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Design of an automated control system for subway escalators

Master's Thesis

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Guides for elaboration

During the elaboration of the master's thesis follow the outline below:

- Meet with the topic of escalators for subway stations. Focus on the state of the art, e.g. subway stations structure, escalators systems, pedestrians detection, traffic flow of pedestrians, crowds and capacity issues, measured data, etc. Develop appropriate analysis.
- Design a system for automated control of escalators for a specific station, including the architecture of the system, simulation models, control algorithms.
- Analyze the improvement of usage of proposed design in comparison with another common used principles. Analyze the reliability of the designed application. Discuss possible constraints and improvements of proposed method.
- Implement appropriate algorithms into the PLC technology, with proper documentation.
- The thesis structure can be the following: Introduction, Objectives, Background – State of the art, Measurements and methods, Proposal, Evaluation, Implementation, Discussion, Conclusions.

Graphical work range: according to supervisor's instructions

Accompanying report length: Minimum 55 pages of text (including images, graphs and tables which are part of the text)

Bibliography:

[1] Kuutti, J. (2012) A Test Setup for Comparison of People Flow Sensors, Licentiate Thesis. Retrieved from http://lib.tkk.fi/Lic/2012/urn100598.pdf

[2] Daamen, W., Modelling Passenger Flows in Public Transport Facilities, PhD thesis, TRAIL Thesis Series, no. T2004/6, Delft University Press, Delft, 2004.

[3] Kelton, W. David, Randall P. Sadowski, and Deborah A. Sadowski. Simulation with Arena. Boston, MA: WCB/McGraw-Hill, 1998.

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I confirm assumption of master's thesis assignment.

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Student's name and signature

Prague ....June 16, 2016

Declaration

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David Hoyos Posada

Abstract

This thesis is focused on the proposal and evaluation of an automated control system based on pedestrian detection technologies for the escalators located in the metro of Prague. The proposed system has as main goal to increase the reactiveness of the escalators allowing them to react to fast changes of pedestrian flow and at the same time reducing the formation of queues. For that, this thesis provides an overview of the current system used in a selected station of the metro system, and compares its operation with the proposed system by using simulation models developed for both cases.

The results in this thesis show that the proposed system, together with a change of the pedestrian behavior in escalators, could bring significant benefits for the users of the public transport by reducing the total time spend in queues.

Keywords

Public transport, escalators, automated control, simulation, Arena Rockwell

List of abbreviations

CCTV	Closed-circuit television
CEN	European committee for standardization
CZK	Czech crown
DPP	Dopravní podnik hl. m. Prahy or The Prague public transit Co. Inc. in English.
ELA	European lift association
HSE	Health and safety executive
OC	Operation cost
PT	Public transport
SAFed	Safety assessment federation
TWT	Total waited time

List of content

List of figures

List of Tables

1 Introduction

The need of having strong systems that can rapidly react to unexpected changes or events in the environment is more critical every year, especially in environments like the public transportation systems where the presence of dense crowds is expected.

As one can imagine, systems like the public transport are highly susceptible not only to failures but also to elements of our modern life like public events or terrorist threats. Elements that could not only overwhelm the systems, but also cause severe malfunctions and eventually bring repercussions to their daily users.

From these systems related to public transport, this thesis is focused on the escalators used in most of the subway stations located in Prague, which are currently controlled by a manual operation, making it difficult to rapidly adjust them to any event that could affect the correct operation of the Metro system.

1.1 Target of study

The main target of this thesis is to propose the general design of an automated control system based on pedestrian detection technologies for the escalators located in the metro stations in Prague, and to study the possible benefits or repercussions that this newly design system could bring.

1.2 Scope of study

The scope of this thesis is focused on the general design of the mentioned system and the comparison between the current one used in the metro stations in Prague and the proposed system, designing simulation models for each case to evaluate their benefits. Any physical implementation or change to the systems located in the metro stations in Prague fall out of the scope of this thesis.

2 Background

This chapter includes an overview of what escalators are and their main features, as well as a description of escalators as a general system and an overview of pedestrian detection technologies. Information about European safety standards for escalators is also presented.

2.1 Electric escalators

"*Escalators are load carrying units designed to transport people between two landings. They are driven by an electric motor and a drive system that moves steps and handrails at synchronized speeds. The escalator is supported by a truss which contains all the mechanical components, such as the drive unit, brakes and chain*". [5]

As it can be inferred, escalators are one of the most important elements in public transport stations, being the element that performs the process of pedestrian movement from one landing to another. It was estimated in 2010 by ELA (European Lift Association) that there are around 75 thousand escalators in EU-27, where 60.000 of these escalators are in commercial buildings and the other 15.000 are in public transportation facilities like subway stations, airports and train stations [5].

It is important to mention that the escalators are complicated element that in most of the cases should be considered as a system since they are integrated by several complex mechanisms as it can be seen in the figure 1. In this thesis, the escalators will be considered as one element and the components of the escalators won't be analyzed any further.
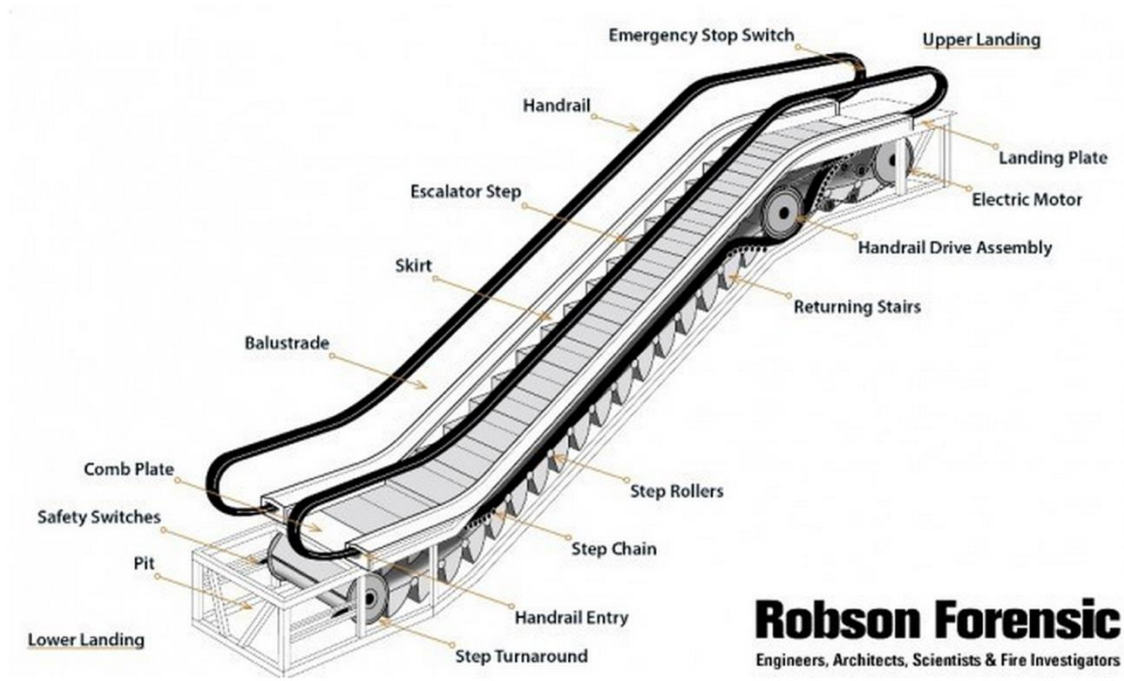
Figure 1: Basic design of an escalator [6]

Another important point to consider when analyzing escalators is the operation modes that they can take. The usual states that modern escalator can take are the following [5]:

1. Transient starting
2. Acceleration period
3. Normal speed mode
4. Low speed mode
5. Stop mode

Each one of these states has different power consumption as it can be seen in the figure 2 where the vertical axis represents the power consumption in kW and the horizontal axis the operation time in seconds. It is worth mentioning that not all the escalators can take all the mentioned states, talking specifically about old designs of escalators that are present in public transport stations in Prague which can't operate at the low speed mode.
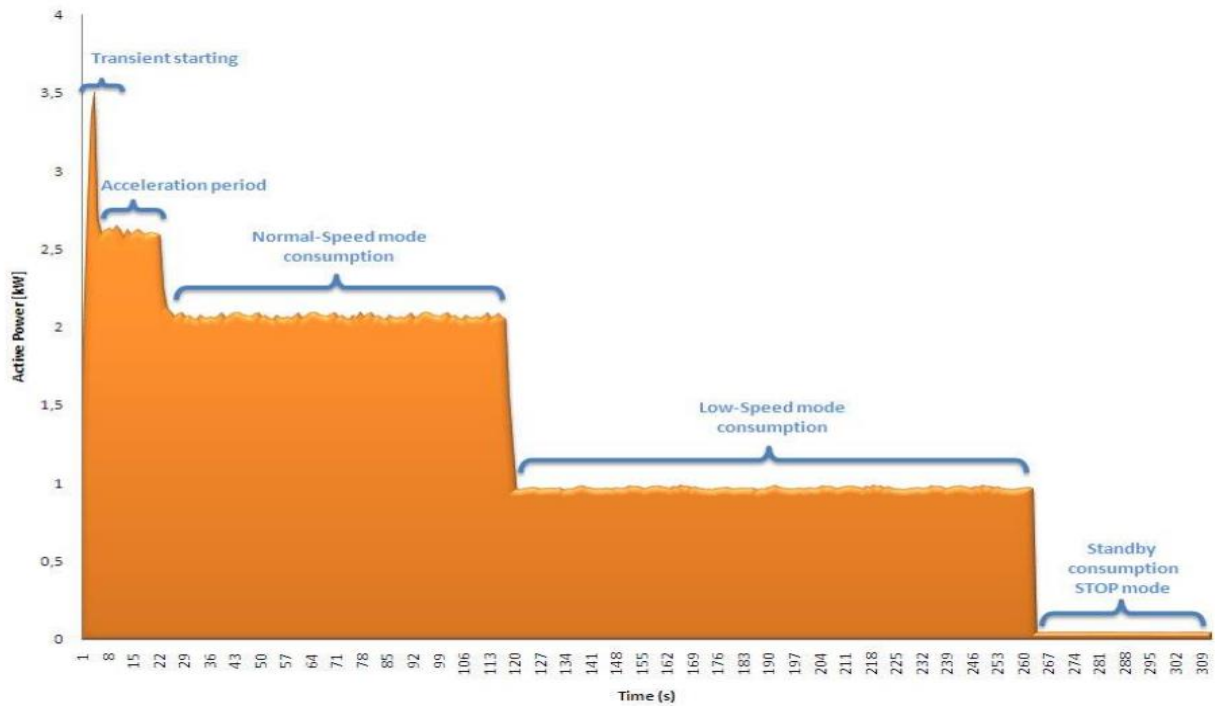
Figure 2: Operation states of modern escalators [5]

2.1.1 Safety recommendations and normativity for escalators

For the European market, there can be found several sources of norms and guidelines about the installation, operation, repair and use of escalators and lifts. Two of the main sources of these guidelines are the CEN (European committee for standardization) and the BSI (British Standards Institution) which collaborates with ISO.

One of the most relevant norms draft by these groups is the EN 115-2:2010 titled "Safety of escalators and moving walks. Rules for the improvement of safety of existing escalators and moving walks" [9]. This norm provides the guidelines for improving the safety during the operation of escalators according to each mechanical and safety component of the escalators.

Besides the EN 115-2:2010 standard, it is necessary to mention another guideline that proves to be of special use, especially when thinking about the operation escalators. This guideline is the "Guidelines for the Safe operation of escalators and moving walks"

redacted by the SAFed (Safety Assessment Federation) together with HSE (Health and Safety Executive). This guideline is not a mandatory document, but it provides a compressive and sufficient analysis of safety measures during the operation of escalators. The information most relevant from this guideline for this thesis is the recommended procedure for switching on any escalator. This recommended procedure goes as following. [10]:

1. Check all warning and safety notices are in place.
2. Check that there are no objects or people approaching the escalator and measures are taken to prevent access.
3. Check unrestricted area at landings is clear of obstructions
4. Perform visual check of the conditions of the general lighting of the steps/pallets and all emergency stop buttons.
5. Start the escalator and observe and listen during at least one circuit of steps/pallets.
6. Perform a visual check of operation of handrail/skirting/comb/under-step lightning.
7. If the above is satisfactory and the escalator is considered safe for use start the escalator and place into service.
8. Log and report all the observations and checks.

This procedure can also be applied to the process of switching off, where the only relevant step would be the number 2.

2.2 System analysis of escalators in subway stations

A subway station is the point where a user enters or exits the public transport subway system. Usually, subway stations are composed by many subsystems that are focused on the movement of users, for example the escalators systems or the lift systems. In this thesis, the focus will be on the escalators systems that are used in subway stations, which main objective as a system is to facilitate and speed the transfer of pedestrian between landings. Thinking about the escalators in a subway station as system allows identifying a series of specific elements that allow the system to perform as it is intended.

14

The most common elements present in the mentioned system can be recognized in the figure 3, where the boundary of the system is defined by the dotted line, meaning that any element outside of the dotted line is not part of the system itself but it is rather an actor that interacts with the system.
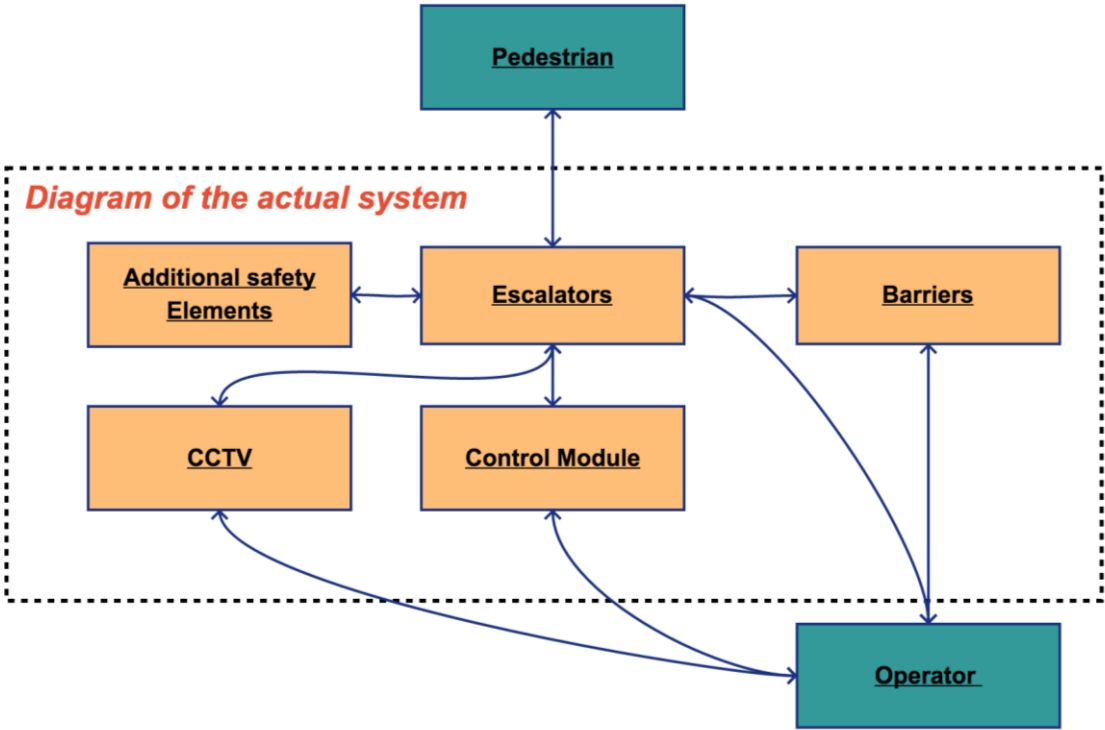
Figure 3: General scheme of an escalator system located in Prague metro station

The elements present in the system can be divided in two main groups: 1. Actors (represented as green squares) and 2. Those elements related to electro/mechanical or safety equipment. (represented as orange squares)

2.2.1 Actors of the system

The Operator: The operator is the person in charge of the correct operation of the escalators, meaning by correct operation: the timely control of direction of the escalators, their activation and deactivation. The operator has two options to control the escalators: The first option (and most used one) is to use the control module that directly controls the

operation of the escalators and the second option is to use the emergency buttons located at the escalators, being this option a more restricted way of controlling the escalators due to the fact the direction of the escalators cannot be controlled from the emergency button. Besides the control of the operation, the operator also interacts with the system by using the CCTV system (to have direct sight of line) and by manipulating and placing the safety barriers.

The pedestrians: It is important to mention that the pedestrians are the main actors that have contact with the system, being the goal of the system to speed up and facilitate the transfer time between the landings in the subway station. As actors, the pedestrians can interact with the system in two ways:

1. Using the escalators to move between the landings
2. Controlling the escalators by using the emergency buttons place at the beginning and end of the escalators.

It is also necessary to mention that the system should assure the safety of the pedestrian during all the processes of transfer between landings. The safety of the system is achieved by following the European guidelines for escalators that were already mentioned (Chapter 2.1.1).

2.2.2 Electric/Mechanical and safety elements of the subway escalator system

Control Module: The control module is the element of the system that has direct control over the operation of the escalators. It is used by the operator to: Initiate/stop the escalators as well as to change the direction of it.

Barriers: The barriers can be found at the beginning and the end of each escalator. Their objective is to prevent the access to the escalators when they are in Stop mode or during the process of change of state. They are managed by the operator, who is the person in charge of locating them before and after any change of state to prevent accident. In some

cases, the barriers also contain signs to inform the pedestrians that the use of the escalators is not allowed.

Additional safety elements: These safety elements are a group of sub elements which goal is to increase the safety of the escalators. Not all the escalators have the same safety elements, therefore some of the most common ones are:

1. Awareness signs: which are signs that inform the pedestrians of what precautions to take during the usage of the escalators
2. Deflector brushes: The deflecting brushes are passive safety features that prevent any element to be trapped between the gaps at the edges of the escalators, preventing that way any possible accident related to shoelaces and similar elements [8].

CCTV system: As it was mention in previous subchapters, one aspect to have in mind when operating a system that involves the use of escalators is that the operator in charge of the system should always have direct sight of line to the system. Having direct sight of line could easily be achieved by placing the operator working space close to the escalators as it can be seen in figure 4. Yet in most of the cases it is not possible to do so and therefore it is required to have CCTV (closed-circuit TV) system that allows the operator to have a clear view of the escalators even if he is not close to them.
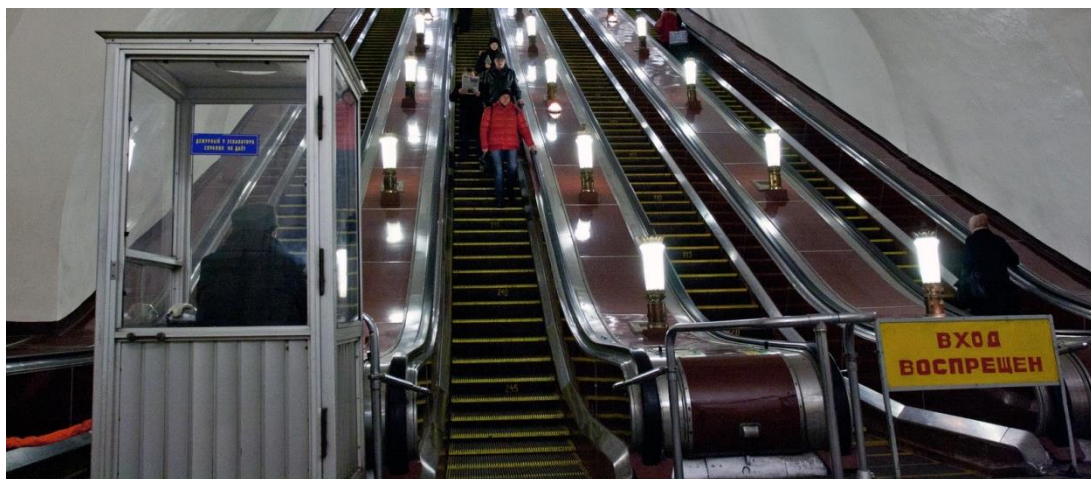
Figure 4: Russian approach to the design of escalators in subway stations [18]

17

2.3 Pedestrian detection technologies

In this section, the most relevant technologies for the detection of pedestrians will be discussed. It is important to mention that these technologies are not relevant for the current state of the system, but they are relevant to the new design of the system that will be presented in following chapters. In a general way, the new proposed system is designed to react and adjust the number of available escalators according to parameters measured from the pedestrians.

Now, talking about pedestrian's detection technologies can be ambiguous since one may think these technologies are only used for the detection of pedestrian's presence. It is for this reason that it's important to define that pedestrian detection technologies are those that allow to measure at least one of the following parameters:

- **Pedestrian flow:** Number of pedestrians per unit of time entering the system.
- **Pedestrian presence:** It refers to the presence of a pedestrian in the system or the absence of it.
- **Time gap:** It means the time between the arrivals of two consecutive pedestrians to the system.
- **Pedestrians speed:** It refers to the speed of individual pedestrians entering the system.

Having defined what pedestrian detection are technologies and the main measured parameters by these technologies, it becomes important to explain why they are relevant to this document: The importance of these technologies lie in the ability to detect and measure parameters from the pedestrians using the system, especially the flow of pedestrians, which is the fundamental parameter that will be used to control the operation of the new proposed system, activating or deactivating the available escalators according to the amount of pedestrians entering and leaving the system.

Due to the technological advance in the area of pedestrian detection there are many options from where to choose for the new system, but the most used or most relevant for scenarios related to escalators are the following technologies

2.3.1 Infrared sensors

Infrared motion sensors are one of the most common types of pedestrian detection technologies used today. Due to their low cost, they can be used for many applications like the control of lightning based on presence detection and even the measurement of pedestrians using public transport facilities. The difference between the two mentioned applications lays in the type of infrared sensors used, using passive sensors for the control of lightning and active sensors the measurement of pedestrians. [11]

From both types of sensors, the most relevant one for the proposed system are the active infrared sensors, which are already in used in most of the subway stations in Prague and their main objective is to count the number of pedestrians leaving/entering the stations.
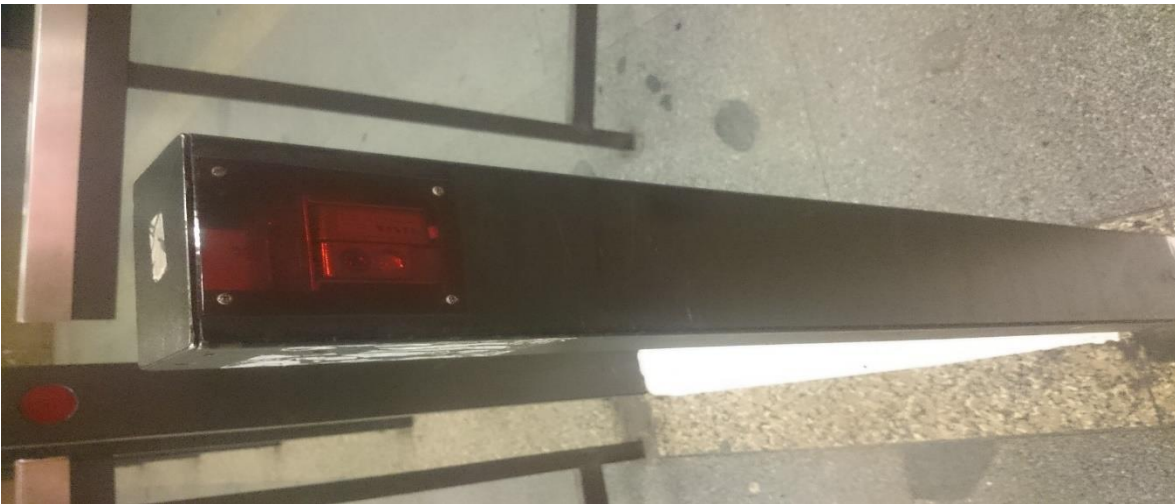
Figure 5: Pedestrian counter using active infrared sensors (Prague)

The most common components of an active infrared sensor are: 1. The transmitter which is the source of an infrared beam, 2. A receiver that detects the beam and 3. A reflector. In some cases the reflector is not a necessary element, but due to the common practice of having the transmitter and the receiver in the same side it is necessary to have a

reflector to redirect the infrared beam [11]. As it can be inferred, this type of sensors works based on the detection of the beam. When the beam is interrupted by an object, the system assumes the presence of a pedestrians/element and triggers the actions it is programed to do.

The main advantage of using active infrared sensors is their low cost and rather simple implementation (when comparing with other technologies), but they also have a serious disadvantage that needs to be taken in mind, especially for the design of system that may affect the safety of the pedestrians: This kind of sensors are not the most accurate technologies in the market, and they are severally affected in rush hours when the presence of crowds is common. Because these sensors detect the interruption of the infrared beam, it is not possible to know if the interruption is due to an external object, a pedestrian or a group of pedestrians walking in parallel, therefore the quality of the information depends heavily on the number of people going thought the sensors space.

2.3.2 Piezoelectric sensors

These types of sensors are often used in escalators where it is possible to reduce the speed of them when there are no pedestrians in the system. The goal of this type of sensors is to detect the entrance of a pedestrian to the system and therefore increase the speed of the escalators from a reduced speed state to its normal operation state. To detect pedestrians with these type sensors it is necessary to use piezo-cables, which are usually fabricated in a "mat" structure and located in the floor in front of the entrance of the escalators. When a person encounters the mat, the piezoelectric materials generated an electric signal until the pedestrians leaves the mat area. [12]

As one can imagine, this type of sensors have similar advantages and disadvantages to the infrared sensors, where the main advantage is the low cost and simplicity. The disadvantages of these sensors are the lack of ability to count pedestrians or any other relevant parameter with accuracy, especially in situations where crowds and groups are very common.

2.3.3 Ultrasonic sensors

The ultrasonic sensors are one of the most mentioned and used technologies in the recent years, especially due to the increasing popularity of intelligent vehicles and their usage of ultrasound sensors to detect pedestrians and obstacles. One good example is the vehicle model S produced by Tesla, which has a total of 12 sensors that provide a 360-degree view of the surroundings of the car. This can be seen in the figure 6 where the yellow area represents the area of detection created by the ultrasonic sensors. [13]
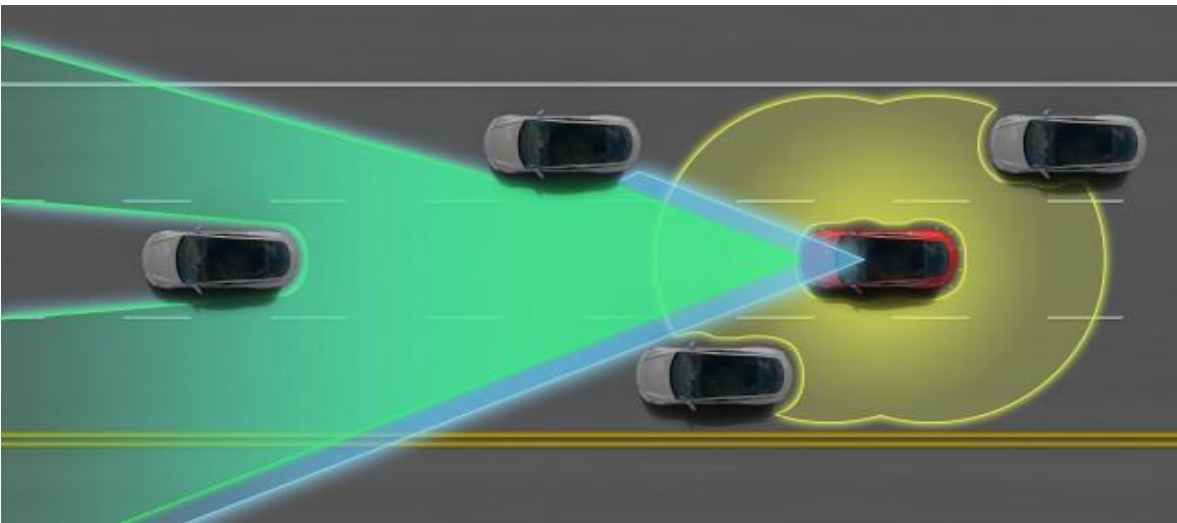
Figure 6: Tesla ultrasonic sensors [13]

These types of sensors detect objects by using ultrasonic waves and their reflection from the objects near the devices. Depending on the sensor, different features from the object can be measured, for example the presence of the object, the speed and the distance to the sensor. It is important to mention that these features depend on the type of ultrasonic sensor, being able to differentiate two main categories [12]:

- **Pulse ultrasonic sensors:** This type of sensors measure the presence or distance to an object by creating pulse signals and calculating the travel time until the reflection of the signal arrives to the sensor.

- **Continuous wave sensors:** This type of sensors uses continuous ultrasonic waves and the Doppler Effect principle to detect objects and measure their speed.

The usage of ultrasonic sensors is widely spread due to their low cost, expanding their possible uses further than intelligent vehicles. Couple of examples worth to mention are the use of ultrasound sensors to measure the occupancy of classrooms [14] and the measurement of pedestrian flow using this type of sensors [19]. The main disadvantages of the ultrasound sensors can be divided in two [12]:

- To prevent the loss of ultrasonic energy from the bounce back the ultrasound it is important to position the detectors either facing downward above the target area or aiming from a horizontal mounted side viewing position.
- The quality of the signal may vary depending on the materials of the clothes used by the pedestrians, where the natural fibers are more absorbent than synthetic fibers, therefore being the synthetic fibers easier to detect.

2.3.4 Video detection

Video detection is a technique widely used in transportation to detect both pedestrians and vehicles. It is a more complex method that any of the mentioned above and it requires a significant amount of investment, especially when talking about infrared cameras. Due to its complexity, the detection of pedestrians using video detection can be divided per hardware and software. Even though both software and hardware are very relevant to the measurement of pedestrians, this subchapter will be mainly focused on the types of camera based on their hardware.

Types of video detection based on hardware:

According to the type of hardware use, the video detection technology can be divided in [15]:

- **2D Cameras:** In standard 2D cameras the captured image is flat, meaning that it only has information about length and width of the objects, ignoring the information

about height. This situation limits the camera to certain positions to improve the quality of the information obtained. Even though the 2D cameras don't have information about height, they can be used in live pedestrian counting, which requires the camera to transfer data either via Wi-Fi or Ethernet.

- **3D Stereo cameras:** Opposite to the 2D cameras where the image is flat, the 3D Stereo cameras provide information about width, length and height of the objects, as well as information about object rotation around the three axes. This kind of cameras are widely used not only in pedestrian detection but also in robots, where picking elements is a necessary function. It is important to mention that even though the 3D stereo cameras provide much more information than the 2D cameras; their price is significantly higher, especially when the cameras have added functions like infrared sensors.
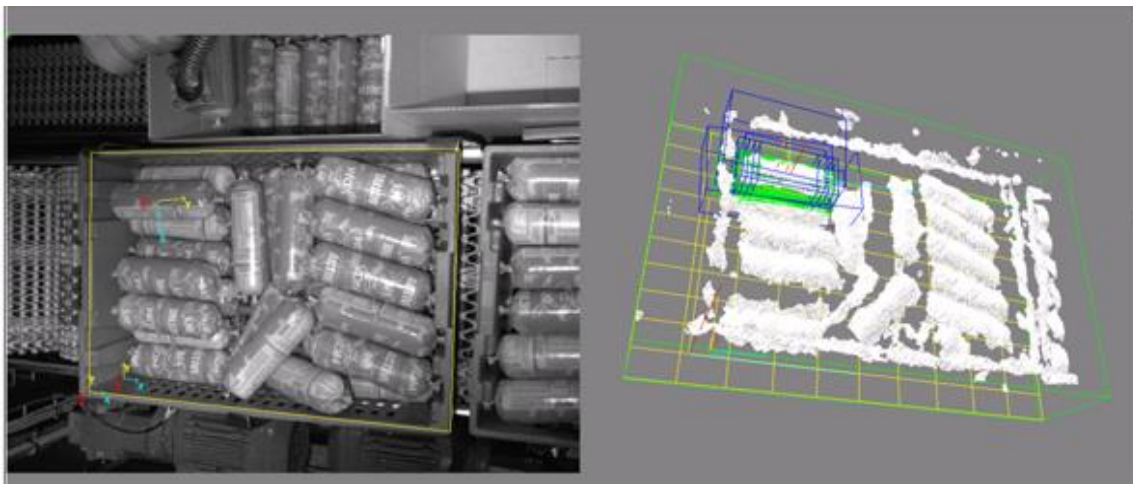
Figure 7: Example of a 3D stereo camera output [15]

In general, the use of video detection technologies is widely spread in processes where the detection of pedestrians/vehicles or other elements is necessary. Even if their price and complexity is much higher than any of the other mention technologies, they represent a good option due to ability to measure most of the mentioned parameters, and to have a direct sight of line to the analyzed system, which is mandatory in the case of the selected system.

3 Measurement, methods and tools

In this chapter, the selection of a subway station located in Prague is done for the further analysis presented in this thesis. Also, the methods used to measure the parameters needed for the simulation models that will be developed are presented. Finally, the basics and logic behind the software "Arena Rockwell simulation" are explained.

3.1 Selection of subway station: I. P. Pavlova

For this thesis, the system selected was the escalator system located in the subway station I. P. Pavlova. This subway station was considered as ideal for the analysis that will be developed due to the presence of the following factors:

1. The high flow of pedestrians in the system.
2. The presence of four escalators that allows the study of more scenarios than the usual array of three escalators.
3. The control process of the escalators, which requires that the operator in charge of the transfer station to manually change the number of operating escalators based on their perception, schedule and rush hours.

When the mentioned factors are combined, as they are in the I. P. Pavlova subway station, it causes the system to be unable to react to fast changes of pedestrian flow. This situation can be easy seen when the system has only one escalator activated each direction even though the flow of pedestrians is much higher than what one escalator can handle.

3.1.1 History of the I. P. Pavlova station

The mentioned subway station started operating in 1974 when the line C was opened to the public, connecting the stations between Florenc and Kacerov. The station was constructed at a deepness of 19 meters, with a total longitude of 165 meters and a width of 10.2 meters [1].

24

It is important to mention that the construction of the I. P. Pavlova station took place during the soviet occupation of Czechoslovakia (From 1968 until the end of 1989), therefore most of the equipment were developed during the Soviet Union [2], but latter most of the equipment in the escalator system located in the mentioned station was remodeled, which can be easily seen by comparing the different photographs in figure 8. One aspect to highlight is the fact that the I. P. Pavlova subway station is one of the stations with higher flow of pedestrians in the whole system. According to a survey done in 2008 by DPP, which is the company in charge of managing the subway station, the I. P. Pavlova station served around 118647 users per day, making it the most used station at the time of the survey [3]. It is due to this reason that the I. P. Pavlova station counts with a system array of four escalators, array that is rarely used in stations that are not connections between lines, like the Florenc and the Muzeum stations.

Figure 8: Escalators from the Florenc station (left) and modern escalator from the station I.P Pavlova (right)

3.1.2 Parameters of the escalators located in the I. P. Pavlova station

It is important to mention that most of the escalators located in the public transport system have unique parameters that depend mainly on which station they are located. These parameters are relevant for the analysis that will be presented in this document, therefore it is necessary to define which of the parameters are relevant and why are they relevant to the analysis to be done.

Operation modes of the escalators: The escalators installed in the I. P. Pavlova station can only operate in two modes: The stop mode and the normal speed mode, which is used during the normal operation of the escalators.

Structure array of the escalators: As it was mentioned the previous sub chapter, the selected station has a total amount of four escalators, which can be used in any direction. This array structure has the advantage of being more flexible when comparing with other arrays of three escalators, allowing the system to have a maximum of three escalators operating in one direction.

Speed of the escalators and travel time: The escalators in I. P. Pavlova operate at a speed of 90 cm per second. This speed, together with the specific length of the escalators located in the system, translate to a specific travel time that defines how long does it take to move between landings. This travel time will be presented in the following chapter.

Flow structure: Even though the structure of the flow is more relate to the station itself than the escalators, it becomes important to mention that the I. P. Pavlova station only counts with one main entrance/exit limiting the possibilities how a pedestrian can enter the system to: By using the main entrance or by arriving from other stations using the trains in the C line. It is due to this structure that most the pedestrians in the system must use the analyzed escalator system.

3.2 Measurements

This subchapter is focused on the measurements done during the development of this thesis. The measurements below are fundamental for the development of the simulation models that will be presented later and they are related to the parameters mentioned in the previous chapter.

3.2.1 Measurement of escalators capacity

The task of measuring the total number of pedestrians that can be at any given time in an escalator is quite complicated when the escalator is activated. When the escalator is not operating, the task becomes much simpler, requiring to count the total number of steps

visible and that could be used for a pedestrian. In the case of the select system, the total number of available steps is 62, meaning that the total number of pedestrians at any given time in one escalator is 124 since the escalator is wide enough to have two persons per step.

3.2.2 Measurement of travel time in the system

The travel time in the system was measured by counting the number of seconds since a pedestrian enters the system until it leaves it. The measurement was done a total of 12 times, three times for each available escalator. It was found that the travel time it's constantly 37 seconds, independent from the escalator or the direction taken. This measurement corresponds only for those pedestrians that only stand during the time in the system

3.2.3 Measurement of pedestrian flow

The flow of pedestrians is one of the main parameters of the subway station and its impact in the simulation model is very significant. The information regarding this parameter was obtained from DPP and consists on the total number of pedestrians entering and leaving the station per hour:

Table 1: Pedestrian flow in the I. P. Pavlova Station per hour on 23.11.2016

Station: I. P. Pavlova	Number of pedestrians who entered	Number of pedestrians who left	total
05:00-06:00	420	621	1041
06:00-07:00	1214	2581	3795
07:00-08:00	2602	5821	8423
08:00-09:00	3205	5292	8497
09:00-10:00	2440	3509	5949
10:00-11:00	2142	2640	4782
11:00-12:00	2225	3093	5318
12:00-13:00	2748	3025	5773
13:00-14:00	3249	2688	5937
14:00-15:00	3896	2901	6797
15:00-16:00	4212	3160	7372
16:00-17:00	4371	3922	8293
17:00-18:00	4589	4755	9344
18:00-19:00	3696	3518	7214
19:00-20:00	2667	1937	4604

20:00-21:00	1832	1203	3035
21:00-22:00	1388	768	2156
22:00-23:00	1166	573	1739
23:00-00:00	1035	370	1405
Total (05:00-00:00)	**49097**	**52377**	**101474**

As it can be seen in the table above, the flow of pedestrians entering and leaving the station is relatively symmetrical, behavior that is expected from a subway station located in central area Prague. It is important to mention that these results will be use for the development of the simulation models that will be presented in further chapters.

3.2.4 Pedestrian distribution leaving the trains in I. P. Pavlova

The distribution of the pedestrians inside of the trains arriving to I. P. Pavlova is a relevant parameter that needed to be studied to design a simulation that represents the real behavior of the system, since this information will be used in the simulations that will be presented in the next chapters. For this reason, it was decided to measure how many pedestrians leave each wagon of the train. The measurements were done in a period of two hours.

Table 2: Distribution of pedestrians leaving the Trains arriving to I. P. Pavlova

	Measurements Pedestrian distribution per train				
	Wagon 1	*Wagon 2*	*Wagon 3*	*Wagon 4*	*Wagon 5*
	11	9	11	11	5
	14	14	8	9	4
	16	10	8	8	7
	17	8	6	6	6
	15	9	6	9	7
	21	8	7	7	5
	19	9	9	10	7
	17	14	8	10	6
	30	14	8	11	5
Total	160	95	71	81	52
Percentage	0.348583878	0.206971678	0.154684096	0.176470588	0.11328976

Regarding the measurements, it is important to mention that they do not correspond to the same train due to the difficulty of measuring all the wagons at the same time. For this

reason, it was decided to measure a wagon two consecutive arrivals and then measure the next wagon under the same method.

3.3 Software tools: Arena Rockwell Simulation

Arena Rockwell Simulation is a discrete event simulation software used around the world in a wide variety of industries. According to the website of Arena: "Discrete event modeling is the process of depicting the behavior of a complex system as a series of well-defined and ordered events and works well in virtually any process where there is variability, constrained or limited resources or complex system interactions" [16].

Independent of the industries, there are specific challenges that most of the companies/institutions need to tackle, and Arena facilitates that by allowing to [16]:

- Evaluate the possible alternatives or scenarios to define which alternatives optimize specific objectives like: Cost, usage time, availability and usage of resources, cycle time, among others.
- Reduce the risk of alternatives by simulating and testing changes to process that involve big amounts of capital or resources.
- Determine the impact of uncertainty and variability on system performance.
- Displays results with 2D or 3D simulations based on the analyzed system.
- Perform „What-if" analysis, where it is possible to change the parameters and see how these changes affect the results.

Another important aspect to mention from Arena is the included tool called OptQuest, which increases the analytical capabilities of Arena by allowing to search for optimal solutions within simulation models based on a series of user defined constrains. The importance of this tool lies in the fact that the user doesn't require any specific knowledge behind the optimization algorithms used by OptQuest, allowing most users to do deep multi scenarios analysis. [17]

3.3.1 Functions of Arena Rockwell Simulation

As it was mentioned, Arena is a widely used simulation software that can be applied in different industries due to its general design. Design that is based on the use of the following three types of elements:

3.3.1.1 Entities and resources

The basic principle of Arena is the creation of entities and the use of them as elements that participate, trigger or take part in a studied process. Thanks to the fact that the entities are a general concept, they can be used in a wide range of activities to represent completely different elements of the real world. In the case of the simulations that will be presented in further chapters, the entities represent pedestrians that enter the system, but they could represent a wider range of elements like the operator of the system, the arrival of trains at the subway station or even just certain intervals of time.

The Resources are in a way like the entities because they also interact or allow a process to take place. As its names indicate, the resources are actual elements that are needed to perform an action. One simple example to understand the difference between an Entity and a Resource is the case of a public bus where the pedestrians need empty seats or space to use the bus. In this case, the pedestrians could be represented as entities and the seats as resources since they limit the maximum number of pedestrians that can use the bus at any given time.

It is important to mention that Arena allows defining as many type of entities as the user requires, and each entity can have its properties and specific images that represent them.

3.3.1.2 Blocks

One could define the Blocks in Arena as the main modules that allow to perform any desired process, ranging from production processes to the movement of elements between two points. Since the Blocks can perform a wide range of operations they are

divided in "Basic processes", "Advance transfer processes", "Advance processes" and more specialized blocks that are not relevant to this thesis. From each of the mentioned categories the most relevant blocks for this thesis are:

Create and Dispose blocks: These blocks are the simplest and at the same time more important blocks in Arena. As their names indicate it, their function is to allow the creation of entities and the dispose of them once they are not needed in the simulation. As it can be seen in figure 9 the Create block not only allows to create entities but also to select which kind of entity is going to be created, how many entities per arrival should be created and the time between the arrival of two consecutive entities. Most of the mentioned parameters can be based on statistical distributions, expressions or even schedules.
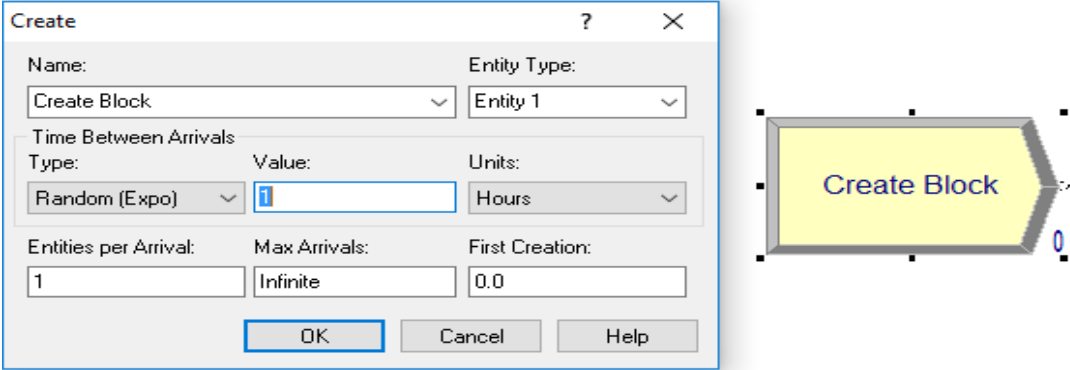
Figure 9: Create block and its parameters

In the other hand, the Dispose block is much simpler in terms of parameters and functions since its only function is to dispose of not needed elements. As it can be seen in figure 10 the interface of the Dispose block is much more reduced than the one used in the Create block.
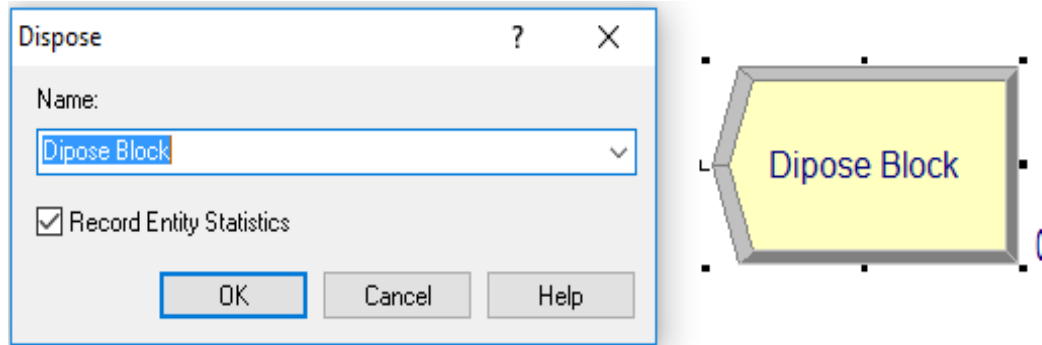
Figure 10: Dispose block and its parameters

Decide block: The main function of the decide block is to split the flow of the incoming entities. The splitting process could be done based on simple percentages or more complicated conditions which can be created with help of the Expression builder tool. This block not only allows splitting the flow in two but also in N number of different paths according to what the user needs.
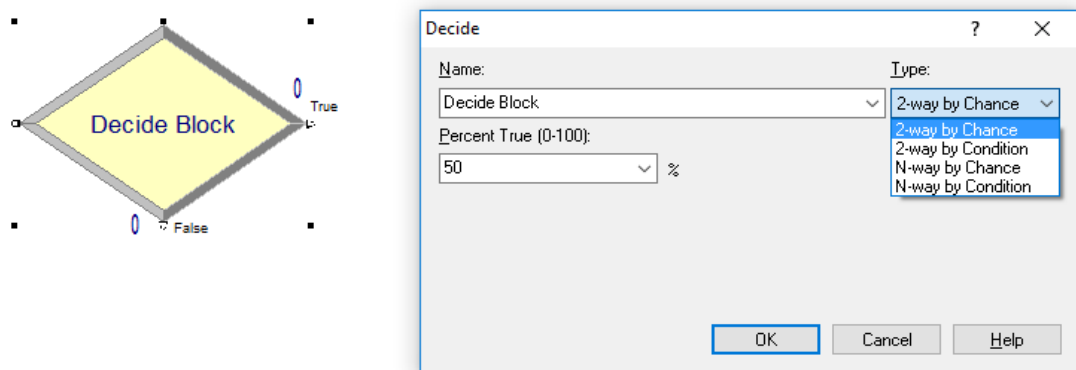
Figure 11: Decide block and its parameters

Process block: The process block is the main block used when it is needed to represent general processes of any kind. It is based on the idea that entities arrive to the block, perform an activity for a certain amount of time and then leave the block. There are two types of actions that can be identified in this block:

- **Seize-Delay-Release actions:** For this kind of actions the entities require a certain amount of resources to perform it. In the case an entity requests an

amount of resources and if there are not enough resources, then the entity should wait until the resources are liberated, therefore creating a queue at the beginning of the block.

- **Delays:** These kinds of actions are usually individual and do not require any type of resources. In these actions, no queue is created because each entity can perform an action independently from the other entities.

Both mentioned types of actions have something in common and it is the fact that both require the "Process time" as main parameter. As it can be seen in figure 12, it is necessary to input the time each action will last, where the time can be expressed as a statistical distribution, a constant or any expression created by the user.
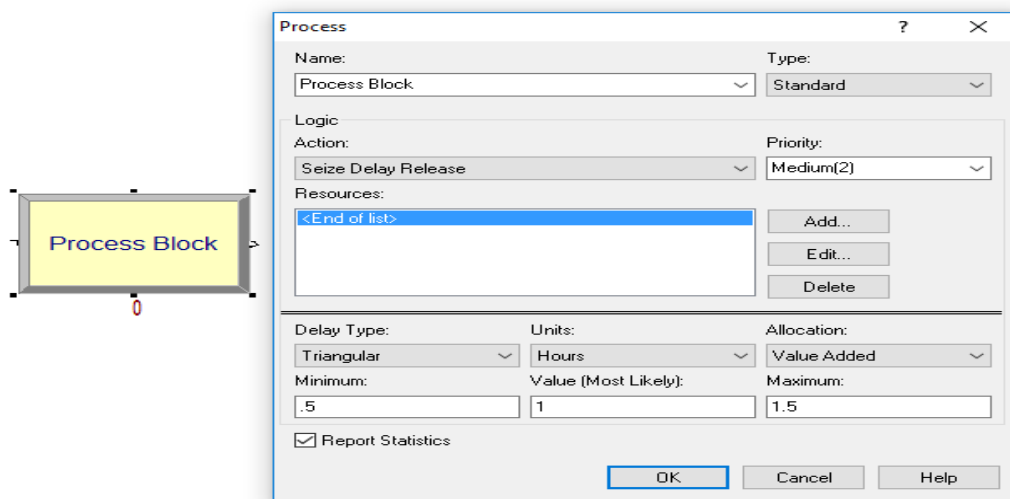
Figure 12: Process block and its parameters

Assign block: The function of this block is very different from those already mentioned, and up to some point it is more abstract. One could think about this block as a common assignment used in any programming language, where one variable takes a desired value, function, etc. Following the same principle, this block allows to assign values or general expressions to either variables or attributes.

Now, the difference between a Variable and an Attribute is based on how global they are. On one hand the Variables have a Global character and are unique for each simulation model, while the attributes are applicable for each entity and are unique for individual entities. Thinking about a room of people one can say that a Variable is the average age while the Attributes are the individual age of each person in the room.
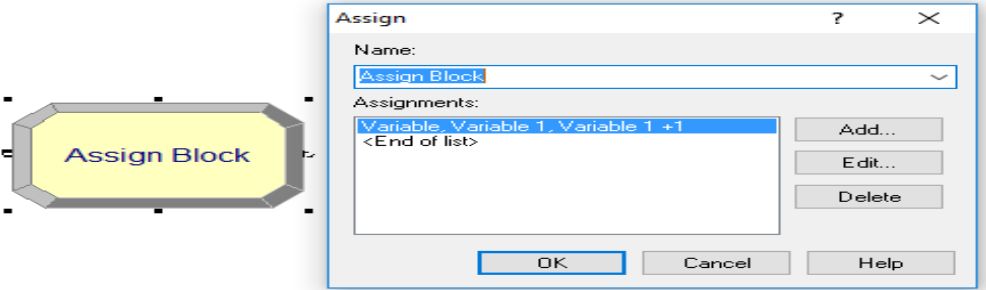
Figure 13: Assign block and its parameters

Station blocks: The station block allows to define specific areas and to track the flow of entities in and out of these areas. Since Arena works in general level of logic the entities do not have any information about geographical spaces, therefore making it necessary to use this special type of blocks.
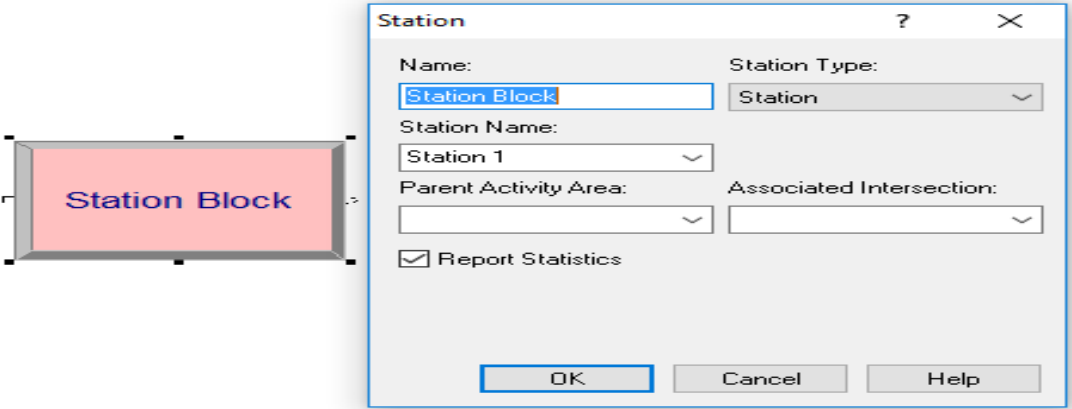
Figure 14: Station block and its parameters

Besides their basic function, the stations block is also a fundamental part of any block related to the movement of pedestrians. More advance transfer blocks like the conveyor require inputting the initial and the last station for the movement, that way specifying form where to where the entities are moving.

Conveyor related blocks: A real representation of a conveyor from Arena would be a one lane escalator where only one person is allowed per step. The conveyor function depends on more than one type of blocks, having three mandatory types of blocks and two extra optional types.

The first type in the convey process is the Access Block, which oversees assigning the number of Cells or spaces that each entity will use in the conveyor. As it can be deduced, different types of entities can use different number of cells depending on how the user defines the simulation model.
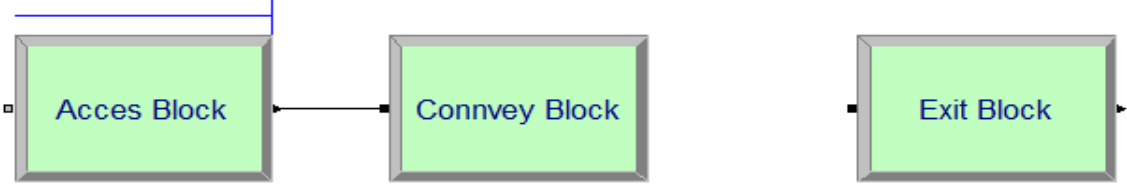
Figure 15: Main blocks of the convey process

The second type is the Conveyor block which has the objective of defining which conveyor is going to be used and where are the entities going. This is important because the entities could be directed throw different conveyors and to different destinations according to their type or other attributes. The final type used in these processes is the Exit Block which liberates the cells or spaces in the conveyor once an entity exit it. The liberation of the free cells is one of the most important aspects in the convey process. If an entity requests a cell and there not enough free cells, then the entity is put in a queue until enough cells are liberated.

The last two extra blocks that can be used for the convey process are Start and Stop blocks, which allow to start and stop the conveyor at any time.

3.3.1.3 Global information

The last type of elements that are used in Arena could be called "Global Information" due to the fact that they don't have an actual block where they could be visualized. Examples of these types of elements are the Attributes and the Variables which are used in most of the simulations with Arena, but still don't have any specific block where they can be visualized. For this type of elements Arena offers the option of visualizing them as a list, depending the specific element that the user wants to analyze.

4 Design of simulation models

This chapter will be divided in 3 main subchapters, where the first subchapter is focused on the development of a simulation model for the current state of the system. In the second subchapter, a proposal for a new system will be designed based on pedestrian detection technologies with the goal of reducing the total amount of waiting time. In the final subchapter, the simulation model of the newly proposed system will be developed.

It is important to mention that the simulations present in this chapter are important because they allow to determine parameters that otherwise couldn't be calculated without affecting the normal operation of the system. Also, the second advantage of using simulation models is the ability to compare different scenarios and the decision support it represents to choose which scenario is the best. Some examples of mentioned parameters are:

The average waiting time of the system: Meaning the average amount of time that the pedestrians spend in queue.

Max waiting time: Meaning the longest waiting time spend by any of the pedestrians that entered the system.

Total waiting time: Meaning the sum of all the time waited by all the pedestrians.

4.1 Design of the simulation for the current state of the system

The simulation of the current state of the system is based on the mentioned parameters of the selected stations and a series of assumptions needed to simplify some of the processes to simulate. These assumptions are based either on information obtained from DPP or a series of researches about relevant topics. Before the simulation itself is presented, the assumptions made will be explained as following. Also, it is important to

mention that the simulations that are presented in this chapter are developed on Arena (Chapter 3.2.4).

4.1.1 Assumptions made for the simulation

Behavior of pedestrians in escalators: One of the most relevant decisions to take regarding the simulation model is which kind of behavior the pedestrians will have when using the system. This is especially relevant in a country like Czech Republic where the behavior of the pedestrians in escalators is particularly different from what can be seen in other countries. In Czech Republic, the pedestrians are taught to use the right lane of the escalator when they want to be standing and to use the left lane of the escalator when they decide to walk. This behavior is seen as good manners in Czech Republic and it allows pedestrians to reduce the time spend in the escalators when they need to.

Now, even if this behavior is considered as the standard behavior it doesn't mean that it is optimal for the society. In a research done in the subway of London, it was found that the behavior present in Czech Republic can reduce the total capacity of an escalator system up to 30%, especially when the escalators are long deterring the pedestrians from walking. [20]

The second factor against the behavior present in Czech Republic is a more technical one, and it is the fact that due to the load of pedestrians being present mostly in one side of the escalators, the escalators are suffering extreme wear and tear on the tracks, bearings and other mechanical elements, being that the reason why DPP is asking the pedestrians to modify their behavior and use both sides of the escalators. [21]

Having the mentioned reasons in mind, it was decided that during the simulation of the system the pedestrians will stand in both lanes of the escalators and not the Czech behavior.

Distribution of pedestrians leaving the trains: At a first glance, it may look like the distribution of the pedestrians inside of the wagons is not relevant for the analysis of the escalators, but it has a great impact in the simulation because the time between arrivals to the system depends on which wagon did the pedestrians use.

It has been proved in different papers that the distribution of the pedestrians inside the trains depends mainly on the structure of station of arrival. In the case of the arrival station having only one exit, like it happens in I.P Pavlova station, the distribution of the pedestrians tends to be denser closer to the exit of the station. [22]

To simulate this behavior many statistical distributions could be used, but it was decided to use the distribution obtained based on the measurements already explained in previous chapters, where the number of pedestrians leaving each wagon was measured.

Based on these measurements, the distribution of the pedestrians leaving the trains can be seen in the following chart where the vertical axis represents the % of the total amount of pedestrians that leave the train.
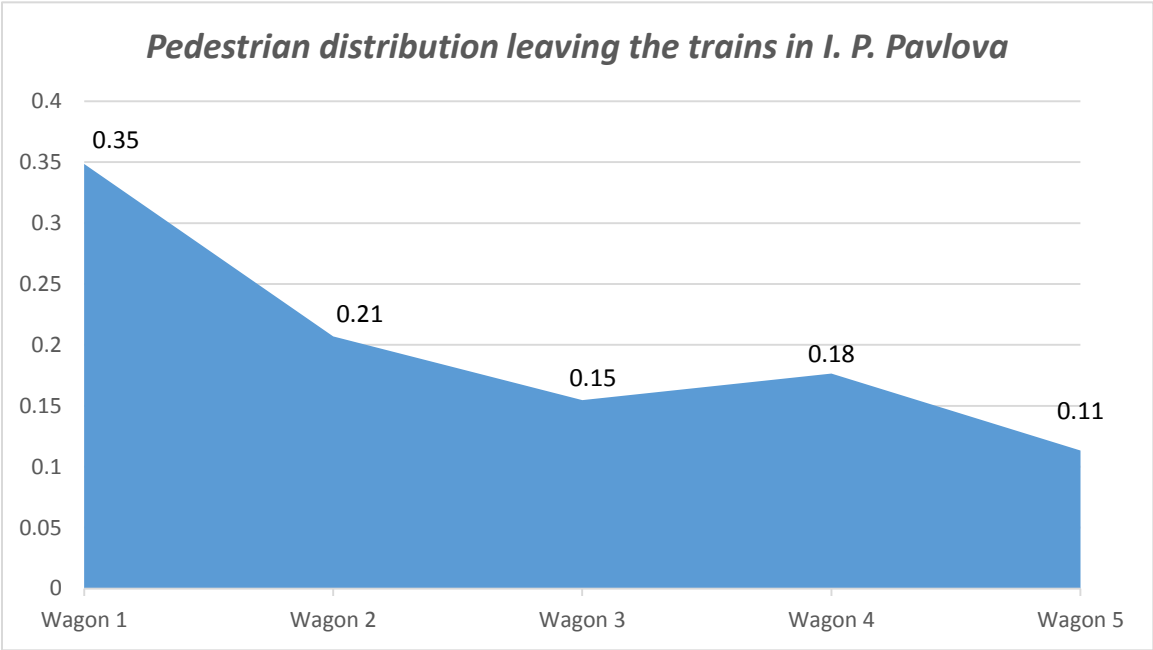
Figure 16: Distribution of pedestrians leaving the Trains in I. P. Pavlova

Flow of pedestrians: As it was mentioned in previous chapters (Chapter 3.2.3), the information about the pedestrian flow was obtained from DPP, where it is detailed the number of pedestrians entering and leaving the station per hour. Even though this information is very complete, it represents a problem when simulating the pedestrians arriving by train to the station because it is necessary to have an average number of

pedestrians per train and not per hour. To simplify this situation, it was decided to symmetrically divide the flow of pedestrians per hour by the number of trains arriving at each hour, therefore having the same number of pedestrians per train in the same hour.

Now, the case of the pedestrians arriving from the street is much simpler because it can be directly simulated using the information obtained by DPP.

4.1.2 Simulation model of the current system

Due to the complexity of the model, it was decided to divide the simulation in "sub models" or sections for a better understanding. Each of the sections represent physical or logical processes necessary to achieve the goal of pedestrian movement. The main sections of the simulation are the following:

Arrival of pedestrians to the escalators: As it was mentioned, the arrival of pedestrians to the escalators can happen either by arriving from other stations or by entering the station from the street. Both arrivals have different characteristics and need to be defined individually.

On one hand, the arrival of pedestrians that are coming from other stations depend on the arrival of trains to the station, which also depends on the direction from where train is coming and the day of the week. For the simulation, it was decided to use the schedule of arrivals provided by DPP, which specifies at what time should arrive every train depending on the direction of the line and the day of the week. Since the schedule for weekends and working days are different, it was decided to use the schedule from working days. The schedules used can be found in the Attachment 1. Besides the arrival of trains, it was also necessary to implement the assumptions of the pedestrian flow and the distribution of pedestrians in the wagons mentioned in the previous chapter.

One las aspect to mention regarding the pedestrians arriving by train, is that their movement from the wagons to the escalators is simulated based on the information of which wagon are they using, the distance of the wagon to the system and an average speed of walking of 1.4 meters per second, which corresponds with the average walking speed in Czech Republic.

40

On the other hand, the case of the pedestrians arriving from the street is simpler to simulate. In this case, it was decided to use a Poisson distribution to simulate the arrival of pedestrians per hour, where the mean of the used distribution matches the value of arrivals given by DPP for each hour.

Decision on which escalator to should the pedestrians use: The second section after the arrival to the escalators is the logical decision of which escalator to use, which depends on the amounts of escalators active in the system. Since the station has an array of four escalators there are different possibilities on how many escalators can be active for each direction. All the possible states of the system can be seen in the following table:

Table 3: Possible estates of the escalator array

Minimum case	One escalator for each direction
Intermediate cases	1. Two escalators active in one direction and one escalator active in the opposite direction. 2. Two escalators active in both directions.
Extreme case	Three escalators in one direction and one escalator in the opposite

Even though all the states presented in the table above are possible, not all of them are used in the simulation of the current system. The reason behind this will be explained further in this chapter.

Now, when the pedestrians arrive to the escalators it should decide which escalator to use based on which of the above presented cases is active. For this, the simulation has a series of decision threes that follow the logic presented in the picture below:

41
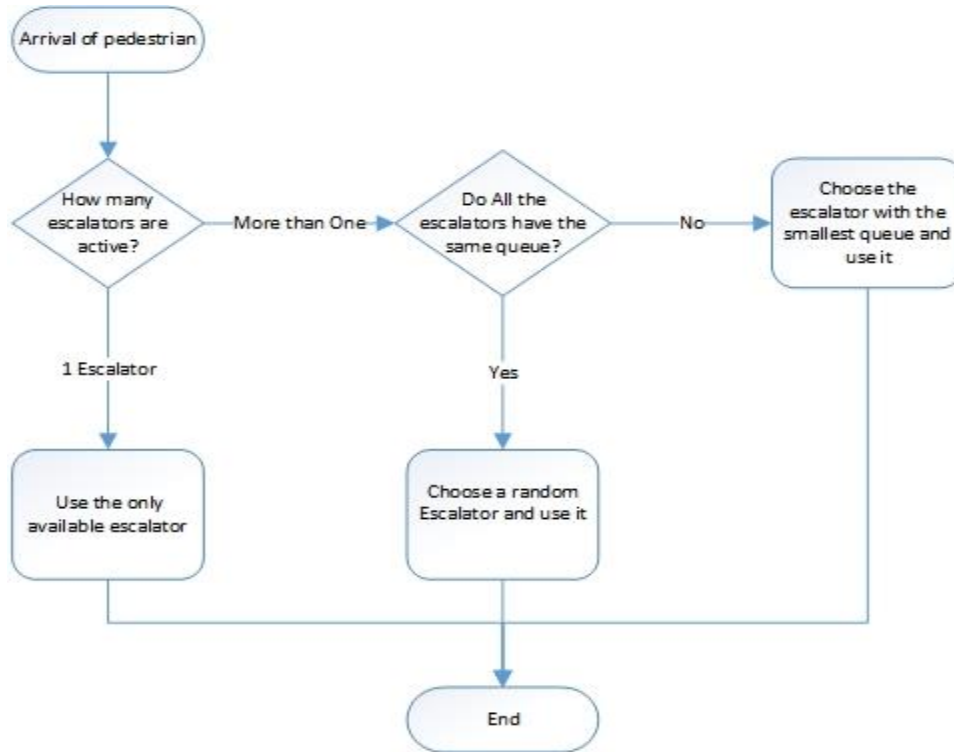
Figure 17: Decision of choosing which escalator should the pedestrian use

Looking at the table 2 it becomes important to mention that it is not possible to have more than three escalators active in one direction since the system does not have any other main entrance/exit to the station, therefore restricting the flow of pedestrians from one of the directions.

Simulation of escalators and lane decision: To simulate escalators in Arena it is necessary to use the already mentioned conveyors modules. Due to the limitation that one conveyor is restricted to one lane it is necessary to use one conveyor per lane of each escalator, having a total of eight conveyors. Each conveyor has a maximum capacity of 62 pedestrians at any given time and the time it takes for a pedestrian to exit the conveyor is 37 seconds.

Having defined the usage of conveyor modules for the escalators, it is necessary to mention that once the pedestrian has chosen which escalator to use (based on the logic presented above) it needs to choose which lane to select. This decision is quite simple since

42

the normal behavior would be to choose the lane with the smallest queue. In case the queue in both lanes is the same, the pedestrian chooses randomly between the two possible lanes.

Disposal of entities: The last section of the simulation related directly with the pedestrians is the disposal of the pedestrians as entities. This is done once the pedestrians leave the escalators by using the disposal modules. In this case two disposal modules were created to differentiate the pedestrians leaving the station by train from those pedestrians leaving to the street. The separation of the disposal modules was done mainly to allow Arena to record the total number of pedestrians that left in each direction.

Logic control of the escalator operation: Based on information given by DPP, it was found that the control of the escalators is based on the definition of rush hour. When it is a rush hour, the operator activates two escalators in each direction allowing the system to handle a higher flow of pedestrians. It was also found that the operation of the escalators could change based on the experience of the operator and the decision it could take based on the CCTV system installed in the station.

Since it is not possible to simulate the human behavior of the operator in the system it was decided to base the control of the escalators only on the rush hours, which based on the information obtained from DPP are the following: between 7:00 and 9:30 and between 16:00 and 19:30.

During the mentioned time the system operates with the array of having two active escalators for each direction. For other cases the system operates with only one escalator per direction.

Measurements and variable related modules: The last important aspect to mention for the simulation are the Assign modules used to measure most of the parameters and information from the simulation. Some of the most relevant measurements for the current state of system are:

- Maximum waiting time
- Flow the pedestrians
- Total size of queues per escalator

4.2 New system proposal and its simulation

As it has been mentioned before, the main purpose of designing a new system for the selected stations is to avoid a series of processes that require a human operator and to possible reduce the waiting time by introducing a more reactive procedure that can react faster and more precise to changes of pedestrian flow.

The mentioned reactiveness can be reached by using pedestrian detection technologies to measure the flow of pedestrians and adjust the system accordingly. From all the pedestrian detection technologies that were mentioned in previous chapters, it was decided that the most relevant for this system would be the video detection technologies. Even though these technologies could be more expensive than other alternatives like ultrasonic detection, they have a serious advantage that no other technology could replace:

- The ability to precisely track and follow pedestrians in different crowd densities, which increases the quality of the data measured and allows the system to take more precise decisions.

4.2.1 System analysis of the proposed design

Besides the video detection technology, the system requires a series of new elements to ensure the safety of the pedestrians and the correct operation of the system. These new elements can be seen in the figure 18, which is the same scheme of the selected system presented before (Chapter 2.2) but with the addition of the new elements which are represented as the red rectangles.
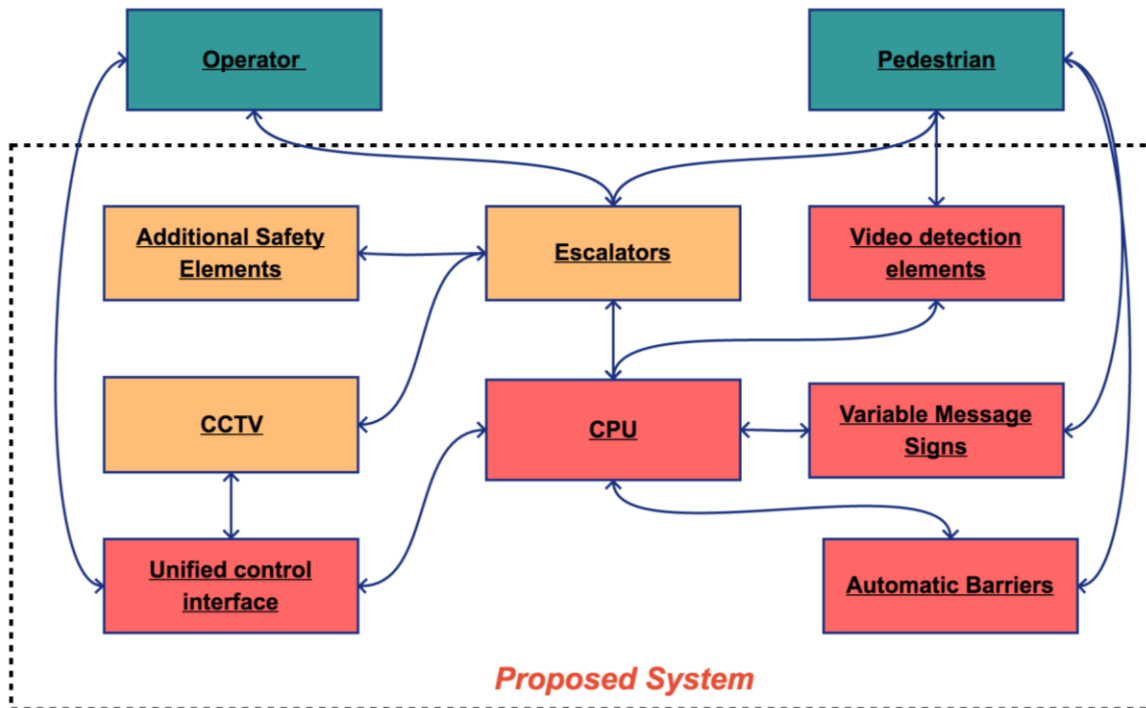
Figure 18: Scheme of the proposed system

Variable message signs: This element consists of a series of signs that inform the pedestrians on which escalator can be used. The suggested variable message signs would have a similar structure to those variable message sings used in highways to inform which lane is open, as it can be seen in figure 19, where a red cross mean that the escalator can't be used and a green arrow mean that the escalator can be used.

Figure 19: Variable message signs used in parking displays [23]

45

It is important to mention that the current system has already similar signs integrated in the escalators but they are considered no adequate mainly due to their location. The existing sings are located in a low position in the entrance of the escalators, making it easy to block them in cases where there are big queues. Therefore, it is suggested to use the same approach as variable message sings in highways and locate the signs on the roof where they can't be blocked by crowds.

It goes without saying that the variable message signs are not a mandatory element of the system, but they could improve the harmonization of the queues and the decision process of which escalator use.

Automatic safety barriers: With the proposal of the new system, it is necessary to introduce new measures to ensure the safety of the users. In the current system, the process of deactivating an escalator required the direct action of a human operator who needed to perform a three-step process:

1. Block the entrance of the escalator with physical barriers
2. Wait until the escalator is empty
3. Deactivate the escalator

This process can be avoided in the new proposed system by integrating the new elements of the system. The deactivation of the escalators depends on the measurement taken with the video detection technology, which triggers a signal in case a certain flow is reached. Once the limit flow is reached, the system needs to close the automatic barriers in the desired escalator in the direction the pedestrians are moving. After the barriers are closed, the system needs to wait a minimum of 37 seconds, which is the total travel time in the escalator, assuring that way that the escalator will be empty once the deactivation signal is triggered.

The case of activating an escalator is much simpler because there are no pedestrians inside of the escalators. In this case, the system needs to generate a signal which activates the desired escalator. The opening of the barriers could be done based on the time it takes the escalator to reach its normal operational speed.

Now, the last situation that needs to be analyzed is when it is necessary to change the direction of an escalator. For this it is necessary to apply both mentioned procedures, starting with the deactivation and the finishing with the activation.

As a recommendation for the design for the barriers, it would be an extra safety measure to apply a type of barrier that doesn't block completely the exit from the escalator. This measure is to prevent the possible situation of having trapped pedestrians in the escalator and therefore preventing any unnecessary action from the operator.

Central processing unit (CPU): The central computing unit refers to the central element of the system that would work as its brain. It would oversee the following processes:

- Computing the information received from the video detection technologies
- Controlling the operation of the variable message sings
- Controlling the operation of the automatic barriers
- Controlling the activation, deactivation and operation of the escalators

In the proposed system, the central processing unit would replace the control unit that exists in the current system. The CPU would also provide more functions than the current control unit and a unified interface that would allow a complete control over the system in the cases where actions from the operator would be required.

Video detection units: The video detection units are the elements in charge of detecting pedestrians and measuring their flow, which is the main parameter used to control the operation of the escalators.

One of the important aspects to define when talking about the video detection units are the location where they would be positioned for the measuring of both directions of flow. For the flow entering the station from the street, the location of the units can be done in the hall that communicates the entrance of the station with the escalators, since the mentioned hall is considerably long and allows to have a good view of the pedestrians entering the system.

On the other hand, the location of the units measuring the flow going out of the station is more complicated since the pedestrians are arriving from different wagons and the way they arrive to the escalators depend of which wagon they used. For this situation, there are two possible solutions:

1. Locate the units close to the escalators but having a minimum distance, that way ensuring that the cameras are not having biased measurements due to the formation of queues.
2. Locate the units at the front of the exits of the wagons, that way measuring the flow of pedestrians directly from the pedestrians leaving the wagons.

The second presented option has the serious disadvantage of having a much higher cost due to the need of units to cover all wagons from both arriving trains, but it could also represent a much higher accuracy.

4.2.2 Simulation of the proposed system

The simulation of the proposed system is based on the already explained simulation of the current system (Chapter 4.1.2), with the necessary modifications regarding the newly added elements.

The first mayor modification of the simulation is the creation of a logic module that controls the measurement of pedestrian flow from both directions (Entering the station and leaving it). The measurement of the flow, and the eventual control of which escalator should be active, is done based on the information obtained from certain number of minutes from the moment of measurement, where the exact quantity is controlled by a variable called "Measurement unit". As an example, if the "Measurement unit" variable is set to five, then the system will compute the flow of pedestrians per minute every interval of five minutes and it will take the decision of which escalator should be activate based on that measurement. It is important to mention that for the proposed system it was decided to use the corner escalators, meaning the escalators that are located most to the left and to the right, as the main escalators. That way the escalator located in the left corner (when going out of the station) is the main escalator for the pedestrians going inside and the right corner

escalator is the main escalator for the pedestrians going out of the station. So, in the case the system requires only one active escalator per direction, then only the main escalators would be active.

The second modification is the creation of a set of variables that controls the operation of the escalators based on the measurements of the flow. For this it was necessary to create the four following variables:

- Limit flow for two escalators, for the pedestrians going in and out of the system.
- Limit flow for three escalators, for the pedestrians going in and out of the system.

Each of the mentioned variables control the operation of the amount escalators that are active, so if for example the flow of pedestrians entering the station is higher than the variable "Limit flow for two escalators going in", then the system activates two escalators for the mentioned direction. The complete logic behind the operation of the escalators in one direction can be seen in the following figure.
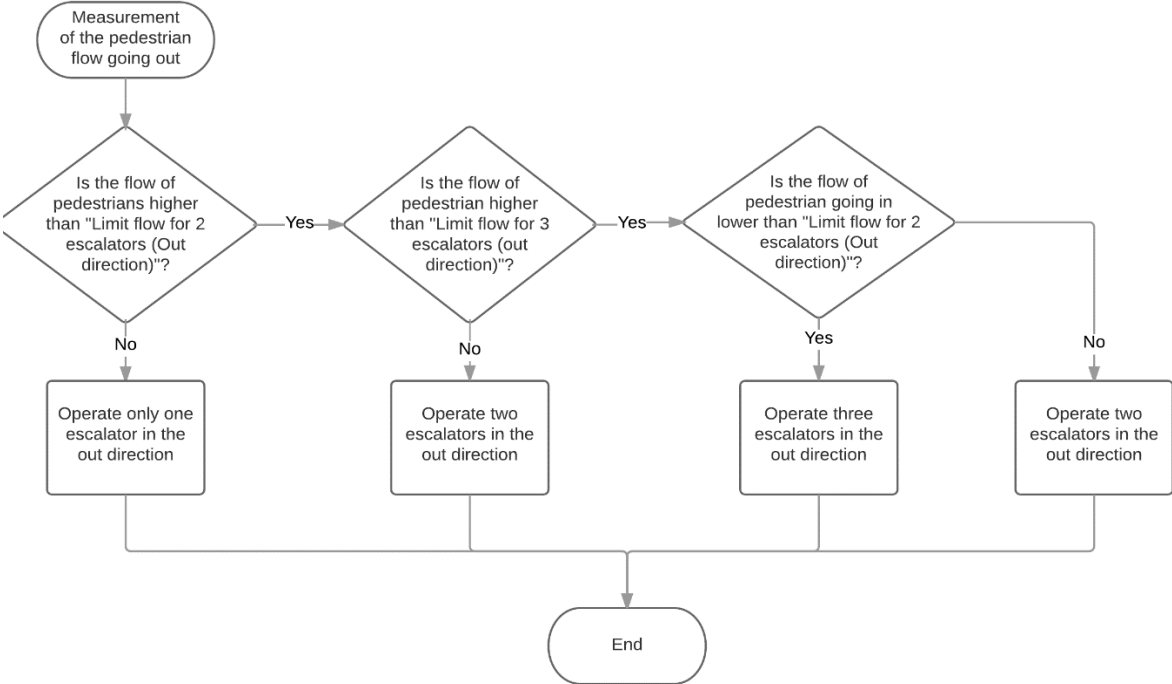
Figure 20: Control process for the escalators going out of the station

As it can be seen in the figure above, the control of the escalators depends on the "Limit flow" variables, the "Measurement unit" variable and the actual measurement of the flow in both directions. For the opposite direction than the one presented in the figure above the same algorithm would apply but with the respective changes.

It is also important to mention that the case of having three escalators active in the same direction at the same time can only happen when the flow of the opposite direction is too low that it doesn't require more than one escalator active. This rule was settled to prevent uncontrolled grow of queues caused by the restricted capacity.

5 Results

5.1 Critical flow of pedestrians

The first step before using the simulations to compare the proposed system and the current system is to calculate the critical flow that each escalator can handle, meaning by critical flow the maximum flow of pedestrians per minute than an escalator can handle before the formation of queues. This calculation can be done by using the parameters of the escalators that were presented in previous chapter, where it is known that the maximum number of pedestrians that can leave an escalator in a period of 37 seconds (total travel time) is 124, therefore the critical flow is as following:

$$Critical\ Flow = \frac{124\ Pedestrians}{37\ Seconds} * \frac{60\ Seconds}{1\ Minute} = 201.08\ \frac{Pedestrians}{Minute} \qquad (1)$$

These results were tested using the developed simulations and it was confirmed that the formation of queue at any escalator starts when the flow of pedestrians per minute is higher than 201. In the case of having two escalators, the critical flow of the system is duplicated, so the system can handle any flow lower of 402 pedestrians per minute without the formation queues.

5.2 Performance metrics of the systems

As it was explained in the previous chapter, the control of the proposed system is based on a series of variables which up to this point haven't been fixed to real values. In order to fix these variables, first it is necessary to run the simulation of the current system and to analyze its performance, so it is possible to decide based on these results how to fix the variables of the prosed system. From all the available performance measures that there are, the most relevant for this chapter are the following:

Total waited time (Seconds): It means the total number of seconds waited by all the pedestrians who used the system. It is also important to clarify that by the waited time is

only considered when the pedestrian is in a queue to use the escalator, that way excluding the travel time between landings or any other time related to the use of the escalators.

Total operation time (Seconds): The operation time refers to the total number of seconds that all the escalators were in operation.

Number of activations (Per day): This measurement refers to the total number of times any of the escalators of the system were activated, meaning a changed from a stop mode to a normal operational speed mode.

Max waited time (Seconds): This measurement refers to the maximum time spent in queue by any of the pedestrians that entered the system during the time of the simulation.

Average queue length (Pedestrians per day): The average queue length means the average length of the queue during a day of simulation. This parameter is measured in numbers of pedestrians and it will be used only in the corner escalators, since they are the main escalators and are always activated during the simulation.

Max queue length (Number of pedestrians): This measurement refers to the maximum length reached by any of the queues created during the simulation.

Cost of operation (CZK per day): The cost of operation refers to the cost of operating the escalators in one day of operation. This cost comes from two sources: 1. The power consumption due to the normal operation mode and 2. The power consumption due to the activation of the escalators.

For this measurement, it is important to highly that it was impossible to obtain the energy consumption of the specific escalators used in the selected system, therefore it was decided to use an average energy consumption of 3.33 kWh during the normal operation speed mode [5] and 2.6 Wh for each activation of the escalators [24].

For the calculation of the cost it was decided to use a price of 1.93 CZK (0.073 EUR) per kWh, which corresponds to the price of kWh for industrial use in Czech Republic during 2016 [25]. The exact formula used for the calculation of the cost of operation is the following, where CO refers to cost of operation:

$$CO = (kWh\ used\ per\ operational\ hour * Total\ operation\ time\ (Hours) +$$
$$kWh\ per\ activation * Number\ of\ activations) * Price\ per\ kWh \qquad (2)$$

5.3 Results from the simulation of the current system

To measure the performance of the current system it was decided to run the simulation a total of ten times. The simulations were set during a week day where the operation of the escalators starts at 4:30 am and finishes at 12:00 pm. From these simulations, the results in the table 3 were obtained. As it can be seen, the total waited time is different in each run since it depends on variables like the number of pedestrians that used the system. On the other hand, the cost of operation of the current system is constant since it only depends on the operation time and the number of activations, which in this case are fix (As mentioned in chapter 4.1.2).

Table 4: Results obtained from the simulation of the current system

Replications	Total waited time (sec)	Max queue length (Pedestrians)	Max waited time (sec)	Operation time (sec)	Cost of operation (CZK per day)
1	142147	48	18.7		
2	140812	44	18.1		
3	140771	46	17.5		
4	142359	46	18.7		
5	140226	45	18.1		
6	142500	44	18.1	*172800*	*327.523481*
7	141102	50	18.7		
8	140504	50	20.8		
9	140181	45	16.9		
10	141666	52	18.7		
Average	*14122.8*	*47*	*18.43*		

5.4 Tuning the control variables of the proposed system

Once the results of the current system were obtained, the following step was to tune the control variables used in the proposed system. This process of "tuning" the variables of the system is necessary because the performance of it depends on the values that the variables take. So for example, the proposed system would perform in different ways if the measurements of the pedestrian flow and the eventual control of the escalators is done every 5 minutes rather than once every two hours.

It is for the mentioned reason that the tool OptQuest from Arena becomes a mayor advantage when using Arena as a simulation software. As it was explained before, OptQuest allows the user to optimize any performance indicator by finding an optimal value for the variables that affect that indicator.

Also, it is important to mention that in this chapter more than one optimizations or tuning were done, always with the objective of refining the result as much as possible.

5.4.1 Tuning of control variables using OptQuest

Now, to use OptQuest it was necessary to define two groups of elements: 1. The constraints of the optimization and 2. The objective of the optimization.

Objective of the optimization: In this case, it was decided to use the total waited time as the objective of the optimization, where the optimal value would be the lowest Total Waited Time that could be achieved by variating the values of the variables.

Constraints of the optimization: For the constraints, it was decided to define the following set:

1. The "Limit flow for two escalators" (In any direction) shall be lower or equal to the "Limit flow for three escalators" in the same direction.

2. The minimum value that any of the "Limit flow" variables can take is 0 pedestrians per minute and the maximum value is 500 pedestrians per minute. This decision was made based on the calculations of the critical flow, where it was found that de formation of the queues in one escalator starts when the flow entering is higher than 201 pedestrians per minute. Therefore, the limit of 500 pedestrians per minute is higher than the theoretical critical flow of two escalators operating in the same direction (402 pedestrians per minute).

3. The "Measurement unit", shall be higher than 0 and lower than 120, which means that the maximum possible value that this variable can take during the optimization process is 120.

5.4.2 Results of the optimization

With the constrains of the optimization already set, it was decided to run the first optimization for a total of 1000 times, where each run is composed by 3 replications to assure that the data obtained in each run is representative and not an extreme value. The results with the lowest Total waited time obtained in the first simulation can be seen in the following table.

Table 5: Top 8 results of the first optimization based only on minimum waited time

Ranking	1	2	3	4	5	6	7	8
Limit flow for 2 escalators in direction:	500	500	500	500	486	483	488	486
Limit flow for 3 escalators in direction:	500	500	500	500	493	498	495	500
Limit flow for 2 escalators out direction:	4	3	4	3	4	4	5	3
Limit flow for 3 escalators out direction:	21	20	20	21	20	22	22	21
Measurement unit:	9	9	9	9	9	9	9	9

Average queue length in escalator one:	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Average queue length in escalator four:	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Max queue length:	26	26	26	26	26	26	26	26
Average number of activations:	3	3	3	3	3	3	3	3
Total operation time:	270134	270134	270134	270134	270135	270135	270134	270134
Max waited time:	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6
Total waited time:	76376	76376	76376	76376	76376	76376	76376	76376

The first observation that can be done from these results is that the values given to the "Limit Flow inside direction" variables is much higher than the critical flow. For example, in the first replication the values of the "Limit Flow for two escalators inside direction" is 500 pedestrians per minute, meaning that the system will only activate two escalators in that direction when the flow per minute is higher than 500.

This result may seem strange, specially knowing that the formation of queues in one direction starts when the flow is higher than 201 pedestrians per minute in the case of having only one escalator is active. But this result is easily explained by the fact that the flow entering the station can be handled by only one escalator (assuming that the behavior of the pedestrians is the one mentioned in chapter 4.1.1). Therefore, OptQuest will push the values of the mentioned variables as higher as it can, that way allowing more escalators to operate in the direction going out of the station and eventually reducing the Total Waited Time.

Now, the situation with the "Limit flow outside direction" is different from the one that was just explained because the arrival of pedestrians going in this direction depends mainly on the arrival of the trains to the station. Since the arrival of the trains is done in such short bursts, the system requires a higher capacity than the direction going inside.

Even if in the long run the flow of pedestrians could be handle by only one escalator, the short-burst characteristic of their arrival makes it impossible to have such array and still avoid the creation of queues.

It is for this reason that the normal behavior presented during the optimization process was to assign the "Limit flow inside direction" variables as higher as possible and set the same variables for the opposite direction as low as possible.

5.4.3 Refining the solution space

Given these results, it was decided to perform a second optimization process but with different settings:

1. The number of runs was increased to 2000
2. The "Limit flow for two escalators inside direction" was set to the critical flow that one escalator can handle (201 pedestrians per minute), meaning that if the flow is higher than the critical flow the system will activate to escalators in the mentioned direction.
3. In a similar way, "Limit flow for three escalators inside direction" was set to the critical flow that two escalators can handle (402 pedestrians per minute)

As a final comment, it is important to notice that no matter how many escalators are active in each direction, there will always be an unavoidable waited time created by the arrival of pedestrians in groups, where this situation is most obvious for the pedestrians going outside of the station since they always arrive in groups.

5.4.4 Selecting the ideal parameters

As it was mentioned in the previous subchapter, it was found that if the global objective is to reduce the Total Waited Time as much as possible, then the best approach would be to operate three escalators in the outside direction and one escalator in the inside direction during all day.

Even though this approach may have the mentioned advantage, it also brings the disadvantage of having a much higher Total Operation Time and an eventual higher Operation Cost not only due to the operation time but the stress created on the system which will eventually generate higher maintenance cost.

For this reason, it was decided to create a performance index that would facilitate the process of selecting appropriate parameters. This performance index is calculated as following, Where TWT refers to the total waited time and OC refers to the operation cost:

$$Performance\ index = \frac{TWT\ of\ the\ replication}{Average\ TWT\ actual\ system} * 2 + \frac{OC\ of\ the\ replication}{OC\ of\ the\ actual\ system} \quad (3)$$

As it can be seen in the formula, it was decided that the total waited time has a bigger impact on the Performance index since the minimization of it is the main objective of the system. Also, it is important to notice, that even though the percentage difference of operation cost between the cheapest and the most expensive option is high, it does not necessarily translate to a significant cost in monetary terms. So, for example the difference in cost of operating the system with the cheapest option and the most expensive option is 244 CZK per day, which can be translated to 91800 (3464 Euros) per year.

With that in mind, the performance index was applied and the solutions obtained from OptQuest were reorganized based on the index obtained. The top eight replications can be seen in the following table.

Table 6: Top 8 solutions organized by best performance index

Ranking	1	2	3	4	5	6	7	8	2000
Limit flow for 2 escalators in direction:	201	201	201	201	201	201	201	201	201
Limit flow for 3 escalators in direction:	402	402	402	402	402	402	402	402	402
Limit flow for 2 escalators Out direction:	2	35	37	2	19	17	32	18	173
Limit flow for 3 escalators Out direction:	71	44	46	58	38	36	41	60	493
Measurement unit:	1	14	14	1	9	11	47	11	49

Average queue length in escalator one:	0.37	0.46	0.46	0.35	0.30	0.30	0.42	0.31	2.56
Average queue length in escalator 4:	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.2286
Max queue length:	43.33	46.67	46.67	43.33	28.33	29.00	46.67	29.00	48
Average number of activations:	50.33	2.00	2.00	53.33	3.00	2.00	2.00	2.00	0
Total operation time:	237120	229014	229014	242090	249824	250909	235710	247579	136802
Max waited time:	18.09	18.09	18.09	18.09	17.58	17.58	18.09	17.58	18.48
Total waited time:	83574	87139	87139	81913	78808	78655	84958	80152	198484
Performance index:	2.5563	2.5592	2.5592	2.5616	2.5616	2.5657	2.5670	2.5676	3.602

Now that the solution space was greatly reduced, the last step is to choose an appropriate solution. This decision was done based on the following criteria:

1. The simulation parameters should translated to a good performance index
2. The difference between the "Limit flow for two escalators inside direction" and the "Limit flow for three escalators inside direction" should be as high as possible, that way preventing an excessive amount of activations and an excessive operation time.
3. Relatively low "Measurement unit", that way ensuring that the system can react to fast changes of pedestrian flow.

With these criteria in mind, the following replication and its respective parameters was chosen:

Table 7: Selected Parameters for the proposed system

Parameter Name:	Value
Limit flow for two escalators (In direction)	201
Limit flow for three escalators (In direction)	402
Limit flow for two escalators (Out direction)	18
Limit flow for three escalators (Out direction)	60
Measurement unit (Minutes)	11

Table 8: Performance of the proposed system with the selected parameters

Performance measure	Value
Average queue length main escalator out direction (Pedestrians):	0.314435
Average queue length main escalator in direction (Pedestrians):	0.228647
Max queue length (Pedestrians):	29
Number of activations (per day):	2
Total operation time (Seconds):	247579
Max waited time (Seconds):	17.58091
Total waited time (Seconds):	80152.42
Cost of operation (CZK per day)	469.2113
Performance Index:	2.567692

5.5 Performance analysis of the selected parameters

As it can be seen in the table 8, The "Limit flow for two escalators out direction" it's quite low, which allows the system to operate two escalators in the mentioned direction most of the time. This parameter, together with the "Limit flow for three escalators out direction", allow the proposed system to have a total waited time which is approximately 43% lower than the current system. This reduction of total waited time translates to a total of 16 hours of waited time avoided per day or 6.192 hours avoid per year.
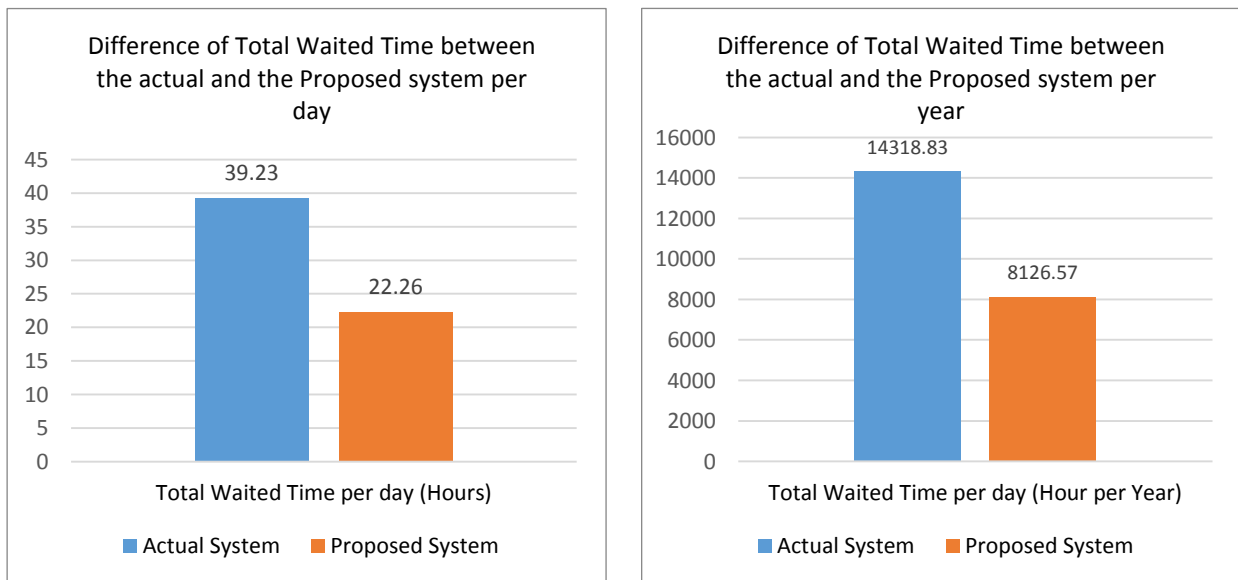

Figure 21: Total waited time comparison between the proposed system and the current system

Now, regarding the operational cost of the system, the proposed system implicates a 30% higher cost of operation when comparing with the current system, which is a consequence of the 30% increase of the operation time. In monetary terms, the difference between the operation cost is 1951 Euros per year.
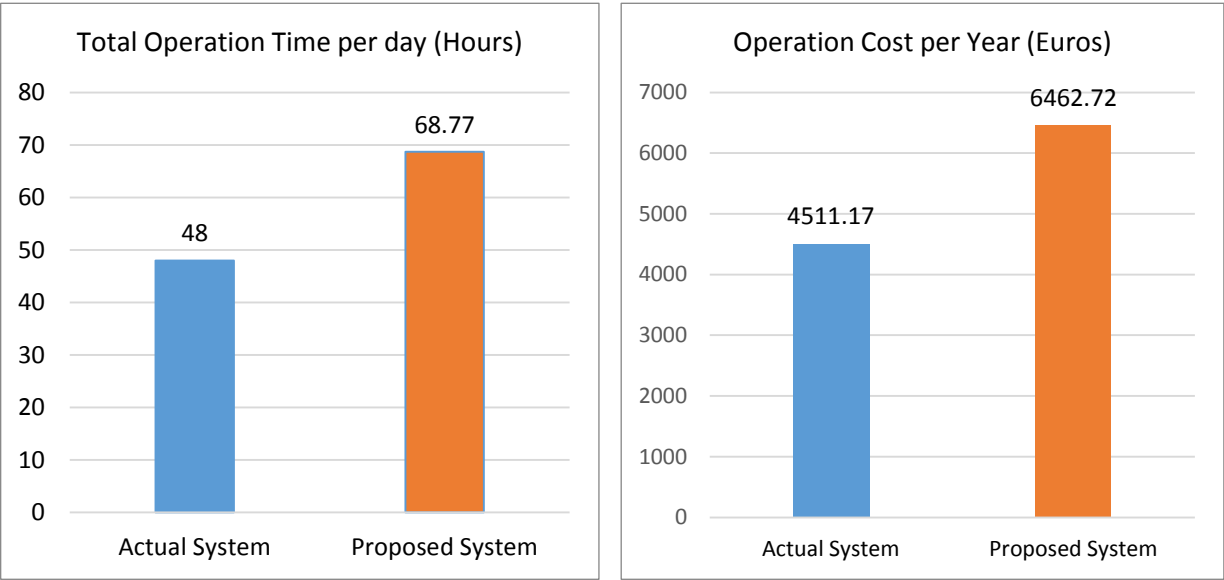

Figure 22: Total operation time and operation cost comparison between the proposed system and the current system

It is also important to mention that the select parameters allow the system to have a maximum waited time of 17 seconds and a maximum queue length of 29 pedestrians, which is caused by the short-burst characteristic of the flow going out of the station.

When comparing the max waited time and the max queue length, the selected parameters allow a reduction of one second in the Max waited time and a decrease from 47 pedestrians to 29 when talking about the max queue length.

One last remark about the propose system is that it also brings the advantage of being able to react to fast changes in the flow of pedestrians, which is fundamental in situations where the flow of pedestrians increases rapidly for specifics periods of time, life for example at the end/beginning of sport and music events.

6 Discussion

This chapter discusses the difficulties that were faced during the process of measuring, design of the simulations and other relevant steps taken during the development of this thesis.

The first aspect to mention is the behavior of the operator that was assumed for the simulation of current system. As it was mentioned, the operation of the escalators in the current system depends on both the definition of rush hours and the personal behavior that each operator assumes. Since the second factor couldn't be simulated, talking about the personal behavior of the operators, then the operation of the escalators was set to depend entirely on the rush hour. Even though this assumption does not different in big manner from the real operation of the escalators, it would be helpful to define somehow the behavior of the operators which could influence the parameters used in the proposed system and the performance of it.

The second aspect to mention is the data used for the calculation of the cost of operation. As stated before, the calculation of the cost of operation was simplified by using average energy consumption indicators which could impact in some degree the results obtained. For better understanding of the current and proposed system, it would be very helpful to measure the energy consumption directly from the system. This way, the simulation and optimization processes would include many variables that affect the energy consumption like the weight of the pedestrians and the state of the equipment's in the system.

Regarding the proposed video detection technologies that are used in the proposed system, these technologies and their implementation couldn't be studied any further since any real modification of the current system wasn't allowed. For this reason, it would be interesting to implement them in the selected station and two evaluate two main aspects: 1. The quality of the measurements and 2. Where to set them.

One final aspect to mention would be to study the possibility of not implementing the proposed system itself but rather to implement a similar controlling behavior of the escalators to the current one (meaning controlling the escalators through an operator) where the number of active escalators would try to be as similar as the one implemented in the simulation models. This implementation could also reduce the waiting time in a big manner but it would also bring the disadvantage of not being able to react to fast change in the flow of pedestrians, limitation present in the current system.

7 Conclusions

Escalators are elements that became fundamental not only in commercial buildings like shopping centers but also in public transportation where their main goal is to facilitate and speed the movement of pedestrians between landings.

Even though those are the main goals of escalators, they aren't always fully reached mainly because their suboptimal operation. This situation can be seen in the subway station I. P. Pavlova located in Prague, which counts with four escalators that are operated manually by a human operator based on criteria like rush hours and personal experience, criteria that doesn't always fit the needs of the station.

For this reason, a new system was proposed where the escalators are automatically controlled based on the flows of pedestrians entering and leaving the station measured by video detection technologies, system that has as goal the reduction of the time spend in queues and the automatization of some processes that are done by a human operator. During the development and evaluation of the proposed system some improvement factors of the current system were found.

The first of these factors is the current behavior of the pedestrians while using the escalators, where most of the pedestrians use only one lane of the escalator. This behavior even though is considered as good manners in Czech Republic, it brings many disadvantages like the reduction of the capacity of the escalators (especially in longer escalators) and the unnecessary stress on the system caused by the uneven distribution of the weight. For this reason, it was proposed to modify the behavior of the pedestrians and promote the usage of all the available space in the escalators.

When this new proposed behavior was implemented together with the proposed system it was found that the main cause of queue formation and waited time in the escalators is the short-burst characteristic of the pedestrian flow going out of the station, characteristic that is a consequence of the dependency between the flow of pedestrians going out of the station and the arrival of trains to the station. Regarding the flow of

pedestrians entering the station, it was found that in most of the cases the proposed system could handle it by only activating one escalator in that direction.

Through the simulation, optimization and selection of ideal parameters of the proposed system, it was found that if the proposed system would be applied, it could reduce the total waited time up to a 43%, meaning that the total waited time would be reduced by a total of 6192 hours per year.

Finally, it is important to mention that the reduction of waited time would also bring an increase of the operational cost caused by the increased operation time of the escalators, where both the cost and the operation time would increase 30% compared to the current system, meaning that the proposed system would be 1951 Euros more expensive per year.

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Attachments

1. Arrival Schedules for the station I. P. Pavlova

Schedule 1 — směr: HÁJE

PRAŽSKÁ INTEGROVANÁ DOPRAVA (PID) - Městská doprava Praha
Dopravce: Dopravní podnik hl. m. Prahy, akciová společnost, Sokolovská 217/42, 190 22 Praha 9
Informace o provozu PID na tel.: 296 191 817; na internetu: www.dpp.cz

Platnost: od 3.1.2017

Tarifní pásmo P

Stanice	PONDĚLÍ (①) - ČTVRTEK (④)	PÁTEK (⑤)

směr: HÁJE

LETŇANY · Prosek · Střížkov · Ládví · Kobylisy · Nádraží Holešovice · Vltavská · Florenc · Hlavní nádraží · Muzeum · **I. P. Pavlova** · Vyšehrad · Pražského povstání · Pankrác · Budějovická · Kačerov · Roztyly · Chodov · Opatov · HÁJE

K - jede jen do zastávky **Kačerov**

h	PONDĚLÍ (①) - ČTVRTEK (④)	PÁTEK (⑤)
4	44 54	44 54
5	04 14 24 34 44 54	04 14 24 34 44 54
6	01 07 13 19 23 27 31 35 39 41 43 45 47 49 51 53 55 57 59 (K)	01 07 13 19 23 27 31 35 39 41 43 45 47 49 51 53 55 57 59 (K)
7	01 int. 1-3 min ... 56	01 int. 1-3 min ... 56
8	00 int. 1-3 min ... 08 21 31 37 43 51 (K K K K K)	00 int. 1-3 min ... 08 21 31 39 45 51 (K K K K K)
9	00 02 04 07 09 12 15 18 21 23 26 29 32 35 38 40 43 46 49 52 55 57 (K ... K)	00 02 04 07 09 12 15 18 21 23 26 29 32 35 38 40 43 46 49 52 55 57 (K ... K)
10	00 03 06 09 12 14 17 20 23 26 29 31 34 37 40 43 46 48 52 54 58 (K ... K)	00 03 06 09 12 14 17 20 23 26 29 31 34 37 40 43 46 48 52 54 58 (K ... K)
11	01 05 08 11 14 18 21 25 28 31 34 38 41 45 48 51 54 58	01 05 08 11 14 18 21 25 28 31 34 38 41 45 48 51 54 58
12	01 05 08 12 16 20 23 27 31 35 38 42 46 50 53 57	01 05 08 12 16 20 23 27 31 35 38 42 46 50 53 57
13	01 05 08 12 16 20 23 26 29 33 36 40 43 47 51 54 57	01 05 08 12 16 20 23 27 31 35 38 42 46 50 53 57
14	01 04 07 10 13 16 20 23 26 29 32 35 38 41 44 47 50 53 57	01 05 08 12 16 20 23 27 31 34 38 41 45 48 52 55 59 (K)
15	00 03 06 09 12 15 18 21 24 27 29 32 34 36 39 41 44 46 48 51 53 56 58	02 05 09 12 15 18 21 23 26 29 32 34 37 40 43 45 48 51 54 56 59
16	01 03 05 08 10 13 15 17 20 22 25 27 30 32 34 37 39 42 44 46 49 51 54 56 59	02 05 07 10 13 16 18 22 24 28 31 34 37 40 43 46 49 52 55 59 (K)
17	01 03 06 08 11 13 15 18 20 23 25 28 30 32 35 37 40 42 44 47 49 52 54 57 59 (K ... K)	01 05 08 11 14 17 20 23 26 29 32 36 38 42 45 48 51 54 57
18	01 04 06 09 11 13 16 18 21 23 26 28 31 34 37 41 44 47 50 53 56 (K ... K)	00 03 06 09 13 15 19 22 25 28 31 34 37 40 43 47 50 53 57 (K ... K)
19	00 03 06 09 12 15 19 22 25 28 31 35 38 41 45 48 52 55 59 (K ... K)	00 03 07 10 13 17 20 23 27 30 33 37 40 43 47 50 54 57
20	03 06 10 14 18 21 25 29 33 36 40 44 49 54 59 (K K)	01 05 09 14 19 24 29 34 39 44 49 54 59
21	04 14 16 24 34 44 54	04 14 16 24 34 44 54
22	04 14 24 34 44 54	04 14 24 34 44 54
23	04 14 24 34 44 54	04 14 24 34 44 54
0	04 14 24	04 14 24
1		
2	Ostatní provozní dny na zvláštním listu	
3		

O svátcích jede jako v neděli (†); 13.4.,4.7.2017 jede jako v pátek (⑤), 14.4.,5.7.2017 jede jako v sobotu (⑥). — Platí SPP PID a Tarif PID. Jízda s předem zakoupenou jízdenkou. A

Schedule 2 — směr: LETŇANY

PRAŽSKÁ INTEGROVANÁ DOPRAVA (PID) - Městská doprava Praha
Dopravce: Dopravní podnik hl. m. Prahy, akciová společnost, Sokolovská 217/42, 190 22 Praha 9
Informace o provozu PID na tel.: 296 191 817; na internetu: www.dpp.cz

Platnost: od 3.1.2017

Tarifní pásmo P

směr: LETŇANY

HÁJE · Opatov · Chodov · Roztyly · Kačerov · Budějovická · Pankrác · Pražského povstání · Vyšehrad · **I. P. Pavlova** · Muzeum · Hlavní nádraží · Florenc · Vltavská · Nádraží Holešovice · Kobylisy · LÁDVÍ · Střížkov · Prosek · LETŇANY

L - jede jen do zastávky **Ládví**

h	PONDĚLÍ (①) - ČTVRTEK (④)	PÁTEK (⑤)
4	40 50	40 50
5	00 10 20 30 40 48 55	00 10 20 30 40 48 55
6	01 int. 2-3 min ... 13 17 21 25 29 33 37 41 45 49 53 57 (L ... L)	01 int. 2-3 min ... 13 17 21 25 29 33 37 41 45 49 53 57 (L ... L)
7	01 int. 1-2 min ... 05 08 12 16 20 24 28 32 36 40 44 48 52 55 59 (L ... L)	01 int. 1-2 min ... 05 08 12 16 20 24 28 32 36 40 44 48 52 55 59 (L ... L)
8	01 int. 2-3 min ... 03 07 11 16 20 24 28 33 37 42 47 51 56 (L ... L)	01 int. 2-3 min ... 03 07 11 16 20 24 28 33 37 42 47 51 56 (L ... L)
9	01 04 07 10 13 15 18 21 24 27 30 32 35 38 41 44 47 49 52 55 58 (L ... L)	01 04 07 10 13 15 18 21 24 27 30 32 35 38 41 44 47 49 52 55 58 (L ... L)
10	01 04 07 11 14 17 20 24 27 30 34 37 40 44 47 50 54 57 (L ... L)	01 04 07 11 14 17 20 24 27 30 34 37 40 44 47 50 54 57 (L ... L)
11	00 04 07 11 14 17 20 24 27 31 34 38 42 45 49 53 57 (L ... L)	00 04 07 10 14 17 20 24 27 30 34 38 42 45 49 53 57 (L ... L)
12	00 04 08 12 15 19 23 27 31 34 38 41 45 48 52 55 59 (L ... L)	00 04 08 12 15 19 23 27 30 34 38 42 45 49 53 57 (L ... L)
13	02 06 09 13 16 20 23 27 30 33 36 39 42 45 48 51 55 58 (L ... L)	00 04 08 12 15 19 23 27 30 34 38 42 45 49 53 56 59 (L ... L)
14	01 04 07 10 13 16 19 22 25 28 31 34 37 39 42 45 48 51 54 56 59 (L ... L)	03 06 09 13 16 19 23 26 29 33 36 39 42 45 48 50 53 56 59 (L)
15	02 04 07 10 12 14 17 19 22 24 27 29 31 34 36 39 41 43 46 48 51 53 55 58 (L ... L)	02 05 07 10 13 16 18 21 24 27 29 32 35 38 40 43 46 49 51 54 57 (L)
16	00 03 05 08 10 12 15 17 20 22 24 27 29 32 34 37 39 42 44 46 49 51 53 56 58 (L ... L)	00 04 07 10 13 16 19 22 25 28 31 34 37 41 44 47 50 53 56 59 (L)
17	01 03 06 08 10 13 15 18 21 24 27 30 32 35 37 39 42 44 47 49 51 54 57 (L ... L)	02 05 08 11 14 18 21 24 27 30 33 36 39 42 45 48 51 55 58 (L)
18	00 03 06 09 12 15 18 21 24 27 30 34 37 39 42 45 48 51 55 58 (L ... L)	01 04 07 10 13 16 19 23 26 29 33 36 39 42 45 48 51 55 59 (L)
19	01 04 08 11 14 18 21 25 28 32 35 39 42 46 49 53 57	03 06 09 13 16 20 23 26 30 33 37 41 46 50 54 58
20	01 05 09 13 17 22 26 31 37 43 49 56	03 08 13 18 24 31 37 43 49 56
21	03 11 20 30 40 50	03 11 20 30 40 50
22	00 10 20 30 40 50	00 10 20 30 40 50
23	00 10 20 30 40 50	00 10 20 30 40 50
0	00 10 20	00 10 20
1		
2	Ostatní provozní dny na zvláštním listu	
3		

O svátcích jede jako v neděli (†); 13.4.,4.7.2017 jede jako v pátek (⑤), 14.4.,5.7.2017 jede jako v sobotu (⑥). — Platí SPP PID a Tarif PID. Jízda s předem zakoupenou jízdenkou. A

2. *CD ROM with:*

    a. *Simulation models of the current and proposed system which can be found in the file "Simulation models.zip".*

    b. *Text file (.txt) named "Final simulation results – Proposed model.txt" with the results of the last simulation.*