Multi-objective optimization of moving walkway networks in transportation hubs

Charles Jeanbart

Nicholas Molyneaux

Riccardo Scarinci

Michel Bierlaire

Ecole polytechnique fédérale de Lausanne

May 2018

STRC | 18th Swiss Transport Research Conference
Monte Verità / Ascona, May 16 – 18, 2018

Multi-objective optimization of moving walkway networks in transportation hubs

Charles Jeanbart, Nicholas Molyneaux, Riccardo Scarinci, Michel Bierlaire
TRANSP-OR
Ecole polytechnique fédérale de Lausanne

EPFL ENAC IIC TRANSP-OR
GC B2 385 (Bâtiment GC)
Station 18
CH-1015 Lausanne

{charles.jeanbart, nicholas.molyneaux, riccardo.scarinci, michel.bierlaire}@epfl.ch

May 2018

Abstract

Transportation hubs, such as airports and train stations, tend to experience congestion as their recent diversification of services attracts more people and the demand for mobility keeps increasing, while the expansion possibilities of the infrastructure are limited. Moving walkways, whose use is widespread to deal with long walking distances, can be a key infrastructure to reduce congestion and travel time. We develop an optimization framework which explores the disposition of moving walkways in transportation hubs with respect to two contrasting objectives: minimizing both the total travel time and the total installation (capital) cost. We define flow-dependent walking speed functions to model congestion. Its influence on the route choice made by the pedestrians is then included thanks to a user-equilibrium formulation. This methodology is applied to the future train station of Lausanne, Switzerland. Simulations yield positive results with respect to travel time savings and also reveal challenging aspects linked to the intersection between pedestrian flows and moving walkways.

Keywords

Accelerating Moving Walkways, transportation hub

1 Introduction

Pedestrian dynamics get more and more interest as the saturation of the transportation hubs has become a challenging issue for the infrastructure managers. Although vehicular traffic has been extensively studied over the last decades, pedestrian traffic has not received as much attention. However, as larger populations use infrastructures with limited space, the need for a better understanding and management of the pedestrian movements arose in order to relieve potential congestion. Furthermore, there is a diversification of the transportation hubs, leading to an increased demand in these infrastructures.

The present study investigates one of the tools that can be imagined to reduce congestion and that has been widely used in other contexts, such as airports, to deal with long walking distances and reduce transfer times. Moving walkways date from the beginning of the 20th century and have since evolved to accommodate different configurations. The first installations, known as Constant Moving Walkways (CMW), operated at constant speed and are now the most widespread. Since the second half of the century, new prototypes have shown the way towards higher speeds (Kusumaningtyas, 2009). With an acceleration phase at the start and a deceleration phase at the end, the Accelerating Moving Walkways (AMW) are an even faster way to get around without compromising safety and comfort.

Some real life implementations include Montparnasse-Bienvenüe railway and subway station in Paris, France (Gautier, 2000), as well as Pearson International Airport in Toronto, Canada (Gonzalez Alemany et al., 2007). If the former did not survive because of repeated technical difficulties, the latter is still in service and can reach 12 km/h, reducing by half the travel time between Terminals 1 and 2.

Anticipating an improved acceptance of this type of equipment by transportation hub users, one can imagine bringing it to a larger scale as a way to better manage pedestrian flows and address future complexities. The objective of the following work is to provide an optimization framework for the design of such network of moving walkways in stations, with a focus on AMWs. The main idea is to consider the physical constraints of the available space as well as the existing or expected flows to define a set of infrastructure configurations that minimize both the total travel time and installation cost.

The paper is structured as follows. First, the literature is reviewed to evaluate the possible extension of previous work on the topic, especially by Scarinci et al. (2017) that brought the concept of a city-scale system where roads and cars are replaced by moving walkways. Chapter 3 exhibits the adapted methodology in which a demand assignment based on User Equilibrium (UE) is proposed and potential congestion is taken into account. Then, Chapter 4 introduces the case study of Lausanne railway station that illustrates the developed approach. Chapter 5 presents a discussion of the encouraging results and Chapter 6 concludes the article.

2 Literature review

In a new approach to address congestion in city centres and *last-mile* issues, Scarinci et al. (2017) explores the design of a futuristic network of Accelerating Moving Walkways (AMW) that could replace traditional transport modes in hypothetical car-free districts. AMWs might be installed on the existing roads to make pedestrians travel faster, depending on the flows and geometrical characteristics. An optimization algorithm is proposed to test different possible positions and number of lanes and identify the best trade-off between cost and travel time.

To bring the concept of AMWs to a larger scale, Scarinci et al. (2017) distinguish two types of arcs: walking arcs and AMW arcs. The directed graph also includes nodes which correspond to the road intersections. It is possible for AMW arcs to have several lanes. They can also span over several consecutive elementary arcs and constitute what is called ***expressways***. Moreover, intersections are ignored, which means two expressways may overlap at crossroads. This assumption is made considering that overpasses might be built as there is virtually no limitation on the height of the infrastructure. Some ways of avoiding conflicts are more specifically explored by Rojanawisut (2015).

The total travel time depends on the flows on the arcs, which means the demand needs to be **assigned**. The latter is given in an origin-destination (OD) matrix. For each OD pair, the fastest path is determined and the associated flow is assigned to the AMWs on the path if they all have enough capacity. If some are too full to receive additional flow, the remaining demand is assigned by considering the fastest path without those AMWs and the procedure is repeated until the demand is completely assigned. The main drawback of this heuristic strategy is that the demand is more likely to be assigned to the first visited AMW arcs than to the last. Also, the authors simply ignore congestion, considering that roads are wide enough to accommodate any pedestrian flow.

In order to take congestion into account, the assignment procedure will be improved by integrating a **user equilibrium** (UE) problem which was theorized by Wardrop (1952) for cars. Wardrop's first principle considers that "traffic will tend to settle down into an equilibrium situation in which no driver can reduce his journey time by choosing a new route", assuming that drivers have perfect knowledge about travel times on all the possible paths. This was later formulated as a nonlinear optimization problem by Beckmann et al. (1956). The UE problem is convex if the travel time on the links depends on a **monotonically increasing** function and if all the travel times are **mutually independent**. Finally, the UE problem requires a function linking congestion to travel time.

A definition of a travel time function based on the volume of traffic on the link was proposed by the BPR (Bureau of Public Roads, 1964) for cars. In order to deal with pedestrian flows at signalized crosswalks, Lam et al. (2002) use a similar performance function and estimate the values of the parameters with the help of different case studies in Hong Kong. Selected results will be integrated in the new methodology to account for congestion.

The **optimization** approach in Scarinci et al. (2017) starts by equipping all the feasible AMWs (i.e. all the arc combinations that respect given geometrical constraints) and setting an initial solution with the described assignment technique. Then, for a given number of iterations, the network is updated with a certain number of modifications. In the proposed case study, only two types of modifications are selected, with an equal probability: adding or removing a random lane.

Since there are two contradictory objective functions, it is not possible to get a unique optimal solution. In that case, a solution is accepted if it is not dominated by a previous one, which means both total travel time and total capital cost are improved. If it is rejected, the previous situation is restored. At the end of the simulation, the network configurations that are not dominated constitute the **Pareto frontier**, which is the trade-off curve.

3 Methodology

The present work brings the network design concept of Scarinci et al. (2017) to the smaller scale of a transportation hub. This involves adjustments as well as improvements to account for the specificities of closed stations and pedestrian dynamics.

3.1 Characteristics of the network

As mentioned earlier, AMWs differ from the Constant Moving Walkways (CMW) by their higher speed that is reached thanks to an acceleration section (at the start) and an deceleration section (at the end). **Figure 1**, reproduced from Scarinci et al. (2017), shows the different parts from the speed, acceleration and width points of view.

Typical values are selected from the literature for the main parameters:

- For safety reasons, the acceleration/deceleration is limited to $a = 0.43\ m/s$;
- The entry and exiting speeds are set to $v_0 = 0.7\ m/s$;
- The maximum acceptable speed of an AMW is $v_{max} = 4.7\ m/s$;
- The free flow walking speed is commonly chosen as $v_w = 1.34\ m/s$;
- For a standard width per lane of $z_0 = 1.2\ m$, the capacity is defined by $k_0 = 7875\ pax/hour$.

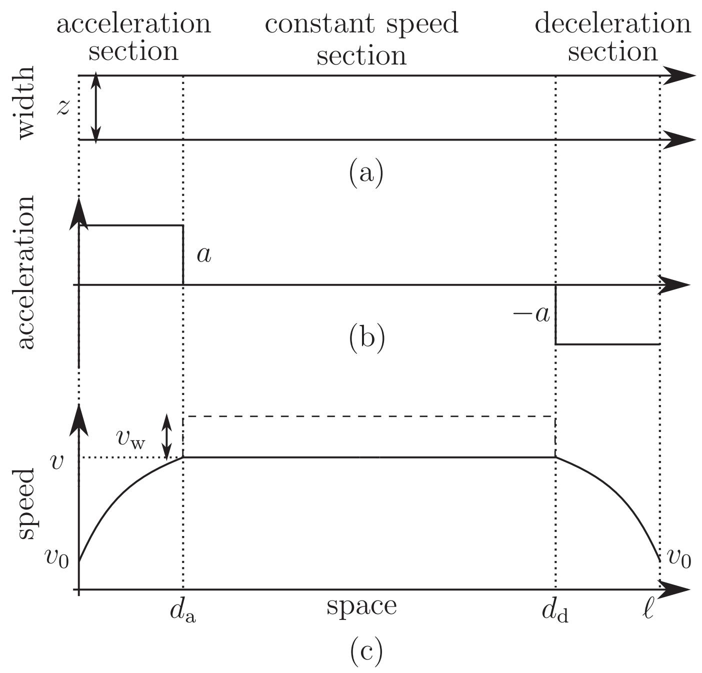


Figure 1: width (a), acceleration (b) and speed (c) profiles (Scarinci et al., 2017)

The definition of the **top speed** (i.e. the constant speed after acceleration) is detailed by Rojanawisut (2015). The optimal top speed is given as a function of the length:

$$v(l) = \max\left(\min\left(\frac{\alpha_1 \cdot l + \alpha_2}{l + \alpha_3}, v_{max}\right), v_0\right) \tag{1}$$

where $\alpha_1 = 4.85\ m/s$, $\alpha_2 = 12\ m^2/s$ and $\alpha_3 = 22.28\ m$ have been estimated by considering the related operational cost (derived from the energy consumption).
Another important aspect of the definition of the AMWs is their **minimum length** that was set to $l_{min} = 120\ m$ by Scarinci et al. (2017) at the city scale. In the case of a transportation hub, this value would not make sense as such distances are unlikely to be found very often. This is the reason why the minimum length is fixed to a lower value (see **Chapter 4**).
As for expressways, in order to respect the constraint on curvature ($\gamma_{min} = 80\ m$), two consecutive arcs can only be part of the same *expressway* if the angle between the streets is at least $\varphi_{min} = 137°$. This is valid for a standard intersection width $\zeta = 11\ m$. For smaller intersections, it might be needed to be more restrictive on the choice of this angle. However, this value was kept for two reasons:

- It would be computationally too heavy to consider each intersection individually and measuring all the widths would be complicated;
- There is much more variability as networks in transportation hubs do not involve physical roads, but corridors and access ramps with irregular widths.

Depending on the applications, one could however decide to change this assumption, especially if the arcs do not cross perpendicularly.
Finally, it was mentioned earlier that intersections were ignored by Scarinci et al. (2017), i.e. two *expressways* could overlap at crossroads. If this can be dealt with at the scale of a city by building underpasses or similar infrastructure (see Rojanawisut, 2015), it is not feasible in the case of a transportation hub where space is limited and there is no possible way around. Thus, intersections of *expressways* will be avoided, as explained in **section 3.4**.

3.2 Objective functions

The design of the network depends on two contradictory objectives: the minimization of the total travel time (z_1) and the total capital cost (z_2). Indeed, equipping stations with moving walkways decreases the overall travel time as they offer a faster alternative to walking, but it also increases the installation cost in a significant way. Hence, one cannot improve the former without deteriorating the latter and there is no unique solution to the optimization problem, as mentioned in **Chapter 2**.

The lower bound of the **capital cost** is defined by Kusumaningtyas (2009):

$c = 34.8 \cdot 10^3 \text{ €}/m$

There are also maintenance and operational costs. However, they are negligible when compared to capital costs and are thus ignored. As for the calculation of travel time, the physical constraints of transportation hubs should be considered. Thus, the walking speed should depend on congestion, which means it should be a function of the flows.

The BPR (Bureau of Public Roads, 1964) gives the following relationship between travel time and flow on a link:

$$t(q) = t_0 \cdot \left[1 + \alpha \left(\frac{q}{k}\right)^{\beta}\right] \tag{2}$$

with:

- t_0 the free flow travel time (per unit of time);
- q the traffic volume (per unit of time);
- k the capacity of the link (per unit of time);
- $\alpha = 0.15$ and $\beta = 4$ in general.

In order to deal with pedestrian flows at signalized crosswalks, Lam et al. (2002) use a similar performance function and estimate the values of the parameters (α and β) with the help of different case studies in Hong Kong. Some of the results are shown in **table 1:**

Site	t_0	B	n
Commercial area with LRT station	0.7292	2.0722	9.2732
Commercial area without LRT station	0.7557	1.4502	6.9373
Shopping area with LRT station	0.7890	1.2395	5.2801
Shopping area without LRT station	0.7927	1.1192	5.0365

Table 1: parameter estimation for the four selected signalized crosswalks (Lam et al., 2002), LRT designates "light rail transit"

Note that the function has a different formulation:

$$t(q) = t_0 + B\left(\frac{q}{k}\right)^n \tag{3}$$

which means that $\beta = n$ and $\alpha = B/t_0$ by identification with equation (2).

It is considered that the situation of a commercial area without LRT station (see **table 1**) would be the closest to a transportation hub. This assumption is motivated by the distinction made in the article between the behaviors of the commuters in the different areas. People in commercial areas might be busier and more focused towards a fixed destination than shoppers, hence the higher walking speeds. In the end:

$$\alpha = \frac{B}{t_0} = \frac{1.4502}{0.7557} \approx 1.919$$

$$\beta = n = 6.9373$$

Travel time on walking arcs

There are walking arcs ($\mathcal{A}^w$ set) and AMW arcs ($\mathcal{A}^a$ set). The directed graph $\mathcal{G}(\mathcal{N}, \mathcal{A} = \mathcal{A}^w \cup \mathcal{A}^a)$ also includes nodes ($\mathcal{N}$ set) which correspond to the road intersections. For a walking arc $(i, j) \in \mathcal{A}^w$, equation (4) describes the free flow travel time:

$$t_{ij}^0 = \frac{l_{ij}}{v_w} \tag{4}$$

Hence the flow-dependent travel time:

$$t_{ij}^{w}(q_{ij}) = t_{ij}^{0} \cdot \left[1 + \alpha \left(\frac{q_{ij}}{k_{ij}}\right)^{\beta}\right] \tag{5}$$

Another assumption on capacity is made at this point. It is usually considered that corridors can accommodate $\kappa = 1.5\ pax/m/s$ (Weidmann, 1992), thus:

$$k_{ij} = \kappa \cdot z_{ij}^{w} \tag{6}$$

where z_{ij}^{w} is defined as half of the available width of the corridor (because flows are separated by direction, see **figure 2**). The nominal width z_c of the full corridor is given by the case study. However, the available width might change depending on the AMW arcs. Indeed, if the corridor is equipped with one or more moving walkways, one should consider the space reduction due to the width of the lanes. For θ_{ij} lanes on the elementary arc from i to j and θ_{ji} lanes on the opposite arc that shares the same corridor:

$$z_{ij}^{w} = z_{ji}^{w} = \frac{z_c - \left(\theta_{ij} + \theta_{ji}\right) \cdot z_0}{2} \tag{7}$$

where z_0 is the standard width of a moving walkway and handrails are ignored.

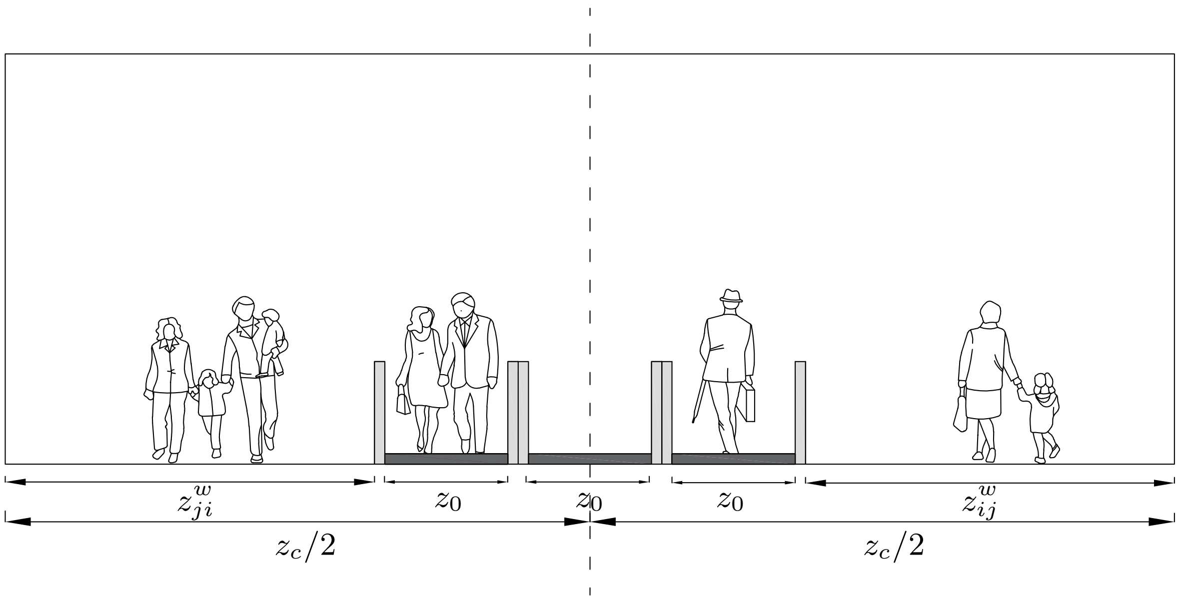


Figure 2: flow separation in corridors, e.g. with three installed AMW lanes

Travel time on AMWs

Pedestrians on equipped AMW arcs travel on the constant part at the top speed of v, plus their flow-dependent walking speed. The free flow travel time is defined by:

$$t_{ij}^0 = \frac{l_{ij} - 2d_{ij}}{v_w} \tag{8}$$

Equation (5) can be applied to derive the flow-dependent walking speed:

$$v_{ij}^w(q_{ij}) = \frac{l_{ij} - 2d_{ij}}{t_{ij}^w(q_{ij})} = \frac{l_{ij} - 2d_{ij}}{t_{ij}^0 \cdot \left[1 + \alpha \left(\frac{q_{ij}}{k_{ij}}\right)^\beta\right]} = \frac{v_w}{1 + \alpha \left(\frac{q_{ij}}{k_{ij}}\right)^\beta} \tag{9}$$

Finally, the travel time on the full AMW is:

$$t_{ij}^a(q_{ij}) = \frac{l_{ij} - 2d_{ij}}{v_{ij} + v_{ij}^w(q_{ij})} + 2\tau_{ij} \tag{10}$$

where:

- v_{ij} is the top speed defined by **equation 1**;
- $\tau_{ij} = \dfrac{v_{ij} - v_0}{a}$ is the travel time on the accelerating or decelerating part (it is symmetric since acceleration and deceleration are equal);
- $d_{ij} = \dfrac{1}{2}a\tau_{ij}^2 + v_0\tau_{ij} = \dfrac{v_{ij}^2 - v_0^2}{2a}$ is the embarking or disembarking distance (corresponding to $d_a = d_d$ in **figure 1**).

Optimization problem

Finally, the optimization problem is expressed as follows:

$$\min \quad z_1 = \sum_{(i,j)\in\mathcal{A}} t_{ij}\left(v, v_0, v_w, a, l_{ij}, q_{ij}\right) q_{ij}\left(x_{ij}, t_{ij}\right) \tag{11}$$

$$\min \quad z_2 = \sum_{(i,j)\in\mathcal{A}^a} c_{ij}\left(x_{ij}, l_{ij}\right) \tag{12}$$

where:

- q_{ij} and t_{ij} depend on each other and are defined by the demand assignment (see **section 3.3**);
- x_{ij} is the **decision variable**, i.e. the number of lanes on arc (i, j);
- $c_{ij} = c \cdot x_{ij} \cdot l_{ij}$ is the capital cost of an AMW.

3.3 User equilibrium assignment

The assignment procedure is very different from the one proposed by Scarinci et al. (2017). In the present case, the **user equilibrium assignment** problem is solved on the basis of the formulation proposed by Beckmann et al. (1956):

$$\min \sum_{(i,j)\in\mathcal{A}} \int_0^{q_{ij}} t_{ij}(\omega)d\omega \tag{13}$$

s.t.

$$\sum_{k\in K^{od}} q_k^{od} - m_{od} = 0 \qquad \forall od \in \Omega \tag{14}$$

$$\sum_{k\in K^{od}} \sum_{od\in\Omega} \delta_{(i,j),k}^{od} q_k^{od} = q_{ij} \qquad \forall (i,j) \in \mathcal{A} \tag{15}$$

$$q_k^{od} \geq 0, q_{ij} \geq 0 \tag{16}$$

where:

- t_{ij} and q_{ij} are the travel time and the flow on arc $(i,j) \in \mathcal{A}$;
- od represents an origin-destination pair from the total Ω set;
- q_k^{od} is the flow on path k linking the od pair;
- m_{od} is the demand for the od pair;
- K^{od} is the set of all the paths linking the od pair;
- $\delta_{(i,j),k}^{od} = 1$ if arc (i,j) is on path k linking the od pair, 0 otherwise.

The first two constraints (14) and (15) account for flow conservation and (16) avoids negative flows. As the travel time function is monotonically increasing and all the travel times are mutually independent, the problem is convex and can be solved using the **Frank-Wolfe algorithm** (Frank and Wolfe, 1956).

3.4 Optimization procedure

The role of the optimization procedure is to explore a variety of configurations and be able to select the most efficient ones. After initializing the network, one or more modifications are made at each iteration and the resulting solution is evaluated and compared to the previous ones.

3.4.1 Initialization

The optimization starts with the initialization of the network. The possible installation possibilities of AMW arcs are computed and a directed graph $\mathcal{G}(\mathcal{N}, \mathcal{A} = \mathcal{A}^w \cup \mathcal{A}^a)$ is created. The number of lanes (x_{ij}) is set to zero on all AMW arcs. The demand is assigned once before the very first network modification. One also needs to store all the potential intersections between expressways, which is done by identifying for each pair of AMW arcs if they share exactly one intermediate node (i.e. any node on the path, excluding the starting and ending ones).

3.4.2 Network modification

At each iteration, one or several modifications are made to the network. There are two sorts of changes, as in Scarinci et al. (2017):

- Add a random lane or
- Remove a random lane.

The choice between the two is made by drawing a random number from a uniform distribution. Contrary to the approach of Scarinci et al. (2017), the first option is selected with a probability of 60% (and the second, 40%) as a way to facilitate the progression of the algorithm from an initially empty network. Before each modification, the current network is saved in case it needs to be restored. In the situation where a random lane is removed, one should simply check if the number of lanes is different from zero. If not, the lane number of the arc is reduced by one, as well as on all the corresponding walking arcs (recall that the number of installed lane per arc is needed to know the available width and thus calculate the walking speed). In order to add a lane however, one should not only control that the maximum number of lanes is not reached on all the intermediate arcs, but also that adding a lane will not create an expressway that would intersect others. If crossing expressways are installed, they shall be removed. This is the main reason for starting with an empty network as this procedure would be complicated to apply otherwise. The number of lanes is then increased by one on the new arc.

3.4.3 Assignment

After all the modifications have been made, it should be decided whether the new solution is to be accepted or rejected. For that reason, the demand is assigned, as described in the previous

section 3.3. The total travel time and total capital cost are then calculated for the proposed solution. If at least one of the two values is larger than for a previous solution, the changes are rejected and the saved previous configuration is restored. Note that if lanes were added and intersecting *expressways* were removed, the latter should also be restored. Otherwise, the network modifications are accepted and a new iteration begins.

3.4.4 End of the simulation

At the end of the assignment and the evaluation of the solution, the next iteration starts with a new modification of the network. The simulation comes to an end when a predefined number of iterations has been reached. From all the accepted solutions, those that are not dominated (i.e. there is no other solution that has better values for both objective functions) constitute the **Pareto frontier**.

The whole process is represented in a flowchart (**figure 3**).

3.5 Intersections

It was mentioned earlier that intersections between expressways should be avoided, as it would be more complicated to implement in a transportation hub than in an open city because of the width and height limitations of the corridors. This is done by removing obstructing AMWs when adding new ones. Moreover, the problems created by pedestrian flows crossing expressways needs to be addressed. In fact, the representation of the network with a simple directed graph is not sufficient to address crossing corridors, hence flows. If an expressway passes trough an intersection, it may block the lateral access and exit of platforms. In this case, neither the graph nor the problem formulation forbid pedestrians to walk over this physical obstacle. Furthermore, there is no information on the disposition of parallel AMWs in the same corridor, which makes it problematic to assess whether a pedestrian exiting a moving walkway can access an adjacent corridor.

For these reasons, it is considered that no more than two AMWs can coexist in the same corridor (which is more consistent with real-life expectations) and that nodes can be doubled when such intersections might occur. Doubling the nodes means that an additional, infinitely small arc is created to represent the physical obstacle of the expressway. When the latter is installed, a very high cost is associated to the new arc and the shortest path algorithm yields the expected avoidance. Of course, doubling the intersection node means that the number of arcs in the main corridor should also be doubled. This requires some adjustments, especially for the calculation of the available width for the walking arcs. **Equation 7** is adapted for the case of a corridor with four directed arcs (i, j), (j, i) and their respective corollaries (k, l) and (l, k):

$$z_{ij}^w = z_{ji}^w = z_{kl}^w = z_{lk}^w = \frac{z_c - \left(\theta_{ij} + \theta_{ji} + \theta_{kl} + \theta_{lk}\right) \cdot z_0}{4} \tag{17}$$

In this situation, the corridor configuration from **figure 2** is changed as the flows are now bi-directional on each side of the central moving walkways. Note that this procedure cannot be applied to two intersecting main corridors at the same time and one should be prioritised, as it is not possible to use an additional small arc to represent both an obstacle and a usable walking arc. Finally, the maximum number of lanes is set to four by corridor and no moving walkway is added if more than half of the width is already equipped.

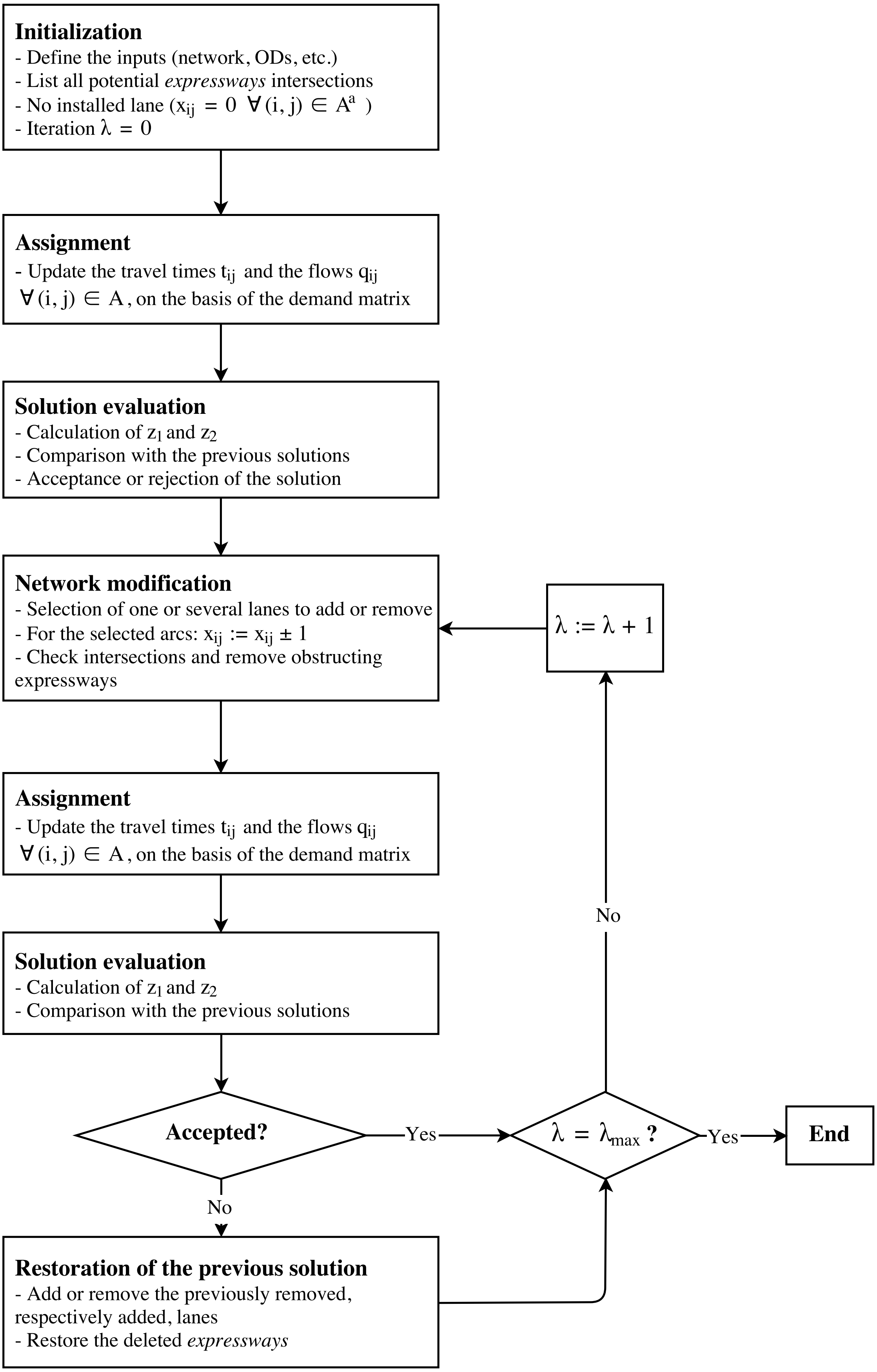


Figure 3: flowchart of the simulation methodology

4 Case study

The location of the case study is set to the future Lausanne railway station, part of the "Léman 2030" project. The objective is to improve the service between Geneva and Lausanne, especially with the new "Léman Express" line that will connect France via Cornavin, Eaux-Vives and Annemasse.

The base documentation for this work comes from a report commissioned by the SBB (Swiss Federal Railways) to a consortium of engineering companies and written in 2013.

The most important aspects of this expansion are the modification of the underpasses, bringing their number from two to three, and the enlargement of the platforms, for better capacity, comfort and safety. It should also be noted that there will be a second metro station for the new M3 line next to the existing M2.

In the present case, it is the first underground level that will be considered, the ground level and the second underground level being ignored. The inclination of the station underpasses will also be set aside. The three main corridors with their access ramps and stairs to the platforms are recognizable in the center (see **Appendix A**). One can also notice two metro platforms in the North-East part which belong to the expected M3 line. The M2 station is currently at this position and will be moved to the second underground level, hence it is not visible here.

Regarding the construction of the OD demand matrix, the following assumptions are made:

- A one-hour peak period is considered, from 7am to 8am;
- The demand is estimated for a typical 2030 timetable and is doubled, since the station is already designed for the expected flows and would not get congested enough;
- For a train passing by the station, 70% of its capacity gets off and 40% gets on;
- Depending on the length of the train, the repartition of the passengers in the three underpasses is different (e.g. shorter regional trains have a greater impact on the central underpass);
- The shares of transport modes (including bus, M2, M3, train and walking) used to access or leave the station have already been forecast in the report;
- The most intuitive paths are selected to get the demand on each OD pair (e.g. a passenger coming from the west or central underpass and willing to take the M3 to the North might rather use the nearest exit to the surface than go around the whole station).

The dimensions of the moving walkways can be set on the basis of this network: $l_{min} = 30\ m$ and $l_{max} = 350\ m$, as in Scarinci et al. (2017). The value of 30 m was selected because it approximately corresponds to twice the distance between two access ramps/stairs in the main underpasses. Intuitively, this should allow AMWs to respect the scale of the transportation hub

and to form *expressways*.
Finally, in order to avoid physical inconsistencies, it is decided not to allow moving walkways on ramps, stairs, platforms and entry arcs to the station. In further work, the possibility of having AMWs on platforms could however be explored.

Appendix B contains a representation of the considered network.

5 Results and discussion

The described methodology is applied to the case study with the following parameters:

- The number of iterations is set to 2000;
- Two random modifications are made per re-assignment;
- There are 534 walking arcs and 279 possible AMW arcs.

First, the full set of explored solutions is represented in **figure 4**. As mentioned earlier, a solution is accepted if it is not dominated, i.e. if there is no previous one that yields both a better total travel time and total capital cost. The Pareto frontier holds the network configurations that are not dominated by any other solution at the end of the simulation. This trade-off curve is expected to have a convex shape, which is the case here. Moreover, one can notice some jumps between some solutions. Several of them share about the same total travel time for different capital costs, whereas others have a different influence on the total travel time for the same total cost. In the first case, it might come from moving walkways that would be installed on less crowded arcs, hence not contributing much to the total travel time reduction (despite the additional cost). In the second case, it could be the opposite, i.e. changing the location of a moving walkway to a more used link would lower the total travel time without affecting the capital cost.

The Pareto frontier is isolated in **figure 5**. The solutions range from $z_1 = 1'841$ hours for the most expensive one ($z_2 = 54'698'805$ €) to $z_1 = 2'171$ hours for the free empty network ($z_2 = 0$ €). The latter is compared with three other selected Pareto optima (see **table 2**).

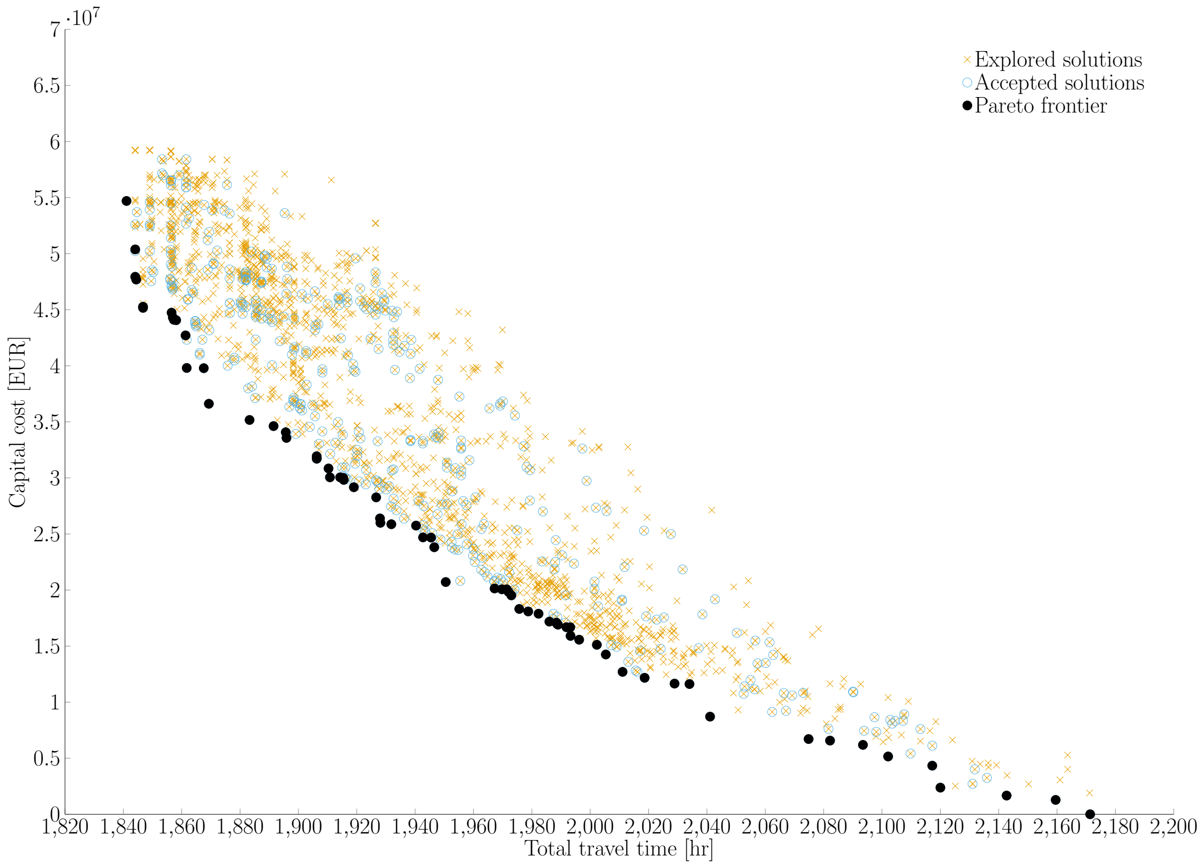


Figure 4: Explored solutions and their acceptance

Iteration [−]	**AMW arcs** [−]	**AMW lanes** [−]	**Total travel time** z_1 [$hours$]	**Capital cost** z_2 [€]
0	0	0	2’171.339	0
1776	6	6	2’041.076	8’707’080.793
1703	12	12	1’950.493	20’712’670.06
1286	22	22	1’869.305	36’610’308.97

Table 2: selected solutions

The flows on the walking arcs are represented in **figure 6** for the initial case where no AMW is installed. The 6 AMWs of iteration 1776 are shown in **figure 7** with rectangles on the arcs, as well as the 12 AMWs of iteration 1703 (**figure 8**) and the 22 AMWs of iteration 1286 (**figure 9**). One can notice that moving walkways are mostly located in long corridors with high demand. The more they are, the more potential intersections are created. This should lead to detours, which can be verified by considering all the OD paths.

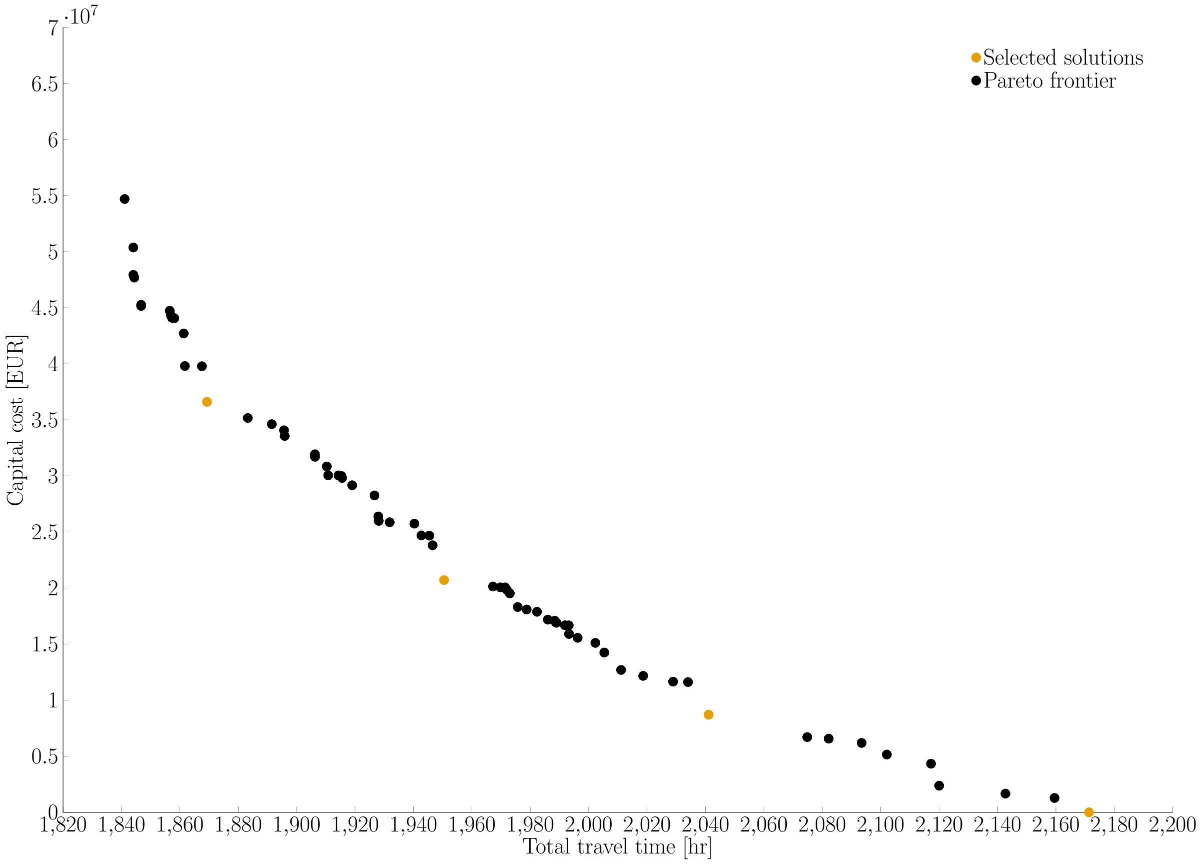


Figure 5: Pareto frontier and selected solutions

On the one hand, **figure 10** exhibits the relative variations of total traveled distances. For each of the 64'236 trips, the difference between its length with the initial empty network and with a given Pareto optimum is calculated. Note that the part of the trips that do not get longer is very high (more than 74%) and is not fully represented for readability reasons. This shows that the impact of intersections is limited in this case and that they do not create a major disruption. However, one can see that the variations for the remaining trips are quite different depending on the number of moving walkways, a greater one leading to a larger distribution tail. In fact, with less equipment (iteration 1776), only 9.9% of the trips become longer, whereas this figure raises to 12.4% for 12 AMWs (iteration 1703) and even 20.9% for 22 AMWs (iteration 1286). Conversely, the trips get shorter for respectively 8.4%, 6.2% and 4.5% of the trips.
On the other hand, **figure 11** considers the relative variations of total travel times, which are based on analogous calculations. Some of the trips are not affected by the added infrastructure, but their share shrinks with the number of moving walkways. One can see that the more AMW lanes are installed, the more the travel time decreases, which is consistent with the previous results (i.e. the Pareto frontier). Furthermore, these savings are more important with more lanes. For 6 AMW lanes (iteration 1776), only 41.1% of the trips are faster, while this percentage climbs to 59.5% for 12 AMWs lanes (iteration 1703) and 75.5% for 22 AMW lanes. Regarding

detours, one can notice that almost no trip is slower. This means that even if the traveled distance is higher, it does not imply a loss of time. Thus, in this case, intersections do not deteriorate the efficiency of the system. In fact, as there are not a lot of close alternative paths, the travel time savings provided by the AMWs probably compensate the time needed to go around the few obstacles.

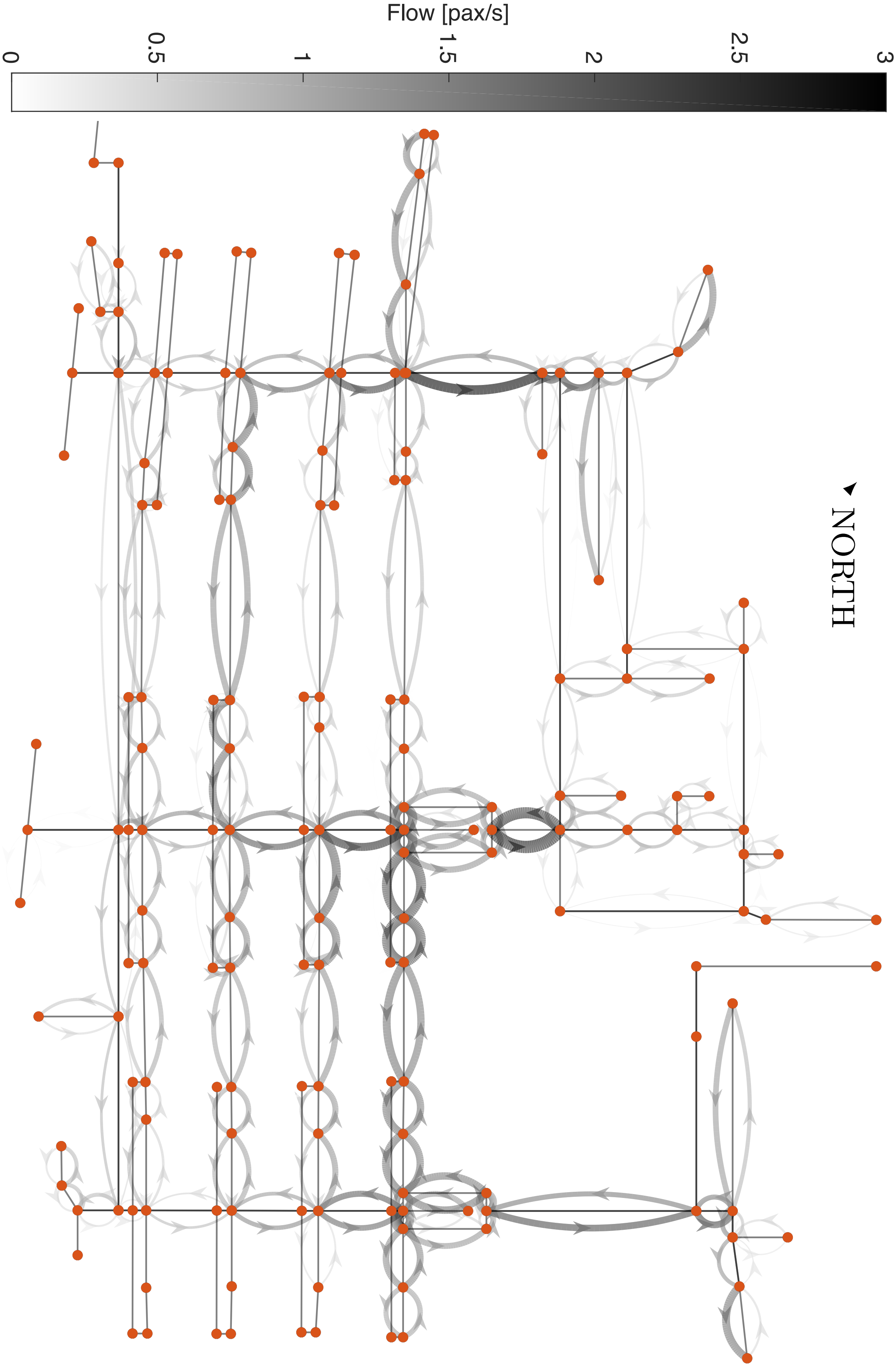


Figure 6: arcs and flows for iteration 0

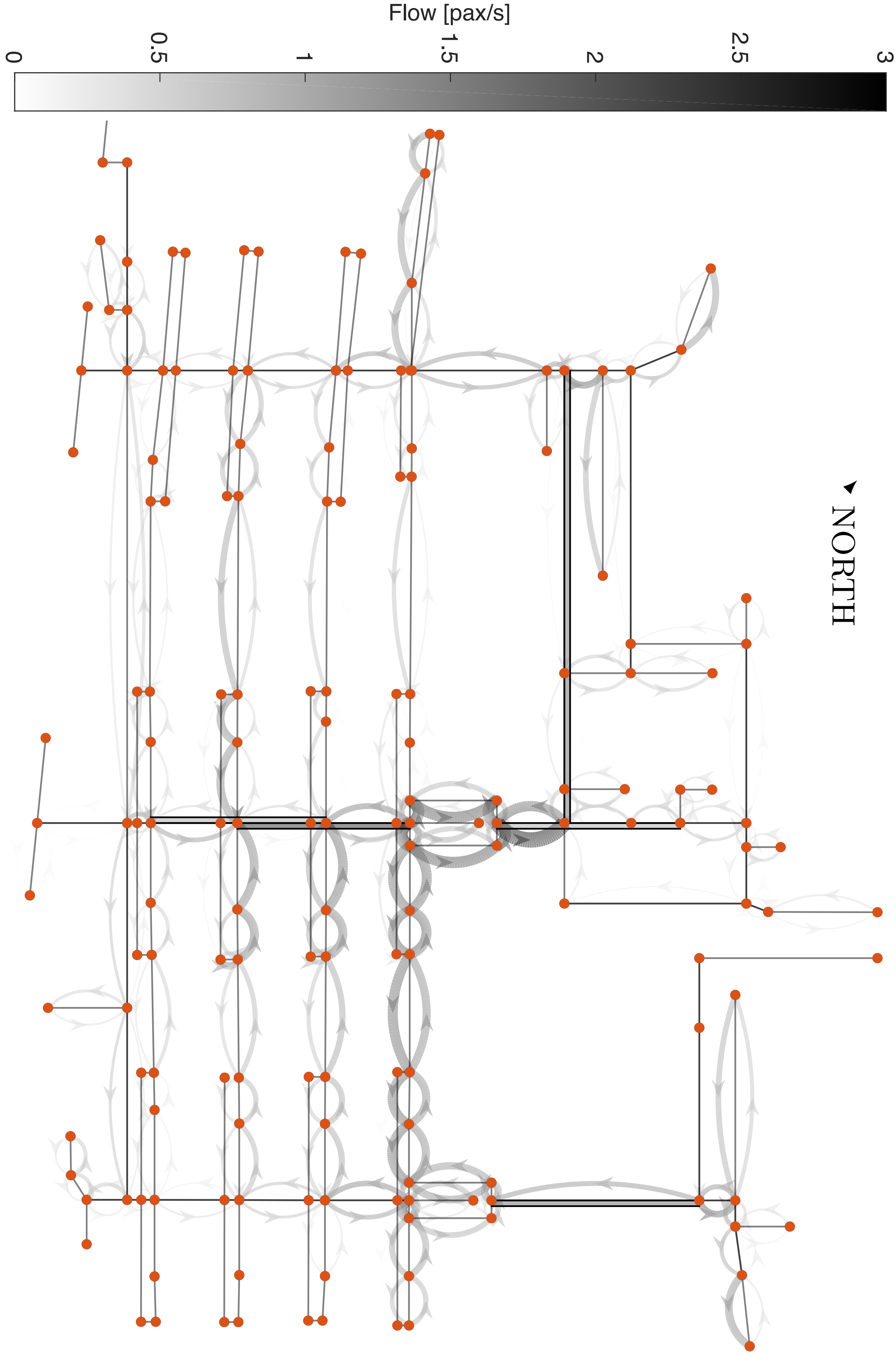


Figure 7: arcs and flows for iteration 1776

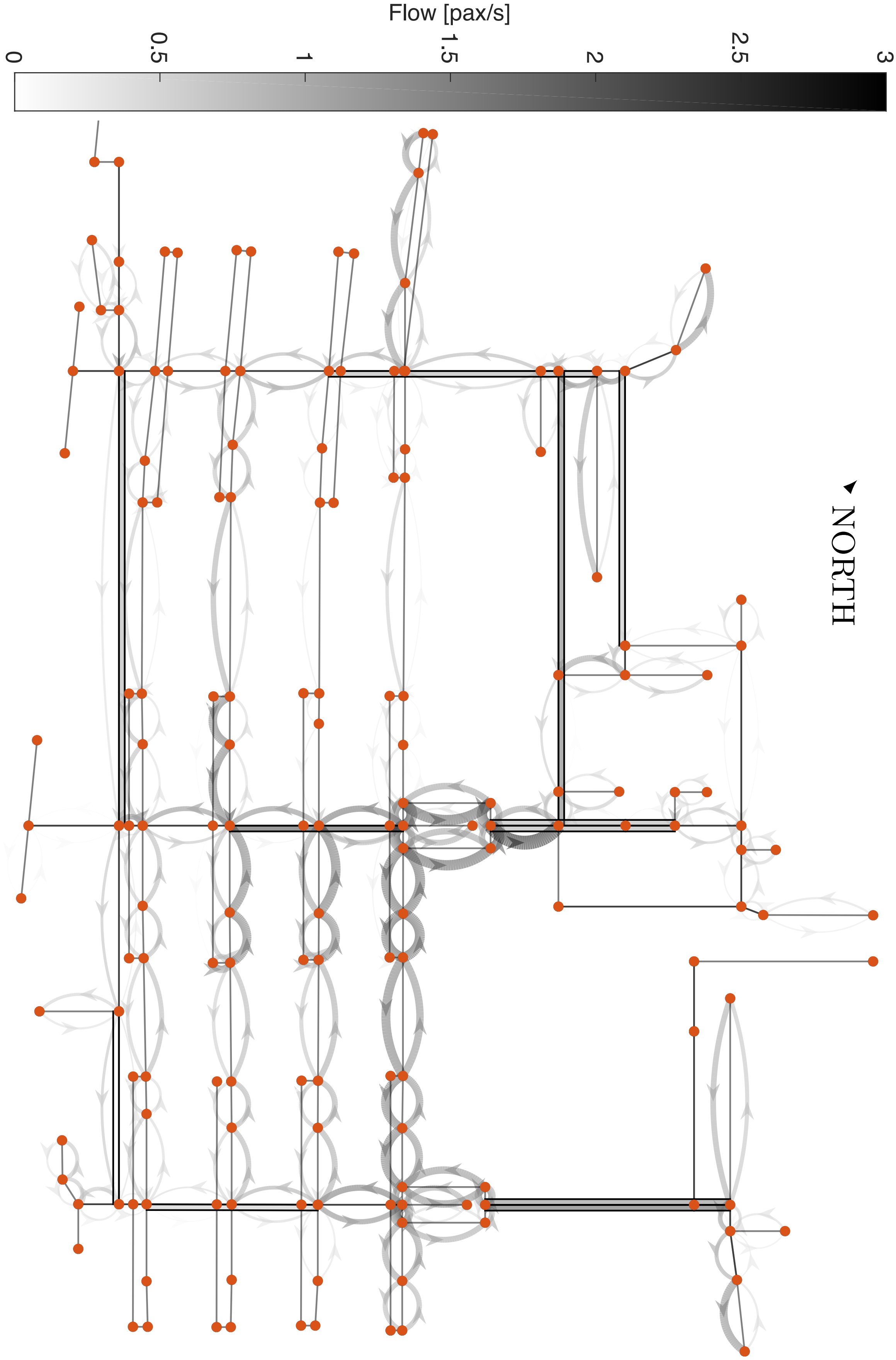


Figure 8: arcs and flows for iteration 1703

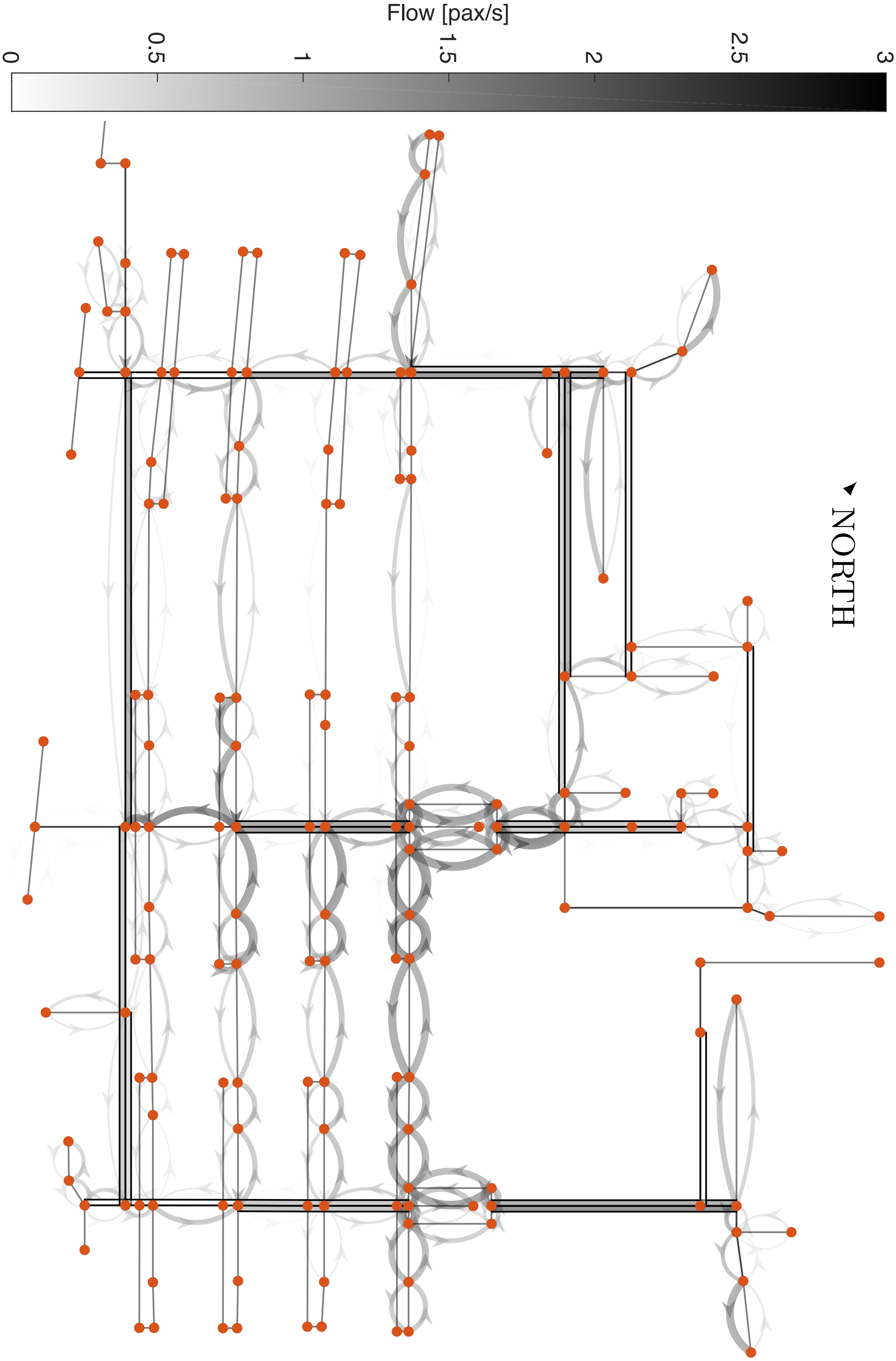


Figure 9: arcs and flows for iteration 1286

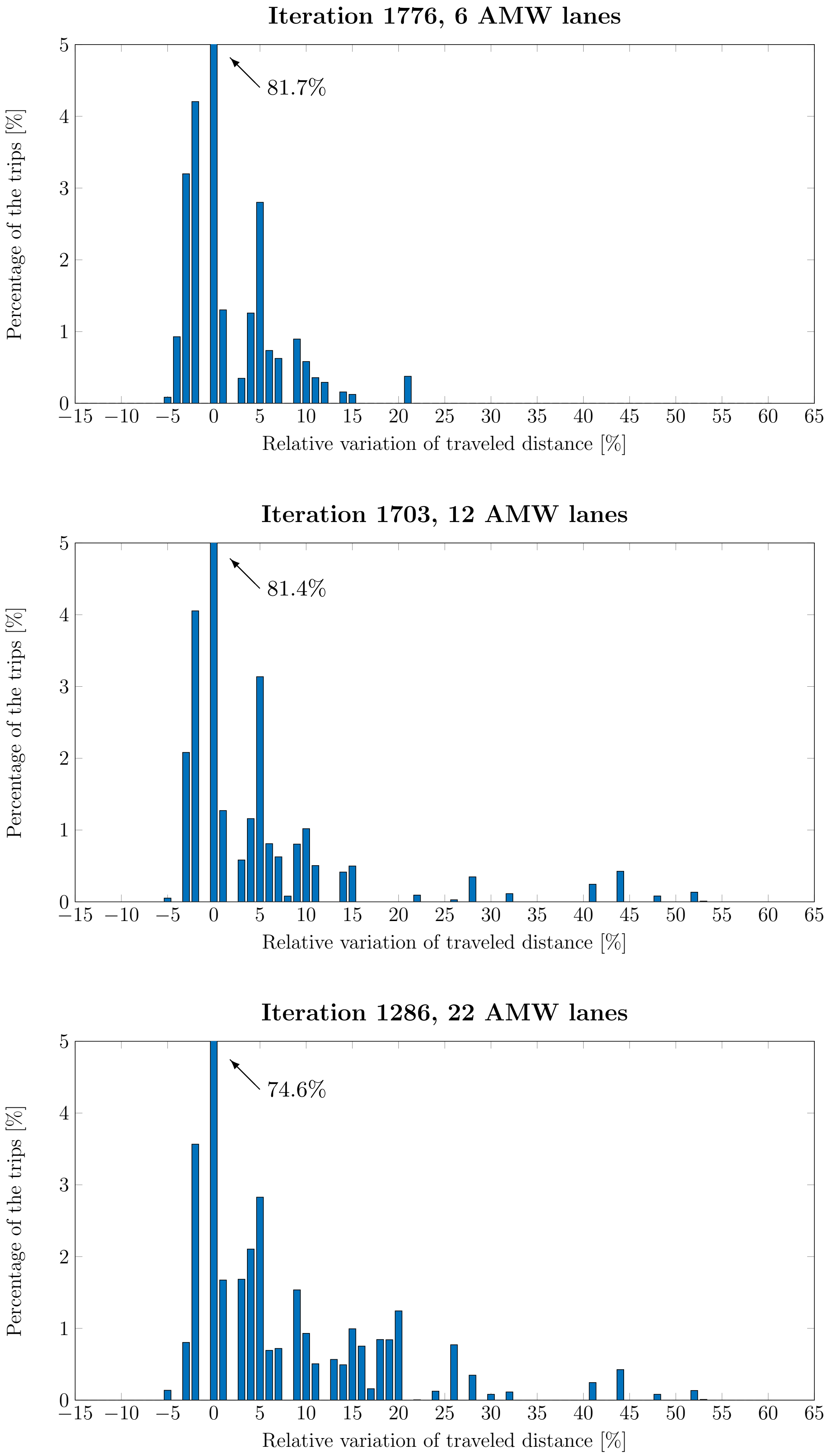


Figure 10: histograms of total traveled distances variations (truncated y-axis)

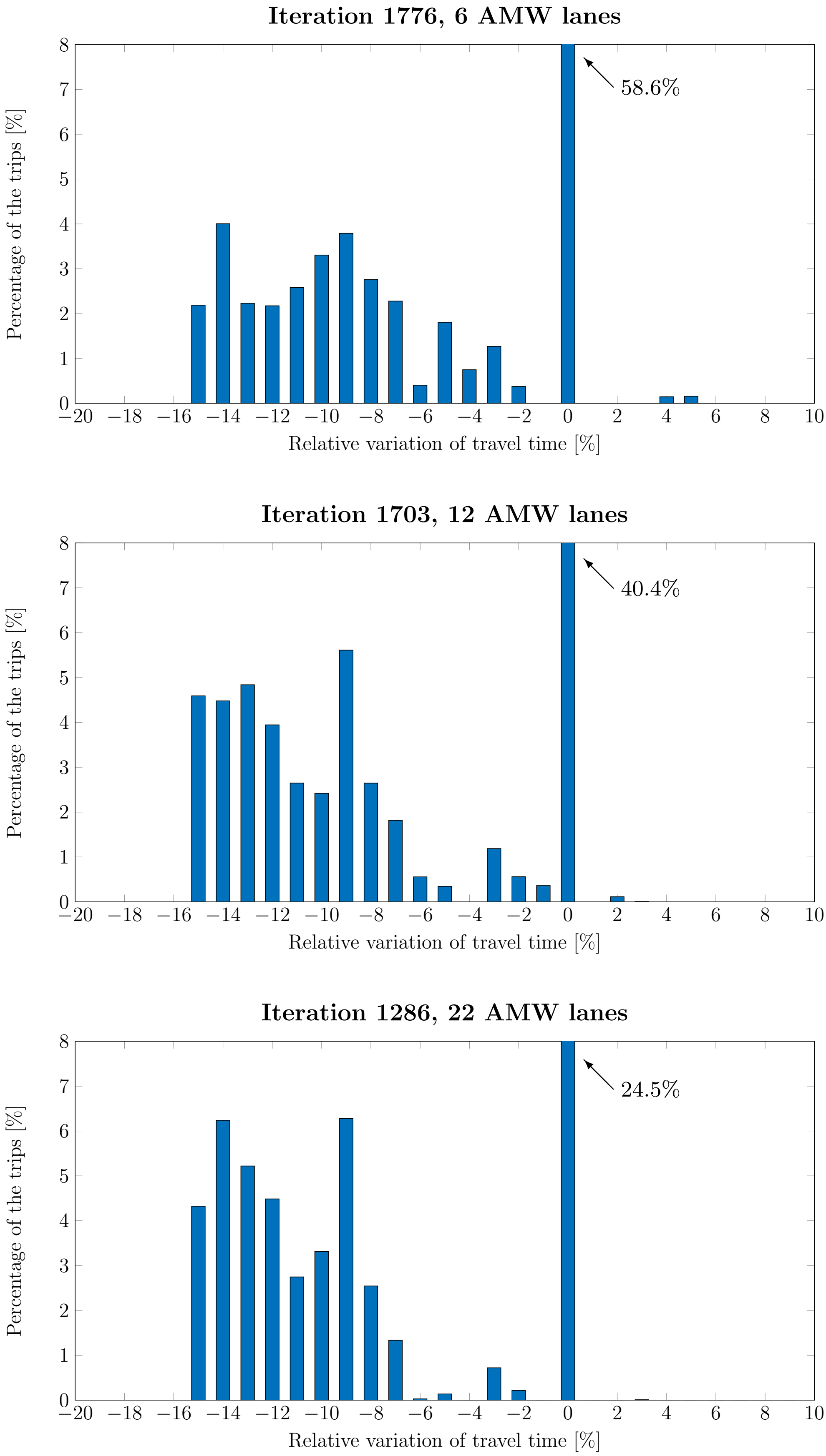


Figure 11: histograms of total travel times variations (truncated y-axis)

6 Conclusion

This article extends the work on network design of moving walkways to the specific case of transportation hubs. This constrained environment is approached by considering a congestion model which is included in a User Equilibrium assignment. The developed optimization framework yields encouraging results that need to be further explored. The case study shows that low-cost solutions can be found to reduce the total travel time by about 6 %, whereas more expensive configurations can lead to a decrease of 14 %. The trade-off between the two depends on the objectives and financial limitations of the infrastructure managers.

Further work should take into account the potential queues that could form at the entrances and exits of the moving walkways. Also, one could improve the approach on demand assignment by considering dynamic pedestrian inputs and outputs (when trains arrive and leave) instead of a uniform peak hour. This would allow to experience more critical congestion and improve the accuracy of the model. Finally, more modification operators should be explored.

7 References

Beckmann, M., C. B. McGuire and C. B. Andwinsten (1956). *Studies in the Economics of Transportation*, Yale University Press.

Bureau of Public Roads (1964). *Traffic Assignment Manual.* U.S. Department of Commerce, Urban Planning Division.

Frank, M. and P. Wolfe (1956). An algorithm for quadratic programming. *Naval Research Logistics Quarterly, 3*(1-2), 95-110.

Gautier, F. (2000). Gateway: the high-speed walkway, in: Rail Transit Conference, 2000.

Gonzalez Alemany, M., Soffritti, M., Behrend, M., Eisele, T. (2007). TurboTrack: making long distances shorter. *ThyssenKrupp techforum* , 68-75.

Kusumaningtyas, I. (2009). Mind your step: Exploring aspects in the application of long accelerating moving walkways (PhD thesis). Delft University of Technology. Mechanical, Maritime and Materials Engineering. Marine and Transport Technology.

Lam, W. H., J. Y. Lee and C. Y. Cheung (2002). A study of the bi-directional pedestrian flow characteristics at Hong Kong signalized crosswalk facilities. *Transportation, 29*(2), 169-192.

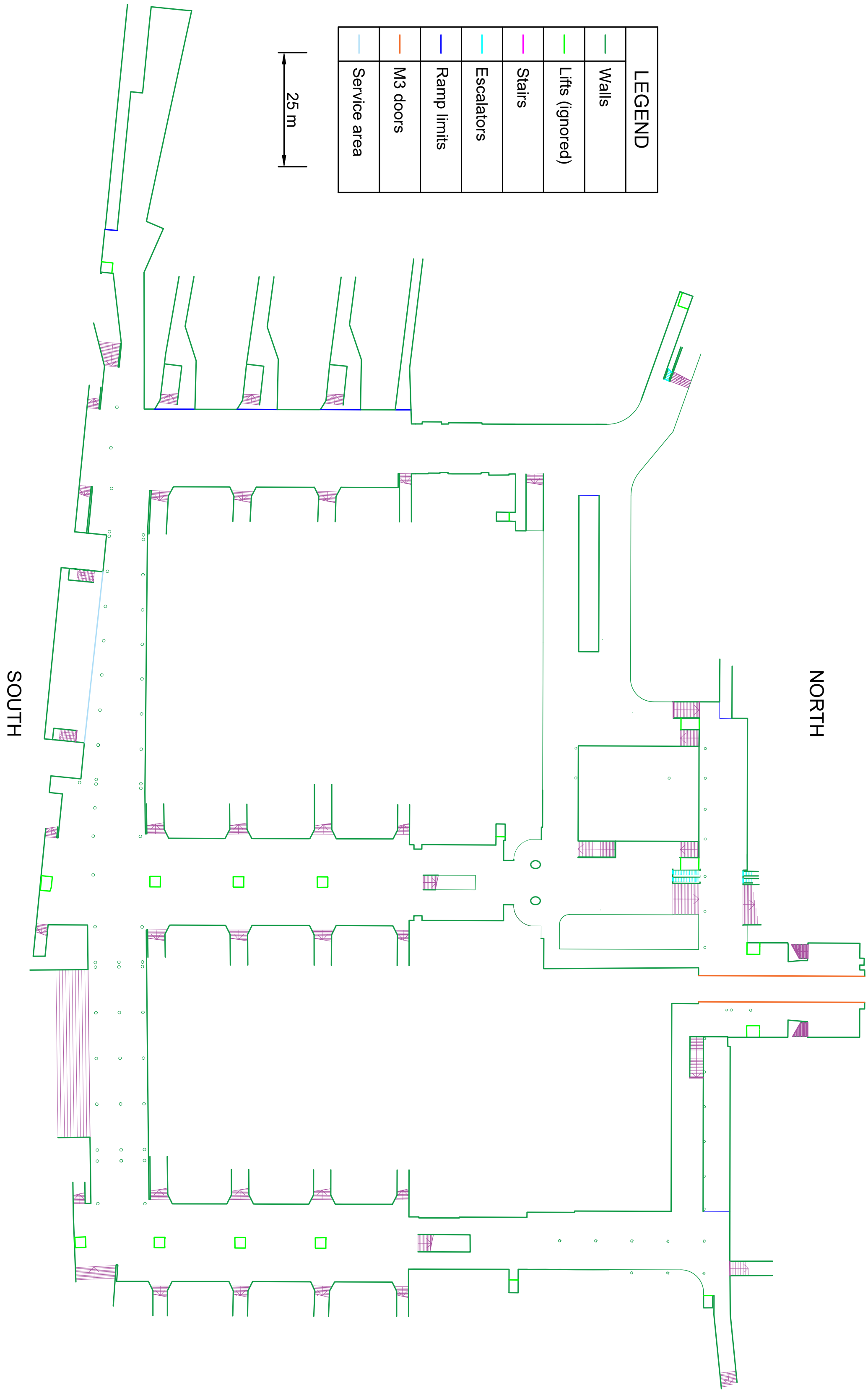
Rojanawisut, B. (2015). Optimisation of the network design of a futuristic transport system based on accelerated moving walkways (Master thesis). Ecole polytechnique fédérale de Lausanne EPFL, Section of Mathematics.

Scarinci, R., I. Markov and M. Bierlaire (2017). Network design of a transport system based on accelerating moving walkways. *Transportation Research Part C: Emerging Technologies, 80*, 310-328.

Wardrop, J.G. (1952). Some Theoretical Aspects of Road Traffic Research. *Proceedings of the Institution of Civil Engineers*, Part II, 325-378.

Weidmann, U. (1992). Transporttechnik der Fussgänger: Transporttechnische Eigenschaften des Fussgängerverkehrs, Literaturauswertung. ETH Zurich.

Appendix A: outline of the 1st underground (Lausanne)



Appendix B: considered network