = [[1, 10, 10, 1, 13, 1], [1, 20, 10, 1, 13, 1],
                          [1, 30, 10, 1, 18, 1], [1, 40, 10, 1, 13, 1]]
     # import four skim matrices (travel time for car, bike, walk; generalised costs for bus)
5
     makeOd.balance = ATTRACTIONS
     makeOd.functionType = EXPONENTIAL
     makeOd.functionSpec = [[0.45, -1], [0.3, -3], [0.2, -2], [0.15, -4]]
     # define the deterrence functions
10   makeOd.odMatrix = [1, [10, 20, 30, 40], 10, 1]
     # compute OD matrix

     makeOd.epsilon = 0.00001
     makeOd.iterations = 100
15   makeOd.execute
```

Code G.5: AON assignment bike and walk.

```
1    # AON assignment for mode 20 (bike)
     assign = OtTraffic.new
     assign.odMatrix = [1, 20, 10, 1]
     assign.skimMatrix = [1, 20, 10, 1, 2, 1]
5    assign.load = [1, 20, 10, 1, 2, 1]
     assign.assignMethod = ALLORNOTHING
     assign.execute

     # AON assignment for mode 40 (walking)
10   assign = OtTraffic.new
     assign.odMatrix = [1, 40, 10, 1]
     assign.skimMatrix = [1, 40, 10, 1, 2, 1]
     assign.load = [1, 40, 10, 1, 2, 1]
     assign.assignMethod = ALLORNOTHING
15   assign.execute
```

Code G.6: DUE assignment car.

```
1    assign = OtTraffic.new
     assign.odMatrix = [1, 10, 10, 1]
     assign.pcuFactor = 0.91
     # decrease the OD car matrix with a factor 0.91 to exclude car passengers (only add car drivers and thus
         cars to the network)
5    assign.skimMatrix = [1, 10, 10, 1, 4, 1]
     assign.load = [1, 10, 10, 1, 4, 1]
     assign.assignMethod = VOLUMEAVERAGING
     assign.bprPerType = [[[1], [10, 500.0]], [[2, 6, 14], [0.15, 4.0]], [[3, 13, 17], [0.20, 5.0]],
                          [[4, 5, 7, 8, 9], [0.5, 4.0]]]
10   # define the BPR functions per link type
     assign.iterations = 100
     assign.epsilon = 0.00001

     assign.execute
```

Code G.7: PT assignment (Zenith algorithm).

```
1    assignPT = OtTransit.new
     assignPT.routeFactors = [[30, 0, 1.0, 1.2, 10, 0]]
     assignPT.modes = [[40, 40]]
     assignPT.network = [30, 10]
5    assignPT.load = [1, 30, 10, 1, 3, 1]
     assignPT.minFind = [[40, 1]]

     assignPT.execute
```

G.2. Codes of Bus Network Performance Analysis

Code G.8: Imported packages.

```python
import pandas as pd
import numpy as np
import networkx as nx
import matplotlib.pyplot as plt

from gtfspy import import_gtfs
from matplotlib.colors import LinearSegmentedColormap, Normalize
from matplotlib.collections import LineCollection
from matplotlib.markers import MarkerStyle

import zipfile
import pickle
import os
from mpl_toolkits.axes_grid1.inset_locator import inset_axes

from bokeh.resources import INLINE
import bokeh.io
bokeh.io.output_notebook(INLINE)
```

Code G.9: Modify GTFS files and make `SQlite`.

```python
## TRIPS TO USE
stop_times_df = pd.read_csv("aalesund-gtfs-txts/stop_times.txt")
trips_df = pd.read_csv("aalesund-gtfs-txts/trips.txt")
stops_df = pd.read_csv("aalesund-gtfs-txts/stops.txt")
calendar_dates_df = pd.read_csv("aalesund-gtfs-txts/calendar_dates.txt")

trips_df["route_id"] = trips_df["route_id"].str.extract(r"(\d+)$").astype(int)

merged_df = stop_times_df.merge(trips_df, how="left", on="trip_id")
merged_df = merged_df.merge(stops_df, how="left", on="stop_id")
merged_df = merged_df.merge(calendar_dates_df, how="left", on="service_id")
merged_df["date"] = pd.to_datetime(merged_df["date"], format="%Y%m%d")

merged_df = merged_df.drop(columns=["stop_id", "shape_break", "arr_time_ds", "dep_time_ds", "shape_id", "
    start_time_ds", "end_time_ds", "stop_I", "code", "desc", "location_type", "wheelchair_boarding", "
    parent_I", "self_or_parent_I", "exception_type"])

def unique_trips(route_id, direction, date, start_time=4, end_time=24):
    df = merged_df[(merged_df["route_id"] == route_id) & (merged_df["arr_time_hour"] >= start_time) & (
        merged_df["arr_time_hour"] < end_time) & (merged_df["date"] == date) & (merged_df["direction_id"]
        == direction)]

    unique_list = df["trip_id"].unique()

    df_direction = merged_df[(merged_df["trip_id"].isin(unique_list)) & (merged_df["date"] == date) & (
        merged_df["direction_id"] == direction)]

    df_both = merged_df[(merged_df["route_id"] == route_id) & (merged_df["arr_time_hour"] >= start_time) &
        (merged_df["arr_time_hour"] < end_time) & (merged_df["date"] == date)]

    unique_list_both = df_both["trip_id"].unique()

    df = merged_df[(merged_df["trip_id"].isin(unique_list_both)) & (merged_df["date"] == date)]

    return unique_list, df_direction, df

def make_trips_to_use(lines, date="2025-09-12"):
    all_trips = []
    for i in lines:
        length = 0
        for j in [0, 1]:
            unique_list, _, _ = unique_trips(i, j, date=date)
            for k in range(len(unique_list)):
                all_trips.append(unique_list[k])
            length += len(unique_list)
        print(f"-> Line {i} has {length} trips")

    df = pd.DataFrame(data=all_trips, columns=["trip_id"])
    df.index = df["trip_id"]
    df = df.drop(columns=["trip_id"])
    df.to_csv("trips_to_use.csv")

    print(f"Number of trips: {len(all_trips)}")
    print(f"trips_to_use.csv saved with {len(lines)} line(s)")
    display(df.head())

make_trips_to_use([1, 2, 3, 4, 10, 11, 12, 13, 14, 31, 32, 41, 1145, 1148, 1149], date="2025-09-12")

## MAKE NEW SQLITE
```

```python
def make_gtfs_from_tripids(path_csv, version="v2", location="aalesund-gtfs-txts copy"):
    df_trip_id = pd.read_csv(path_csv)
    list_trip_id = list(df_trip_id["trip_id"])

    stop_times = pd.read_csv("aalesund-gtfs-txts/stop_times.txt", index_col=0)
    stop_times = stop_times[stop_times["trip_id"].isin(list_trip_id)]

    stop_times.to_csv(f"{location}/stop_times.txt")
    print(f"stop_times saved: {location}/stop_times.txt")

    files = ["agency.txt", "calendar_dates.txt", "calendar.txt", "feed_info.txt", "frequencies.txt",
             "routes.txt", "shapes.txt", "stop_times.txt", "stops.txt", "transfers.txt", "trips.txt"]

    if os.path.exists(f"aalesund-gtfs-{version}.zip"):
        os.remove(f"aalesund-gtfs-{version}.zip")

    if os.path.exists(f"aalesund-gtfs-{version}.sqlite"):
        os.remove(f"aalesund-gtfs-{version}.sqlite")

    zip_name = f"aalesund-gtfs-{version}.zip"

    with zipfile.ZipFile(zip_name, "w", compression=zipfile.ZIP_DEFLATED) as zf:
        for f in files:
            zf.write(f"aalesund-gtfs-txts copy/{f}", arcname=f)

    print(f"GTFS-zip made: {zip_name}")

    zip_path = f"{zip_name}"
    sqlite_path = f"aalesund-gtfs-{version}.sqlite"

    import_gtfs.import_gtfs(gtfs_sources=zip_path, output=sqlite_path)

make_gtfs_from_tripids("trips_to_use.csv", version="v4", location="aalesund-gtfs-txts copy")

## IMPORT NEW GTFS
def load_gtfs(imported_database_path, gtfs_path=None, name=""):
    # reimport only if the imported database does not already exist
    if not os.path.exists(imported_database_path):
        print("Importing gtfs zip file")
        import_gtfs.import_gtfs([gtfs_path],  # input: list of GTFS zip files (or directories)
                                imported_database_path,  # output: where to create new sqlite3 database
                                print_progress=True,  # whether to print progress when importing data
                                location_name=name)
    return gtfs.GTFS(imported_database_path)

def generate_graph(gtfs_feed, mode, start_hour=5, end_hour=24):
    # Generates L-space graph considering the most suitable day from GTFS data. Parameters:
    # gtfs_feed: a gtfspy gtfs feed object
    # mode: string corresponding to the transport mode that we want to consider
    # start_hour: integer with the earliest hour we want to consider (in 0..24)
    # end_hour: integer with the latest hour we want to consider (in 0..24, larger that start_hour)

    if not (start_hour>=0 and end_hour>=0):
        raise AssertionError("Start/end hour should be larger or equal to 0")
    if not (start_hour<=24 and end_hour<=24):
        raise AssertionError("Start/end hour should be smaller or equal to 24")
    if not (start_hour<end_hour):
        raise AssertionError("Start hour should be smaller than end hour")
    if not (isinstance(start_hour, int) and isinstance(end_hour, int)):
        raise AssertionError("Start/end hours should be int")
    if not (mode in mode_code and mode_from_string(mode) in gtfs_feed.get_modes()):
        raise AssertionError("Mode is not available for the city")

    day_start = gtfs_feed.get_suitable_date_for_daily_extract(ut=True)
    day_start = 1757628000
    range_start = day_start + (start_hour * 3600)
    range_end = day_start + (end_hour * 3600 - 1)

    print("Considering trips between %s and %s"%(gtfs_feed.unixtime_seconds_to_gtfs_datetime(range_start),
                                                 gtfs_feed.unixtime_seconds_to_gtfs_datetime(range_end)))

    G = networks.stop_to_stop_network_for_route_type(gtfs_feed, mode_from_string(mode), link_attributes=
        None, start_time_ut=range_start, end_time_ut=range_end)

    #Save original id in node attributes (to keep once we merge nodes)
    for n, data in G.nodes(data=True):
        data["original_ids"] = [n]

    print("Number of edges: ", len(G.edges()))
    print("Number of nodes: ", len(G.nodes()))
    return G

def distance(G, n1, n2):
    # Returns the distance in meters between two nodes in the graph.
```

```python
        coords_n1 = (G.nodes[n1]["lat"], G.nodes[n1]["lon"])
        coords_n2 = (G.nodes[n2]["lat"], G.nodes[n2]["lon"])
        return geopy.distance.geodesic(coords_n1, coords_n2).m
140
    def merge_stops_with_same_name(G, delta=100, excepted=[], print_output=True):
        # Merge stops that share the same name and are closer to delta meters.

        aux = list(zip(*G.nodes(data=True)))
145     df_stops = pd.DataFrame(aux[1], index=aux[0]).reset_index()  # Dataframe of stops

        G_res = G.copy()  # Backup original graph

        aux = list(df_stops.groupby("name").index.apply(list))
150     aux2 = [a for a in aux if len(a)>1]  # Merge stations that share a name

        # Merge only nodes that are at most 100m away from the first node with the same name
        aux3=[]
        for group in aux2:
155         clean_group = [group[0]]
            for n in group[1:]:
                if (not group[0] in excepted) and (not n in excepted):
                    if distance(G, group[0], n) <= delta:
                        clean_group.append(n)
160         if len(clean_group) > 1:
                aux3.append(clean_group)
        for repeated in aux3:
            for i in repeated[1:]:
                if print_output == True:
165                 print("Merged %s - %s"%(G_res.nodes[repeated[0]]["name"],G_res.nodes[i]["name"]))
                merge_nodes(G_res,repeated[0],i)
        return G_res


    def merge_nodes(G,n1,n2):
170     # Merges node n2 into n1, updates in/out edges, and merge attributes

        # Out edges
        for e in G.edges(n2, data=True):
            # If we get duplicated edges, average them. This should be a very odd case.
175         if (n1, e[1]) in G.edges(n1):
                # Average travel time
                G[n1][e[1]]["duration_avg"] += e[2]["duration_avg"]
                G[n1][e[1]]["duration_avg"] /= 2.0
                # Sum total n_vehicles
180             G[n1][e[1]]["n_vehicles"] += e[2]["n_vehicles"]
                # Merge route counter
                G[n1][e[1]]["route_I_counts"] = dict(Counter(G[n1][e[1]]["route_I_counts"]) + Counter(e[2]["
                    route_I_counts"]))
                G[n1][e[1]]["shape_id"] = dict(Counter(G[n1][e[1]]["shape_id"]) + Counter(e[2]["shape_id"]))
                G[n1][e[1]]["direction_id"] = dict(Counter(G[n1][e[1]]["direction_id"]) + Counter(e[2]["
                    direction_id"]))
185             G[n1][e[1]]["headsign"] = dict(Counter(G[n1][e[1]]["headsign"]) + Counter(e[2]["headsign"]))
            # Else, retain edge in the merged graph, except for self loops
            elif n1 != e[1]:
                G.add_edge(n1, e[1], duration_avg=e[2]["duration_avg"], n_vehicles=e[2]["n_vehicles"], d=e[2][
                    "d"], route_I_counts=e[2]["route_I_counts"], shape_id=e[2]["shape_id"], direction_id=e
                    [2]["direction_id"], headsign=e[2]["headsign"])  # We keep the original distance (d),
                    which is not exactly right


190 def make_strongly_connected(graph):
        for i in range(150):
            if nx.number_strongly_connected_components(graph) > 1:
                print(nx.number_strongly_connected_components(graph), end=" -> ")
                pure_sources = [n for n in graph.nodes if graph.out_degree(n) > 0 and graph.in_degree(n) == 0]
195             pure_sinks   = [n for n in graph.nodes if graph.in_degree(n) > 0 and graph.out_degree(n) == 0]

                edges_from_pure_sources = list(graph.out_edges(pure_sources, keys=True, data=True)) if graph.
                    is_multigraph() \ else [(u,v,0,d) for u,v,d in graph.out_edges(pure_sources, data=True)]
                edges_to_pure_sinks = list(graph.in_edges(pure_sinks, keys=True, data=True)) if graph.
                    is_multigraph() \ else [(u,v,0,d) for u,v,d in graph.in_edges(pure_sinks, data=True)]

200             if edges_from_pure_sources:
                    if graph.is_multigraph():
                        graph.remove_edges_from([(u,v,k) for u,v,k,_ in edges_from_pure_sources])
                    else:
                        graph.remove_edges_from([(u,v) for u,v,_,_ in edges_from_pure_sources])
205
                if edges_to_pure_sinks:
                    if graph.is_multigraph():
                        graph.remove_edges_from([(u,v,k) for u,v,k,_ in edges_to_pure_sinks])
                    else:
210                     graph.remove_edges_from([(u,v) for u,v,_,_ in edges_to_pure_sinks])

                graph.remove_nodes_from([n for n in graph.nodes if graph.degree(n) == 0])
            else:
```

```
              print(nx.number_strongly_connected_components(graph))
215           break


def plot_graph(G, space="L", back_map=False, MAPS_API_KEY=None, color_by="",edge_color_by="", export_name=
        "", low=0, high=1):
    # Plots a networkx graph. Arguments:
    # G: the nx graph
220     # space: either "L" or "P" depending on which space you are plotting
    # back_map: either False (no map), "GMAPS" (for Google Maps) or "OSM" for OpenStreetMap
    # MAPS_API_KEY: a valid Google maps api key if back_map="GMAPS"
    # color_by: string with the name of an attribute in G.nodes that will be used to color the nodes
    # edge_color_by: string with the name of an attribute in G.edges that will be used to color the nodes
225
    if back_map=="GMAPS":
        map_options = GMapOptions(lat=list(G.nodes(data=True))[0][1]["lat"], lng=list(G.nodes(data=True))
            [0][1]["lon"], map_type="roadmap", zoom=11)
        p = gmap(MAPS_API_KEY, map_options)
    else:
230         p = figure(height=600, width=950, toolbar_location="below", tools="pan, wheel_zoom, box_zoom,
            reset, save")

    #Build dictionary of node positions for visualizations
    pos_dict={}
    #Reproject for OSM
235     transformer = Transformer.from_crs("epsg:4326", "epsg:3857")
    for i,d in G.nodes(data=True):
        if back_map=="OSM":
            x2, y2 = transformer.transform(float(d["lat"]), float(d["lon"]))
        else:
240             x2, y2 = float(d["lon"]), float(d["lat"])
        pos_dict[int(i)] = (x2, y2)

    # Plot updated graph
    graph = from_networkx(G, layout_function=pos_dict)
245
    # Add hover tools
    node_hover_tool = HoverTool(tooltips=[("index", "@index"),
                                          ("name", "@name"),
                                          ("n_bus_arriving", "@n_arriving_buses"),
250                                         ("n_bus_departing", "@n_departing_buses"),
                                          ("passengers", "@passengers")],
                               renderers=[graph.node_renderer])

    hover_edges = HoverTool(tooltips=[("name_i", "@name_i"),
255                                      ("name_j", "@name_j"),
                                      ("duration_avg", "@duration_avg"),
                                      ("d", "@d"),
                                      ("n_vehicles", "@n_vehicles"),
                                      ("link_load", "@link_load"),
260                                      ("vehicle_load", "@vehicle_load"),
                                      ("saturation", "@saturation")],
                           renderers=[graph.edge_renderer],
                           line_policy="interp")

265     if space == 'P':
        hover_edges = HoverTool(tooltips=[("avg_wait", "@avg_wait")],
                               renderers=[graph.edge_renderer],
                               line_policy="interp")
    p.add_tools(node_hover_tool,hover_edges)
270
    # Define the visualization
    if color_by:
        mapper = LinearColorMapper(palette=Magma256[::-1], low=low, high=high)
        graph.node_renderer.glyph = Circle(size=5, fill_color={'field': color_by, 'transform': mapper})
275         color_bar = ColorBar(color_mapper=mapper, label_standoff=12, border_line_color=None, location
            =(0,0))
        p.add_layout(color_bar, "right")
    else:
        graph.node_renderer.glyph = Circle(size=5)

280     if edge_color_by:
        mapper = LinearColorMapper(palette=Magma256[::-1], low=low, high=high)
        graph.edge_renderer.glyph = MultiLine(line_width=3, line_alpha=.5, line_color={'field':
            edge_color_by, 'transform': mapper})
        color_bar = ColorBar(color_mapper=mapper, label_standoff=12, border_line_color=None, location
            =(0,0))
        p.add_layout(color_bar,"right")
285
    graph.node_renderer.selection_glyph = Circle(fill_color='blue')
    graph.node_renderer.hover_glyph = Circle(fill_color='red')
    p.toolbar.active_scroll = p.select_one(WheelZoomTool)

290     # Different hover and select policies depending on the space
    if space == 'P':
```

```python
            graph.edge_renderer.glyph = MultiLine(line_color = 'edge_color')
            graph.edge_renderer.selection_glyph = MultiLine(line_color='edge_color', line_width=5)
            graph.edge_renderer.hover_glyph = MultiLine(line_color='edge_color', line_width=10)
295         title = "P-space graph"
        if space == 'L':
            graph.edge_renderer.selection_glyph = MultiLine(line_color='blue', line_width=5)
            graph.edge_renderer.hover_glyph = MultiLine(line_color='red', line_width=5)
            title = "L-space graph"
300     p.renderers.append(graph)

        if back_map=="OSM":
            p.add_tile("CartoDB Positron")
        if export_name:
305         export_png(p, filename=export_name+".png")
        else:
            show(p)

    def modify_graph(sqlite, version="v4", print_output=True, merge_hub=False, ferries=True):
310     g = load_gtfs(sqlite)
        L = generate_graph(g, "Bus", start_hour=4, end_hour=24)

        # merge stops with same name
        L = merge_stops_with_same_name(L, delta=1000, print_output=print_output)
315     if print_output == False:
            print(f"* merging stops part 1 *")
        merge_recommender(L, string_match=95, stop_distance=1000)

        # merge mobility hub in city centre
320     if merge_hub == True:
            stop_id1 = next(stop[0] for stop in L.nodes(data=True) if stop[1]["name"] == "Korsegata")
            stop_id2 = next(stop[0] for stop in L.nodes(data=True) if stop[1]["name"] == "Keiser Wilhelms gate
                ")
            merge_nodes(L, stop_id2, stop_id1)
            print(f"* merging Korsegata [{stop_id1}] and Keiser Wilhelms gate [{stop_id2}] into '
                Kollektivknutepunkt' *")
325         L.nodes[stop_id2]["name"] = "Kollektivknutepunkt"
        else:
            print(f"* skipping merging Korsegata and Keiser Wilhelms gate into one hub *")

        # merge ferry stops with mobility hub for consistency
330     if ferries == True:
            L_df_nodes = pd.DataFrame([{'id': k, **v} for k, v in list(L.nodes(data=True))])
            L_df_nodes = L_df_nodes.sort_values(by="id", ascending=True)
            L_df_nodes = L_df_nodes.set_index('id')

335         remove_ferries = ["Store Kalvøy hurtigbåtkai", "Hamnsund hurtigbåtkai", "Hareid hurtigbåtkai"]
            for f in remove_ferries:
                L.remove_node(int(L_df_nodes[L_df_nodes["name"]==f].index[0]))
                print(f"* remove {f} [{int(L_df_nodes[L_df_nodes['name']==f].index[0])}] *")

340         connect_for_walking = [["Langevåg hurtigbåtkai", "Lerheimskaia"], ["Ålesund rutebilstasjon
                hurtigbåtkai", "Kollektivknutepunkt"], ["Ålesund hurtigbåtkai Skateflukaia", "
                Kollektivknutepunkt"], ["Valderøya hurtigbåtkai", "Valderhaugstrand"]]
            for c in connect_for_walking:
                c0_node = int(L_df_nodes[L_df_nodes['name']==c[0]].index[0])
                c1_node = int(L_df_nodes[L_df_nodes['name']==c[1]].index[0])
                merge_nodes(L, c1_node, c0_node)
345             print(f"* merging {c[1]} [{c1_node}] and {c[0]} [{c0_node}] *")

        else:
            print(f"* skipping ferries *")

350     # rename stop Simabakken, exists two times
        L.nodes[4409]["name"] = "Simabakken Sør"
        L.nodes[4415]["name"] = "Simabakken Nord"
        print(f"Simabakken -> Sør og Nord")

355     # remove edges with only one vehicle
        list_1_vehicle_edges = []
        for u, v in L.edges():
            if L[u][v]["n_vehicles"] == 1:
                print(f"* removing edge {L.nodes[u]['name']} -> {L.nodes[v]['name']} ({u}, {v}) *")
360             list_1_vehicle_edges.append((u, v))
        L.remove_edges_from(list_1_vehicle_edges)

        # remove selected edges with only two vehicles
        list_2_vehicle_edges = []
365     delete_edges = [["Sjukehuslomma", "Åse"], ["Åse", "Sjukehuslomma"], ["Tessbygget", "Gatestopp Moa"], [
            "Vindgårdskiftet", "Moa trafikkterminal"], ["Moa trafikkterminal", "Vindgårdskiftet"], ["
            Kollektivknutepunkt", "Nørvegata vest"], ["Hoff vest", "Ellingsøy ungdomsskole"], ["Ellingsøy
            ungdomsskole", "Hoff vest"], ["Hoff", "Ellingsøy ungdomsskole"], ["Ellingsøy ungdomsskole", "Hoff
            "], ["Holskrysset", "Holsmyra"], ["Holsmyra", "Holskrysset"], ["Holsmyra", "Frikirka"], ["
            Frikirka", "Holsmyra"], ["Farstad", "Frikirka"], ["Frikirka", "Farstad"], ["Farstad", "Aannø"], [
            "Aannø", "Farstad"], ["Henning Verksted", "Aannø"], ["Aannø", "Henning Verksted"], ["Fyllingen",
```

```
               "Henning Verksted"], ["Henning Verksted", "Fyllingen"], ["Torget", "Fyllingen"], ["Fyllingen", "
               Torget"]]
       for u, v in L.edges():
           if [L.nodes[u]["name"], L.nodes[v]["name"]] in delete_edges:
               print(f"* removing edge manually {L.nodes[u]['name']} -> {L.nodes[v]['name']} ({u}, {v}) *")
               list_2_vehicle_edges.append((u, v))
370    L.remove_edges_from(list_2_vehicle_edges)

       # fill all duration_avg = 0 with duration of 'other-way-around'-edge, or with trendlijn formula
       check_edges = list(L.edges(data=True))
       check_edges = pd.DataFrame([{'id1': k, "id2": j, **v} for k, j, v in check_edges])
375    check_edges.to_csv("output/csv/edges.csv", index=False)

       for i in range(len(check_edges)):
           if check_edges.loc[i, "duration_avg"] < 1:
               id1 = check_edges.loc[i, "id1"]
380            id2 = check_edges.loc[i, "id2"]
               df_check = check_edges[(check_edges["id1"] == id2) & (check_edges["id2"] == id1)]

               if len(df_check) == 1:
                   if L[id2][id1]["duration_avg"] > 0:
385                    L[id1][id2]["duration_avg"] = L[id2][id1]["duration_avg"]
                   else:
                       L[id1][id2]["duration_avg"] = 0.0749 * L[id1][id2]["d"]
               else:
                   L[id1][id2]["duration_avg"] = 0.0749 * L[id1][id2]["d"]
390
               if print_output == True:
                   print(f"({id1:4.0f}, {id2:4.0f}) has now duration_avg {L[id1][id2]['duration_avg']:8.2f}
                       seconds")

       if print_output == False:
395        print(f"* edges filled with duration *")

       # make strongly connected (remove sinks and sources)
       n_str_connected = nx.number_strongly_connected_components(L)
       if n_str_connected == 1:
400        print(f"Graph is strongly connected!")
       else:
           print(f"Graph is not strongly connected, generating...")
           make_strongly_connected(L)

405    # save graph
       save_graph(L, f"aalesund-gtfs-{version}.pkl")
       print(f"Graph saved in 'aalesund-gtfs-{version}.pkl'")

   modify_graph("aalesund-gtfs-v4.sqlite", version="v4", print_output=False, merge_hub=True, ferries=True)
410 plot_graph(L, "L", back_map="OSM")
```

Code G.10: Network structure analysis.

```
 1 def P_space(g, L, mode, start_hour=5, end_hour=24, dir_indicator=None):
       # Create P-space graph given:
       # g: gtfs feed
       # L: L-space

 5
       if not (start_hour>=0 and end_hour>=0):
           raise AssertionError("Start/end hour should be larger or equal to 0")
       if not (start_hour<=24 and end_hour<=24):
           raise AssertionError("Start/end hour should be smaller or equal to 24")
10     if not (start_hour<end_hour):
           raise AssertionError("Start hour should be smaller than end hour")
       if not (isinstance(start_hour, int) and isinstance(end_hour, int)):
           raise AssertionError("Start/end hours should be int")

15     time=end_hour-start_hour
       # Create a list of backup colors
       backup_colors = ['0000FF', '008000', 'FF0000', '00FFFF', 'FF00FF', 'FFFF00', '800080', 'FFC0CB', '
           A52A2A', 'FFA500', 'FF7F50', 'ADD8E6', '00FF00', 'E6E6FA', '40E0D0', '006400', 'D2B48C', 'FA8072'
           , 'FFD700']

       # Create the P-space graph with the nodes from L-space
20     P_G = nx.DiGraph()
       P_G.add_nodes_from(L.nodes(data=True))

       # Get a list of all routes of the network, with corresponding colors
       routes = get_routes_for_mode(g,mode)

25
       # Exception for Vienna metro network
       if(g.get_location_name() == 'vienna') and (mode_from_string(mode)==1):
           routes = routes[::2]

30     colors = get_color_per_route(g, routes)
```

```python
    if not dir_indicator:
        # Check to see if direction/headsign/shape exists
        dir_indicator = 'empty'

        edge_it = iter(L.edges(data=True))
        check_edge = next(edge_it, None)
        if check_edge:
            if check_edge[2]['direction_id']:
                dir_indicator = 'direction_id'
            elif check_edge[2]['headsign']:
                dir_indicator = 'headsign'
            elif check_edge[2]['shape_id']:
                dir_indicator = 'shape_id'

            # Exception for Bilbao metro network
            if(g.get_location_name() == 'bilbao') and (mode_from_string(mode)==1):
                dir_indicator = 'headsign'

    # Exception for Philadelphia network
            if(g.get_location_name() == 'philadelphia') and (mode_from_string(mode)==1):
                dir_indicator = 'headsign'

    # Exception for Amsterdam network
            if(g.get_location_name() == 'amsterdam') and (mode_from_string(mode)==1):
                dir_indicator = 'headsign'

            # Exception for Paris RER
            if(g.get_location_name() == 'paris') and (mode_from_string(mode)==2):
                dir_indicator = 'headsign'

    print("Using %s field as indicator for the direction of routes"%dir_indicator)

    # Loop through all routes
    for iter_n,r in enumerate(routes):

        # Get the route color (or a backup if unavailable)
        color = colors[r]
        if not color or len(color) != 6 \
            or (g.get_location_name() == 'nuremburg') and (mode_from_string(mode)==1): #All blue lines in
                nuremberg metro GTFS
            #color = next(backup_colors)
            color=backup_colors[iter_n%len(backup_colors)]

        # Create a set of the directions/headsigns/shapes for this route
        dirs = set()
        for e in L.edges(data=True):
            if r in e[2]['route_I_counts']:
                for h in e[2][dir_indicator].keys():
                    dirs.add(h)

        # Create a subgraph for each direction and add the edges to P-space
        for d in dirs:
            # Create an empty (directional) subgraph
            sub = nx.DiGraph()

            # Add all edges (and corresponding nodes) that are on this route and direction
            for e in L.edges(data=True):
                if r in e[2]['route_I_counts'] and d in e[2][dir_indicator]:
                    sub.add_edges_from([(e)])

            # Loop through all nodes in the subgraph that have paths between them
            for n1 in sub:
                for n2 in sub:
                    if n1 != n2 and nx.has_path(sub, n1, n2):

                        aux_out=[(a,b,c) for a,b,c in sub.out_edges(n1, data=True) if a in nx.
                            shortest_path(sub,n1,n2) and b in nx.shortest_path(sub,n1,n2)]
                        out_e=aux_out[0]

                        aux_in=[(a,b,c) for a,b,c in sub.in_edges(n2, data=True) if a in nx.shortest_path(
                            sub,n1,n2) and b in nx.shortest_path(sub,n1,n2)]
                        in_e=aux_in[0]

                        # Take the lowest number of vehicles between the two edges
                        veh_out = out_e[2]['route_I_counts'][r]
                        veh_in = in_e[2]['route_I_counts'][r]
                        veh = min(veh_out, veh_in)

                        # Compute the average waiting time
                        veh_per_hour = veh / time
                        max_wait = 60 / veh_per_hour
                        avg_wait = max_wait / 2
```

```python
                        # If the edge already exists, append the values
                        if P_G.has_edge(n1, n2):

                            # Change the color to black to signify a shared edge
                            P_G[n1][n2]['edge_color'] = '#000000'

                            # Add the vehicles per hour for this route + direction to the wait_dir
                            if r not in P_G[n1][n2]['veh']:
                                P_G[n1][n2]['veh'][r] = {d: veh_per_hour}
                            else:
                                P_G[n1][n2]['veh'][r][d] = veh_per_hour

                            # Update the average waiting time to be the total of all routes' waiting times
                            tot_veh = 0
                            for ro in P_G[n1][n2]['veh']:
                                for di in P_G[n1][n2]['veh'][ro]:
                                    tot_veh = tot_veh + P_G[n1][n2]['veh'][ro][di]
                            P_G[n1][n2]['avg_wait'] = (60 / tot_veh) / 2

                        else:
                            P_G.add_edge(n1, n2, veh={r: {d: veh_per_hour}},
                                         avg_wait=avg_wait, edge_color='#'+str(color))
    return P_G

g = load_gtfs("aalesund-gtfs-v4.sqlite")
L = load_graph("aalesund-gtfs-v4.pkl")
P = P_space(g, L, start_hour=4, end_hour=24, mode="Bus")

plot_graph(P, "P", back_map="OSM")
plot_graph(L, "L", back_map="OSM")

def graph_details(L, P, indicator):
    if indicator=="global":
        nodes_L, nodes_P = len(L.nodes), len(P.nodes)
        print(f"Nodes in L-space: {nodes_L}, nodes in P-space: {nodes_P}")
        edges_L, edges_P = len(nx.edges(L)), len(nx.edges(P))
        print(f"Edges in L-space: {edges_L}, edges in P-space: {edges_P}")
        diameter_uw_L, diameter_uw_P = nx.diameter(G=L, weight=None), nx.diameter(G=P, weight=None)
        print(f"Diameter (unweighted) in L: {diameter_uw_L:.2f}, in P: {diameter_uw_P:.2f}")
        diameter_w_L, diameter_w_P = nx.diameter(G=L, weight='duration_avg'), nx.diameter(G=P, weight='
            avg_wait')
        print(f"Diameter (weighted) in L: {diameter_w_L:.2f}, in P {diameter_w_P:.2f}")
        asp_uw_L, asp_uw_P = nx.average_shortest_path_length(G=L, weight=None), nx.
            average_shortest_path_length(G=P, weight=None)
        print(f"Avg. Shortest Path (unweighted) in L: {asp_uw_L:.2f}, in P: {asp_uw_P:.2f}")

        asp_w_L, asp_w_P = nx.average_shortest_path_length(G=L, weight="duration_avg"), nx.
            average_shortest_path_length(G=P, weight="avg_wait")
        print(f"Avg. Shortest Path (weighted) in L: {asp_w_L:.2f}, in P: {asp_w_P:.2f}")

        V, E = L.number_of_nodes(), L.number_of_edges()
        gamma_L, alpha_L = E / (3*V - 6), (E - V + 1) / (2*V - 5)
        print(f"Connectivity (gamma index): {gamma_L:.2f}, meshedness (alpha index): {alpha_L:.2f}")

    elif indicator=="local":
        print("L-space")
        L_k_vals = list(nx.degree_centrality(G=L).values())
        L_k_avg, L_k_std = sum(L_k_vals) / len(L_k_vals), pd.Series(L_k_vals).std()
        L_k_min, L_k_max = min(L_k_vals), max(L_k_vals)
        print(f"Degree - avg: {L_k_avg:.5f}, std: {L_k_std:.5f}, min: {L_k_min:.5f}, max: {L_k_max:.5f}")

        L_c_uw_vals = list(nx.closeness_centrality(G=L, distance=None).values())
        L_c_uw_avg, L_c_uw_std = sum(L_c_uw_vals) / len(L_c_uw_vals), pd.Series(L_c_uw_vals).std()
        L_c_uw_min, L_c_uw_max = min(L_c_uw_vals), max(L_c_uw_vals)
        print(f"Connectivity (uw) - avg: {L_c_uw_avg:.5f}, std: {L_c_uw_std:.5f}, min: {L_c_uw_min:.5f},
            max: {L_c_uw_max:.5f}")

        L_c_w_vals = list(nx.closeness_centrality(G=L, distance="duration_avg").values())
        L_c_w_avg, L_c_w_std = sum(L_c_w_vals) / len(L_c_w_vals), pd.Series(L_c_w_vals).std()
        L_c_w_min, L_c_w_max = min(L_c_w_vals), max(L_c_w_vals)
        print(f"Connectivity (w) - avg: {L_c_w_avg:.5f}, std: {L_c_w_std:.5f}, min: {L_c_w_min:.5f}, max:
            {L_c_w_max:.5f}")

        L_b_uw_vals = list(nx.betweenness_centrality(G=L, weight=None, normalized=True).values())
        L_b_uw_avg, L_b_uw_std = sum(L_b_uw_vals) / len(L_b_uw_vals), pd.Series(L_b_uw_vals).std()
        L_b_uw_min, L_b_uw_max = min(L_b_uw_vals), max(L_b_uw_vals)
        print(f"Betweenness (uw) - avg: {L_b_uw_avg:.5f}, std: {L_b_uw_std:.5f}, min: {L_b_uw_min:.5f},
            max: {L_b_uw_max:.5f}")

        L_b_w_vals = list(nx.betweenness_centrality(G=L, weight="duration_avg", normalized=True).values())
        L_b_w_avg, L_b_w_std = sum(L_b_w_vals) / len(L_b_w_vals), pd.Series(L_b_w_vals).std()
        L_b_w_min, L_b_w_max = min(L_b_w_vals), max(L_b_w_vals)
        print(f"Betweenness (w) - avg: {L_b_w_avg:.5f}, std: {L_b_w_std:.5f}, min: {L_b_w_min:.5f}, max: {
            L_b_w_max:.5f}")
```

```
190        print("P-space")
           P_k_vals = list(nx.degree_centrality(G=P).values())
           P_k_avg, P_k_std = sum(P_k_vals) / len(P_k_vals), pd.Series(P_k_vals).std()
           P_k_min, P_k_max = min(P_k_vals), max(P_k_vals)
           print(f"Degree - avg: {P_k_avg:.5f}, std: {P_k_std:.5f}, min: {P_k_min:.5f}, max: {P_k_max:.5f}")
195
           P_c_uw_vals = list(nx.closeness_centrality(G=P, distance=None).values())
           P_c_uw_avg, P_c_uw_std = sum(P_c_uw_vals) / len(P_c_uw_vals), pd.Series(P_c_uw_vals).std()
           P_c_uw_min, P_c_uw_max = min(P_c_uw_vals), max(P_c_uw_vals)
           print(f"Connectivity (uw) - avg: {P_c_uw_avg:.5f}, std: {P_c_uw_std:.5f}, min: {P_c_uw_min:.5f},
               max: {P_c_uw_max:.5f}")
200
           P_c_w_vals = list(nx.closeness_centrality(G=P, distance="avg_wait").values())
           P_c_w_avg, P_c_w_std = sum(P_c_w_vals) / len(P_c_w_vals), pd.Series(P_c_w_vals).std()
           P_c_w_min, P_c_w_max = min(P_c_w_vals), max(P_c_w_vals)
           print(f"Connectivity (w) - avg: {P_c_w_avg:.5f}, std: {P_c_w_std:.5f}, min: {P_c_w_min:.5f}, max:
               {P_c_w_max:.5f}")
205
           P_b_uw_vals = list(nx.betweenness_centrality(G=P, weight=None, normalized=True).values())
           P_b_uw_avg, P_b_uw_std = sum(P_b_uw_vals) / len(P_b_uw_vals), pd.Series(P_b_uw_vals).std()
           P_b_uw_min, P_b_uw_max = min(P_b_uw_vals), max(P_b_uw_vals)
           print(f"Betweenness (uw) - avg: {P_b_uw_avg:.5f}, std: {P_b_uw_std:.5f}, min: {P_b_uw_min:.5f},
               max: {P_b_uw_max:.5f}")
210
           P_b_w_vals = list(nx.betweenness_centrality(G=P, weight="avg_wait", normalized=True).values())
           P_b_w_avg, P_b_w_std = sum(P_b_w_vals) / len(P_b_w_vals), pd.Series(P_b_w_vals).std()
           P_b_w_min, P_b_w_max = min(P_b_w_vals), max(P_b_w_vals)
           print(f"Betweenness (w) - avg: {P_b_w_avg:.5f}, std: {P_b_w_std:.5f}, min: {P_b_w_min:.5f}, max: {
               P_b_w_max:.5f}")
215
       else:
           print("Kies een indicator: 'global' of 'local'")

   graph_details(L, P, indicator="global")
220 graph_details(L, P, indicator="local")

   ## SET NODE ATTRIBUTES IN L
   nx.set_node_attributes(L, nx.degree_centrality(G=L), "degree")
   nx.set_node_attributes(L, nx.closeness_centrality(G=L, distance="duration_avg"), "closeness_w")
225 nx.set_node_attributes(L, nx.closeness_centrality(G=L, distance=None), "closeness_uw")
   nx.set_node_attributes(L, nx.betweenness_centrality(G=L, weight="duration_avg", normalized=True), "
       betweenness_w")
   nx.set_node_attributes(L, nx.betweenness_centrality(G=L, weight=None, normalized=True), "betweenness_uw")

   plot_graph(L, "L", back_map="OSM", color_by="degree", low=0.0067, high=0.034)
230 plot_graph(L, "L", back_map="OSM", color_by="closeness_w", low=0.00023, high=0.000630)
   plot_graph(L, "L", back_map="OSM", color_by="betweenness_w", low=0, high=0.56)

   ## FIND (i, j)-PAIR WITH MAXIMUM NUMBER OF STOPS
   spl = dict(nx.all_pairs_shortest_path_length(L))
235 diam_pair, diam_dist = None, -1
   for i, dists in spl.items():
       for j, dist in dists.items():
           if dist > diam_dist:
               diam_pair, diam_dist = (i, j), dist
240 path_unw = nx.shortest_path(L, source=diam_pair[0], target=diam_pair[1])
   print(f"Unweighted diameter: {diam_dist} stops, between {L.nodes[diam_pair[0]]['name']} and {L.nodes[
       diam_pair[1]]['name']}, via {path_unw}")

   ## FIND (i, j)-PAIR WITH MAXIMUM TRAVEL-TIME
   lengths = dict(nx.all_pairs_dijkstra_path_length(L, weight="duration_avg"))
245 diam_pair_w, diam_dist_w = None, -1.0
   for i, dists in lengths.items():
       for j, dist in dists.items():
           if dist > diam_dist_w and dist < float("inf"):
               diam_pair_w, diam_dist_w = (i, j), dist
250 path_w = nx.dijkstra_path(L, source=diam_pair_w[0], target=diam_pair_w[1], weight="duration_avg")
   print(f"Weighted diameter: {diam_dist_w:.0f} s (~{diam_dist_w/60:.1f} min), between {L.nodes[diam_pair_w
       [0]]['name']} and {L.nodes[diam_pair_w[1]]['name']}, via {path_w}")

   ## FOR VISUALISATION
   nx.set_node_attributes(L, 0.5, "diameter")
255 nx.set_edge_attributes(L, 0.5, "diameter")

   path = path_w
   for i in range(len(path)-1):
       u = path[i]
260    v = path[i+1]
       L.nodes[u]["diameter"], L.nodes[v]["diameter"], L.edges[u, v]["diameter"] = 0, 0, 0
       try:
           L.edges[v, u]["diameter"] = 0  # for better visuals in figure
       except KeyError:
265        pass
```

```
plot_graph(L, back_map="OSM", color_by="diameter", edge_color_by="diameter")
```

Code G.11: Network design and passenger flow distribution.

```
1  g = load_gtfs("aalesund-gtfs-v4.sqlite")
   L = load_graph("aalesund-gtfs-v4.pkl")
   P = P_space(g, L, start_hour=4, end_hour=24, mode="Bus")

5  ## DELETE UNNECESSARY KEYS AND ADD NAMES FOR EDGES FOR EASE
   for u, v in L.edges:
       L[u][v].pop('shape_id', None)
       L[u][v].pop('headsign', None)
       L[u][v].pop('direction_id', None)
10     L[u][v]["name_i"] = L.nodes[u]["name"]
       L[u][v]["name_j"] = L.nodes[v]["name"]

   ## COMPUTE SHORTEST PATHS BETWEEN ALL PAIR OF NODES
   # GTC(sp_i) = in-vehicle-time(sp_i) + alpha * waiting-time(sp_i) + beta * N_transfers
15 def save_to_pkl(file, base_name, folder="output/pkl", ext=".pkl"):
       path = f"{folder}/{base_name}{ext}"
       if os.path.exists(path):
           os.remove(path)
       with open(path, "wb") as f:
20         pickle.dump(file, f)

   def get_all_GTC(L_space, P_space, k, wait_pen, transfer_pen):

       # Initialize a dictionary containing all shortest path information, indexed by node pairs
25     shortest_paths = dict()
       print(f"Calculating {len(L_space.nodes)} GTC...")
       # Loop through all node combinations
       for n1 in L_space.nodes:
           if n1%5==0:
30          # print("%d/%d"%(n1,len(L_space.nodes)), end="\r")
               per_done = n1/len(L_space.nodes) * 40
               per_notdone = int(40 - int(per_done))
               print(f"{int(per_done) *''}{per_notdone *''} [{(per_done*2.5):4.1f}%]{10*' '}", end="\r")
           shortest_paths[n1] = {}
35
           for n2 in L_space.nodes:
               # Exclude self-loops
               if n1 == n2:
                   continue
40
               #print("Considering the path between", n1, "and", n2)

               # Retrieve the k shortest paths from L-space, using travel time/duration as a weight
               k_paths = k_shortest_paths(L_space, n1, n2, k, 'duration_avg')
45
               # Two auxiliary datastructures to store the different shortest paths and corresponding
                   attributes
               tt_paths = []
               only_tts = []

50             # Loop through all k-shortest paths and record the different travel time components
               for p in k_paths:
                   # Record the original route/line taken from the origin node
                   possible_routes= get_routes_dirs(P_space, p[0], p[1])

55                 # Initialize the distance, (in-vehicle) travel time, waiting time and number of transfers
                       as 0
                   dist = 0
                   tt = 0
                   wait = 0
                   tf = 0
60
                   # Record the list of transfer stations, having the origin as the first "transfer station"
                   t_stations = [n1]

                   # Check the routes of all successive node pairs in the path,
65                 # if all routes of the original edge are not on the next edge, a transfer must have been
                       made OR
                   # if all routes of the previous edge are not on the next edge, a transfer must have been
                       made
                   # Route(s) on that edge become new route.
                   # Also update the in-vehicle travel time for each edge passed.
                   for l1, l2 in zip(p[::1], p[1::1]):
70                     tt += L_space[l1][l2]['duration_avg']
                       dist += L_space[l1][l2]['d']
                       routes = get_routes_dirs(P_space, l1, l2)
                       possible_routes = set(possible_routes).intersection(set(routes))
                       #if set(orig_routes).isdisjoint(routes) or set(prev_routes).isdisjoint(routes):
```

```python
75                          if not possible_routes:
                                possible_routes = routes
                                tf += 1
                                t_stations.append(l1)
                            #prev_routes = get_routes_dirs(P_space, l1, l2)

80                      # Add the destination node as the final transfer station
                        t_stations.append(n2)

                        # Change travel time to minutes and round to whole minutes
85                      tt = round(tt / 60)

                        # Find the waiting times belonging to the different routes taken by looping through all
                            transfer station pairs
                        for t1, t2 in zip(t_stations[::1], t_stations[1::1]):
                            try:
90                              wait += P_space[t1][t2]['avg_wait']
                            except KeyError:
                                # print("No P-space edge between transfer stations %d and %d"%(t1,t2))
                                pass

95                      # Round the waiting time to whole minutes
                        wait = round(wait)

                        # Calculate the total travel time, take a penalty for the waiting time and per transfer
                        transfer_cost=sum([transfer_pen[i] if i<len(transfer_pen) else transfer_pen[-1] for i in
                            range(tf)])
100                     total_tt = tt + wait * wait_pen + transfer_cost
                        only_tts.append(total_tt)
                        tt_paths.append({'path': p, 'GTC': total_tt, 'in_vehicle': tt, 'waiting_time': wait, '
                            n_transfers': tf, 'traveled_distance': dist, 'transfer_stations': t_stations})

                    if k_paths:
105                      shortest_paths[n1][n2]=sorted(tt_paths, key=lambda x: x["GTC"])
                    else:
                        shortest_paths[n1][n2]=[]

                        # Find the path with the shortest total travel time
110                     #min_path_tt = min(only_tts)
                        #min_path = tt_paths[only_tts.index(min_path_tt)]

                        #print("Shortest path is:", min_path, "\n")

115                     # Record that path as the shortest path belonging to nodes n1 and n2
                        #shortest_paths[n1][n2] = min_path

                        # Find the geodesic distance between the two nodes
                        #x1 = L_space.nodes[n1]['lat']
120                     #y1 = L_space.nodes[n1]['lon']
                        #x2 = L_space.nodes[n2]['lat']
                        #y2 = L_space.nodes[n2]['lon']

                        #crow_dist = round(distance(L_space, n1, n2))
125                     #shortest_paths[n1][n2]['crow_dist'] = crow_dist
        print(100*" ", end="\r")
        print("All GTC computed!")
        return shortest_paths

130 alpha, betas, m = 1.2, [10], 3  # waiting time penalty, transfer penalty, number of shortest paths
    gtc = get_all_GTC(L, P, m, alpha, betas)
    save_to_pkl(gtc, base_name="gtc_all")
    gtc = open_pkl("output/pkl/gtc_all.pkl")
    # gtc[1][2]

135
    ## CREATE ORIGIN-DESTINATION MATRIX
    def number_of_people_in_network(dis, L):
        ylim, xlim = [62.38, 62.6], [5.94, 6.58]
        rot_marker = MarkerStyle("s")
140     rot_marker._transform.rotate_deg(16)
        ms, ec = 15, "w"

        nx.set_node_attributes(L, nx.betweenness_centrality(G=L, weight="duration_avg", normalized=True), "
            betweenness_w")
        nx.set_node_attributes(L, 0, "pop_to_stop")
145     nodes = pd.DataFrame([{'id': k, **v} for k, v in list(L.nodes(data=True))])

        gdf_befolkning_4326 = pd.read_csv("output/csv/gdf_befolkning.csv")
        gdf_befolkning_4326 = gdf_befolkning_4326[(gdf_befolkning_4326["lon"] <= xlim[1]) & (
            gdf_befolkning_4326["lon"] >= xlim[0]) &
                                                  (gdf_befolkning_4326["lat"] <= ylim[1]) & (
                                                      gdf_befolkning_4326["lat"] >= ylim[0])]
150     gdf_befolkning_4326 = gdf_befolkning_4326.sort_values(by="lon").reset_index().drop(columns=["index"])

        pop_used, pop_notused, mean_d = [], [], []
```

```python
      for i in range(len(gdf_befolkning_4326)):
155       coords_pop = [gdf_befolkning_4326.loc[i, "lat"], gdf_befolkning_4326.loc[i, "lon"]]
          d, s = dis, -1
          nodes_compact = nodes[(nodes["lon"] <= coords_pop[1]+0.05) & (nodes["lon"] >= coords_pop[1]-0.05)
              & (nodes["lat"] <= coords_pop[0]+0.1) & (nodes["lat"] >= coords_pop[0]-0.1)]
          p_stop, p_stop_d = [], []
          p_stop_short, p_stop_b_short, p_stop_d_short = [], [], []
160       for stop in nodes_compact["id"]:
              coords_bus = nodes_compact.loc[stop, "lat"], nodes_compact.loc[stop, "lon"]
              distance = geopy.distance.geodesic(coords_bus, coords_pop).m
              if distance < 250:
                  p_stop_short.append(stop)
165               p_stop_d_short.append(distance)
                  p_stop_b_short.append(L.nodes[stop]["betweenness_w"])
              elif distance < d:
                  p_stop.append(stop)
                  p_stop_d.append(distance)
170               s = stop
          if s != -1:
              if len(p_stop_short) > 1:
                  index_to_use = p_stop_b_short.index(np.max(p_stop_b_short))
                  s = p_stop_short[index_to_use]
175                   L.nodes[s]["pop_to_stop"] += gdf_befolkning_4326.loc[i, 'pop_tot']
                  mean_d.append(p_stop_d_short[index_to_use])
              elif len(p_stop_short) == 1:
                  index_to_use = 0
                  s = p_stop_short[index_to_use]
180                   L.nodes[s]["pop_to_stop"] += gdf_befolkning_4326.loc[i, 'pop_tot']
                  mean_d.append(p_stop_d_short[index_to_use])
              else:
                  index_to_use = p_stop_d.index(np.max(p_stop_d))
                  s = p_stop[index_to_use]
185                   L.nodes[s]["pop_to_stop"] += gdf_befolkning_4326.loc[i, 'pop_tot']
                  mean_d.append(p_stop_d[index_to_use])
              pop_used.append(i)
          else:
              pop_notused.append(i)
190
number_of_people_in_network(dis=1625, L=L)  # assigns people to nodes
Q = 757 * 0.32 * 45  # number of bus times average number of people per trip
print(f"Number of trips in one day: {Q:.2f}")

195 ## COMPUTING MATRICES FOR OD
def compute_skims(gtc, nodes):
    """Compute skim matrices: in-vehicle time, waiting time, transfers"""
    t_ij = pd.DataFrame(index=nodes, columns=nodes, dtype=float)
    w_ij = pd.DataFrame(index=nodes, columns=nodes, dtype=float)
200     tr_ij = pd.DataFrame(index=nodes, columns=nodes, dtype=float)
    gtc_ij = pd.DataFrame(index=nodes, columns=nodes, dtype=float)
    for i in nodes:
        for j in nodes:
            if i == j:
205                 t_ij.loc[i, j], w_ij.loc[i, j], tr_ij.loc[i, j], gtc_ij.loc[i, j] = 0, 0, 0, 0
            else:
                t_ij.loc[i, j], w_ij.loc[i, j] = gtc[i][j][0]["in_vehicle"], gtc[i][j][0]["waiting_time"]
                tr_ij.loc[i, j], gtc_ij.loc[i, j] = gtc[i][j][0]["n_transfers"], gtc[i][j][0]["GTC"] / 60
                    # convert to minutes
    return t_ij, w_ij, tr_ij, gtc_ij
210
def compute_impedance(gtc_ij, nodes, alpha, beta):
    """Compute impedance f_ij = alpha * exp(-beta * t_ij)"""
    f_ij = pd.DataFrame(index=nodes, columns=nodes, dtype=float)
    for i in nodes:
215         for j in nodes:
            if i == j:
                f_ij.loc[i, j] = 0
            else:
                f_ij.loc[i, j] = alpha * np.exp(-beta * gtc_ij.loc[i, j])
220     return f_ij

def compute_production(series, Q):
    """Compute production q_i = (betweenness_i / total) * Q"""
    share = series / np.sum(series)
225     return share * Q

def compute_gravity_distribution(q, f_ij):
    """Compute OD matrix x_ij using gravity model"""
    nodes = q.index
230     x_ij = pd.DataFrame(index=nodes, columns=nodes, dtype=float)
    for i in nodes:
        denom = sum(q.loc[k] * f_ij.loc[i, k] for k in nodes if k != i)
        for j in nodes:
            if i == j:
```

```
235                 x_ij.loc[i, j] = 0
                else:
                    numer = q.loc[j] * f_ij.loc[i, j]
                    x_ij.loc[i, j] = (numer / denom) * q.loc[i]
        return x_ij

240
    pd.set_option('display.float_format', lambda x: '%.6f' % x)
    nodes, alpha_grav, beta_grav = len(L.nodes()), 1, 1

    t_ij, waiting_ij, transfer_ij, gtc_ij = compute_skims(gtc, list(range(nodes)))
245 f_ij = compute_impedance(gtc_ij, list(range(nodes)), alpha_grav, beta_grav)
    series = df_nodes.set_index("id")["pop_to_stop"]
    q = compute_production(series, Q).to_frame("number_of_passengers")
    x_ij = compute_gravity_distribution(q["number_of_passengers"], f_ij)
    display(x_ij)

250
    x_ij.to_csv("output/csv/OD_matrix.csv")

    ## PASSENGER ASSIGNMENT
    nx.set_edge_attributes(L, 0, "link_load")
255 for i in L.nodes:
        L.nodes[i]["passengers"] = q.loc[i, "number_of_passengers"]
        for j in L.nodes:
            if i != j:
                n_shortest_paths = len(gtc[i][j])
260             for m in range(n_shortest_paths):
                    path_m, gtc_m = gtc[i][j][m]["path"], gtc[i][j][m]["GTC"]
                    denom = sum(np.exp(-gtc[i][j][p]["GTC"]) for p in range(n_shortest_paths))
                    if denom == 0:
                        prob = 1
265                 else:
                        prob = np.exp(-gtc[i][j][m]["GTC"]) / denom

                    for k in range(len(path_m)-1):
                        node_1, node_2 = path_m[k], path_m[k+1]
270                     existing_load = L.edges[node_1, node_2]["link_load"]
                        L.edges[node_1, node_2]["link_load"] = existing_load + x_ij.iloc[i, j] * prob

    ## DETERMINE VEHICLE UTILISATION
    def graph_df(L, P):
275     df_nodes = pd.DataFrame([{'id': k, **v} for k, v in list(L.nodes(data=True))])
        df_edges = pd.DataFrame([{'id_i': u, 'id_j': v, **d} for u, v, d in list(L.edges(data=True))])
        df_Pspace = pd.DataFrame([{'id_i': u, 'id_j': v, **d} for u, v, d in list(P.edges(data=True))])
        return df_nodes, df_edges, df_Pspace

280 for u, v in L.edges():
        L[u][v]["vehicle_load"] = L[u][v]["link_load"] / L[u][v]["n_vehicles"]
        if [u, v] in [[15, 223], [223, 15]]:
            L[u][v]["saturation"] = L[u][v]["vehicle_load"] / np.mean([250, 130])  # line 1145 and 1149
        elif [u, v] in [[15, 73], [73, 15]]:
285         L[u][v]["saturation"] = L[u][v]["vehicle_load"] / 130  # line 1148
        else:
            L[u][v]["saturation"] = L[u][v]["vehicle_load"] / 45

    df_nodes, df_edges, df_Pspace = graph_df(L, P)

290
    print(f"Mean saturation in the network: {df_edges['saturation'].mean():.2f}")
```

G.3. Codes for Structural Analysis

Code G.12: SLS calculation: Maximum Prestress

```
1 b = 0.7
  h = 1.2
  A = b * h
  fcd = 45 / 1.5 # MPa in N/mm2
5 f_t = 1770
  P = A * fcd * 1000
  print(f'P_max   {-P} kN')

  # OUTPUT
10 P_max   -25200.0 kN
```

Code G.13: SLS calculation: Tensile force of arch & moments in arch

```
1 #q = self weight arch

  N_deck = 1116 #kN from Diana
  print(f'P   {N_deck} kN')

5
  #OUTPUT
```

```
   P   1116 kN

   # Moment top (tension)
10 N_arch = 1523 # kN from Diana
   A_arch = b * h
   W_arch = 1/6 * b * h**2
   M_max = 227 # kNm from Diana

15 print(f'{-N_arch/A_arch - M_max/W_arch} <= {-fcd * 1000} kN/m2')

   # Moment bottom (compression)
   print(f'{-N_arch/A_arch + M_max/W_arch} <= {f_t} kN/m2')

20 # OUTPUT
   -3164.2857142857147 <= -30000.0 kN/m2
   -461.9047619047617 <= 1770 kN/m2
```

Code G.14: SLS calculation: During transport

```
1  # q = self weight arch + deck

   N_deck = 5868 #kN from Diana
   N_arch = 7403 # kN from Diana
5  M_deck = 664 # kNm from Diana
   M_arch = 839 # kNm from Diana

   print(f'{-N_arch/A_arch - M_arch/W_arch} <= {-fcd * 1000} kN/m2')
   print(f'{-N_arch/A_arch + M_arch/W_arch} <= {f_t} kN/m2')
10
   A_deck = b * h
   W_deck = 1/6 * b * h**2
   print(f'{N_deck/A_deck - M_deck/W_deck - P/A_deck} <= {-fcd * 1000} kN/m2')
   print(f'{N_deck/A_deck + M_deck/W_deck - P/A_deck} <= {f_t} kN/m2')
15
   # OUTPUT
   -13807.142857142859 <= -30000.0 kN/m2
   -3819.0476190476193 <= 1770 kN/m2
   -26966.666666666668 <= -30000.0 kN/m2
20 -19061.904761904763 <= 1770 kN/m2
```

Code G.15: SLS calculation: During transport (with half of the prestressing)

```
1  # q = self weight arch + deck

   N_deck = 5868 #kN from Diana
   N_arch = 7403 # kN from Diana
5  M_deck = 664 # kNm from Diana
   M_arch = 839 # kNm from Diana

   print(f'{-N_arch/A_arch - M_arch/W_arch} <= {-fcd * 1000} kN/m2')
   print(f'{-N_arch/A_arch + M_arch/W_arch} <= {f_t} kN/m2')
10
   A_deck = b * h
   W_deck = 1/6 * b * h**2
   print(f'{N_deck/A_deck - M_deck/W_deck - (P/2)/A_deck} <= {-fcd * 1000} kN/m2')
   print(f'{N_deck/A_deck + M_deck/W_deck - (P/2)/A_deck} <= {f_t} kN/m2')
15
   # OUTPUT
   -13807.142857142859 <= -30000.0 kN/m2
   -3819.0476190476193 <= 1770 kN/m2
   -11966.666666666666   -30000.0 kN/m2
20 -4061.9047619047615   1770 kN/m2
```

Code G.16: ULS calculation: Most critical condition

```
1  # q = all permanent and variable loads

   N_arch = 11474 # kN from Diana
   M_arch = 1303 # kNm from Diana
5  N_cable = 821 # kN from Diana

   print(f'{-N_arch/A_arch - M_arch/W_arch}   {-fcd * 1000} kN/m2')
   print(f'{-N_arch/A_arch + M_arch/W_arch}   {f_t} kN/m2')

10 #OUTPUT
   print(f'{-N_arch/A_arch - M_arch/W_arch}   {-fcd * 1000} kN/m2')
   print(f'{-N_arch/A_arch + M_arch/W_arch}   {f_t} kN/m2')


15 N_deck = 9106 #kN
   M_deck = 1063 #kNm
```

```
   W_deck = 1/6 * b * h**2
   A_deck = b * h
   f_t = 1770 #kN/m2
20 P = (N_deck/A_deck + M_deck/W_deck - f_t) * A_deck
   print(P)

   stress = P/4 / (31 * 150) * 1000
   print(stress)
25 print(f'UC = {stress/1522:.2f}')

   # OUTPUT
   -13807.142857142859 <= -30000.0 kN/m2
   -3819.0476190476193 <= 1770 kN/m2
30 -26966.666666666668 <= -30000.0 kN/m2
   -19061.904761904763 <= 1770 kN/m2


   A_cable = np.pi*(50**2)/1000000
35 print(N_cable / A_cable/1000)

   #OUTPUT
   104.53296662275685
```