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Scuola di Ingegneria dei Sistemi

POLO TERRITORIALE DI COMO

Master of Science in

Management, Economics and Industrial Engineering

# *Decision Support Systems in transportation: The case of surface urban public transport*

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*Since the route that brought me to this achievement has been long and difficult there are many people that I would like to thank.*

*I will start with my family, a big thank goes particularly to my mother Ada, my father Franco and my little brother Andrea that have always sustained me, allowing me to do also the incredible experience in the Netherlands that made me growing personally and professionally.*

*I cannot forget my precious friends, the one of the childhood and the one I met during my experience abroad. In particular, I want to thank Robin, Olivier, Maialen, Albert and Eloi that have been my family during my staying in Holland, I will always keep them jealously in my heart even though we do not live in the same country anymore. Many thanks go for right also to my Italian friends Federico, Simone, Mauro and Federica that has always been at my side.*

*Thank you also to my professors, advisers and mentors Michela Arnaboldi (Politecnico di Milano), Wijnand Veeneman and Oded Cats ( Technical university of Delft) and Fabrizio Ronchi (ATM S.p.A.) that have always been fundamental in showing me the direction to keep and to take in order to develop the work in the best way possible and to get this final result.*

# Abstract (English)

A quality leap in public transportation system is necessary to assure a sustainable development of cities that are getting more and more populated. In last years, a general increase of wealth brought to an increase of need of personal mobility and at the same time people kept on rising their requirements related to public transport system service's quality. Meeting customers' expectations is not an easy task for public transport operators because they are forced to work in an environment in which the interaction with external factors (disturbances, disruption events) generate a lot of variability in the process output (the various trips from stop to stop). The lack of adequate decision support tools makes the job of control room operators, which are in charge of keeping the service quality at a desirable level, even more difficult. Nowadays decisions are taken principally manually and due to the short sightedness of this approach, many inefficiencies are generated. The aim of this thesis is the creation of a decision support system able to foresee critical situations and to give suggestions to control room operators. The disruption management support system will be divided in three main parts called: data side, process side and additional information side. These three components will work strictly together. The final objective of the system will be providing suggestions to dispatcher for maximizing the service reliability (travel time reliability + level of comfort) without compromising the other quality aspects considered important by passengers and in this way increasing their acquisition and retention.

# Abstract (Italian)

Un salto di qualità nel sistema di trasporto pubblico è necessario per assicurare uno sviluppo sostenibile delle città che stanno diventando sempre più popolate. Negli ultimi anni, il generale incremento del benessere ha portato a una crescita del bisogno di mobilità e allo stesso tempo le persone hanno continuato ad alzare le loro esigenze relative al servizio offerto dal trasporto pubblico. Soddisfare le aspettative della clientela non è un compito semplice per le aziende di trasporto pubblico che sono obbligate ad operare in un ambiente nel quale le interazioni con fattori esogeni (disturbances, disruption events) generano molta variabilità nel servizio offerto ai passeggeri. La mancanza di adeguati sistemi per il supporto alle decisioni rende il lavoro degli operatori di sala operativa, che sono incaricati di mantenere un buon livello di servizio, ancora più difficile. Al giorno d'oggi le decisioni sono prese manualmente e per questo sono generate molte inefficienze. L'obiettivo di questa tesi è la creazione di un decision support system capace di prevedere situazioni critiche sulle linee e di suggerire soluzioni agli operatori di sala operativa. Il disruption management support system sarà diviso in tre parti principali: Data side, process side e additional information side. Questi tre componenti collaboreranno per offrire soluzioni ottimali. L'obiettivo finale del sistema sarà dare suggerimenti agli operatori per massimizzare la service reliability (travel time reliability + livello di comfort) senza compromettere gli altri aspetti considerati importanti dai passeggeri e in questo modo incrementare l'acquisizione e il mantenimento dei clienti.

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# 1. Introduction

## 1.1 Problem definition and state of art

### *Problem definition*

Nowadays cities are getting more and more crowded and the need of personal mobility is continuously increasing. In the scenario just described public transport system plays a fundamental role in assuring a sustainable development of urban areas.

Unfortunately, the generic trends that describes the choice of transportation modalities made by passengers go in favor to less sustainable mode of transport than public transportation system (PTS). This is also because standards to meet customers' requirements are getting stricter, they do not care only to move from a point A to a point B inside the city but they pay a lot of attention also in the experience that they have along the trip.

In the situation just described it is evident the necessity of a quality leap in the level of service offered by public transportation companies to attract and retain a higher number of passengers. In order to understand on which aspects it is necessary to invest for improving the service of level offered it is necessary to analyze passengers' quality aspects (QAs) and their level of appreciation (see *figure I*).

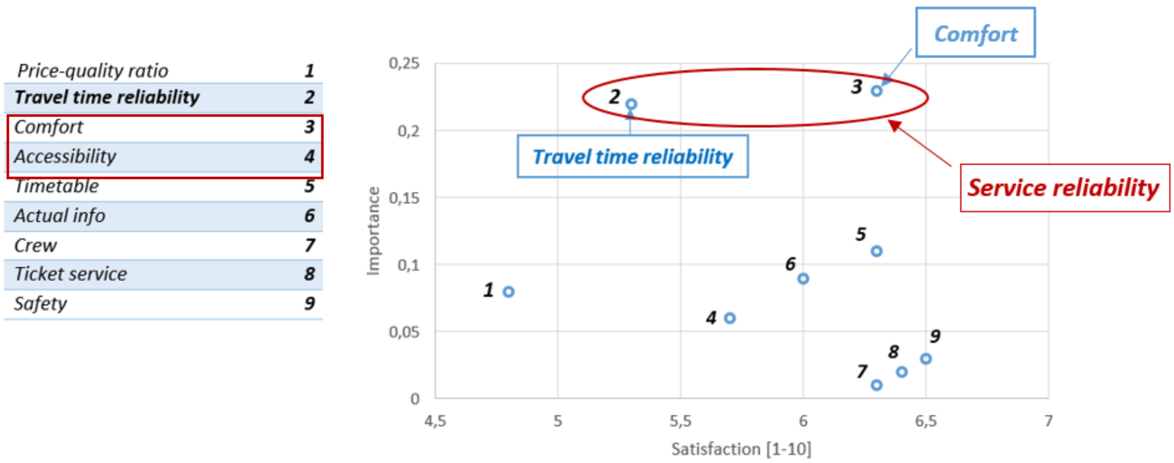



***Figure I:*** *Passengers' quality aspects and their level of appreciation.*

*Figure I (Brons and Retvel 2007)* shows that *travel time reliability (TTR)* and the *level of comfort* during the travel are the QAs more valuable for passengers, the two of them constitute the concept of ***service reliability*** that is defined as the certainty of service aspects compare to the schedule as perceived by the user.

For public transport operators maintaining a good level of service reliability it is  a challenging task because of the presence of ***disturbances*** *(minor distortions*)/***disruption events*** (*major distortions*) that interacting with the operations generate output variability that, overtaken a certain extent it becomes service unreliability for passengers that experience a lowering of the service level.

This generates a loss of customers for public transport operators. *Figure II* summarizes the concepts of *service reliability, variability and unreliability* in urban public transport systems.

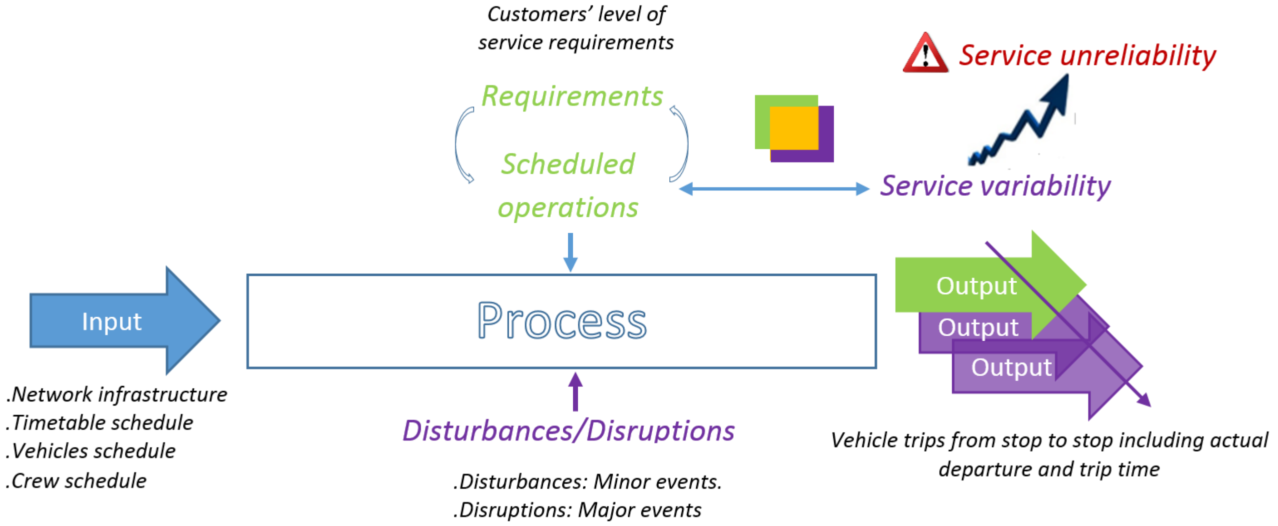



***Figure II****: Service reliability, variability and unreliability in urban public transport systems.*

To better understand how all of this process works in public transport it is necessary to analyze the ***supply side*** (*service provided by the operator*), the ***demand side*** (*passenger side*) and the ***interactions among them*** because unreliability of the service perceived by passengers is the results of the interactions between the two sides.

On the ***supply side*** there are principally two types of service variability:

1. *Terminal departure variability;*
2. *Vehicle trip time variability (driving time + stopping time + dwell time).*

The two main aspects that are cause and effect of the variability of these two components are the *propagation of delays* and *headway irregularity* that, among others, trigger the bouncing effect that in the end brings to queuing between different means.

While, concerning the ***demand side***, after having analyzed the entire passenger travel process, we have found the existence of a strict relation between the variance of the expected value of passengers' travel time and the level of service reliability perceived by them.

In the end relating and analyzing the links between the two sides, we have identified the relations that there are between variability in the operations and the service unreliability perceived by passengers. A conclusion is that *having an irregular line* (irregular headways) is one of the main causes of service unreliability for passengers because it increases their *expected travel time* and decreases their *level of comfort* (the two most important quality aspects for customers). Another aspect to take care of is the *propagation of delays* that is also a main cause of variability.

Once identified which are the main aspects that lower the level of service reliability we focused our attention on the causes that generates them making a distinction between *internal-external causes* in order to understand on which of them the transport operator has control. What found in the end is that the main internal causes are *vehicle availability, crew availability and other public transport* while concerning external causes we have identified *other traffic, irregular loads and passenger behavior.*

What understood is that the main aspects to enhance in order to provide to passenger a service that meets their expectations are the *level of trip time's variability* and the *level of comfort.* These aspects are heavily influenced by *"headway irregularity"* and *"delay propagation"* that are internally generated mainly by problems with *vehicle availability, crew availability and other public transport.*

## State of art in disruption management

***Disruption management*** *refers to the process of dynamically revising an operational plan to obtain a new one that reflects the objectives and constraints of the actual situation.*

Disruptions are events that cause a big change in the environment in which the system operates and usually they involve a change in resource availability as well. Furthermore, they are characterized by a high level of uncertainty that makes difficult if not impossible to foresee the exact impact that they will generate.

Currently dispatchers carry out the monitoring of the service, that comprehend, among others, the management of these harmful events. They control the service of part of the network (10-15 lines) having the possibility to adjust operations when deviations occur. They intervene hierarchically adjusting according to the new situation (change in the environment and resources) the *timetable*, the *vehicle scheduling* and the *crew scheduling* (see *figure III*).


***Figure III****: Hierarchical process of interventions followed by dispatchers.*

Operational level is fundamental because it delivers the product that passengers evaluate and buy, for this reason it is important to offer a service that meets customers' expectations because it is based on their experience that they choose the modality of transport to adopt.

Unfortunately, nowadays the corrective actions implemented by dispatchers to improve service level are not the optimal ones because they are not provided with appropriate support systems that help them in taking their decisions. The inefficiencies that are generated due to the current process are listed below:

1. ***Decision taken manually,*** this generates three main disadvantages:
    a. *The quality of the decision vary accordingly to the experience and to the capability of the dispatchers*;
    b. *The quality of the decision cannot be considered sufficient since a manual process deny the possibility to consider all the variables in the systems;*
    c. *The operators are not able to identify the degradation of the system performances caused by disturbances.*

2. ***Not critical usage of operational instruments****:*
   Dispatchers have at disposition different operational instruments to recover an inefficient situation on the line, currently operators consider in the same way all of them. The problem is that they should take into account that certain instruments, even if they have a high power in solving inefficiencies, hide side effects since impact negatively on passengers.

3. ***Reactive approach:***
   Another limitation of the approach currently used is that the interventions to solve disruption are always taken after that the inefficiency occur even if sometimes it would be possible to foresee it (difference between <u>*foreseeable disruption*</u> (*Accumulation of little disturbances/ inefficiencies caused by previous manual interventions)* and <u>*unforeseeable disruption*</u> (*crash*)).

4. ***Narrow-short sight approach in solving disturbances:***

   The fact that dispatchers decide manually how to intervene to restore inefficiencies generates more problems because they are not able to foresee how their decisions will change the position of the different means on the line in the future respect to their schedule. Due to this the actions taken to recover the inefficiencies caused by the first disruption event will create more inefficiencies when the operator will have to intervene again with invasive operational instruments (e.g. skipping stops) to allow drivers to reach the change stops on time.

5. ***Stiff structure focus on punctuality:***

   Another problem that is evident is the stiffness of the surface public transport system. The fact that *shift hours* and *shift change stations* are rigid entities create huge problems at the operational side. Usually happens that even if the system is performing well (there are constant headways between means) are needed interventions to restore the punctuality of the means in order to respect crew scheduling, these interventions always lower the quality of the service offered to customers.

Furthermore, we have analyzed and described the state of art of the approaches used nowadays to tackle disruption events in fields not related to urban public transport system (UPTS). We started analyzing *General control method techniques* applied by cybernetics and we found that the three approaches on which they are based (*Using a buffer*; *feedback* and *feed-forward*) are useful also for our purposes.

We focused also on how disruption management is tackled by other industries (*railway and airline*) that face problems comparable to the one tackled by UPTS.

The logics explained in general control methods are used by both airline and railway industries that have been trying to improve the way of tackling disruption events for years. We have found interesting and adaptable to our case the general approaches used by them to tackle critical situations. The disruption management process starts with a continuous monitoring of the operations that has the aim to trigger an iterative process that has the objective to identify, evaluate and then implement corrective actions when a conflict between actual and planned operations is detected.

*Figure IV* shows the approach schematically.

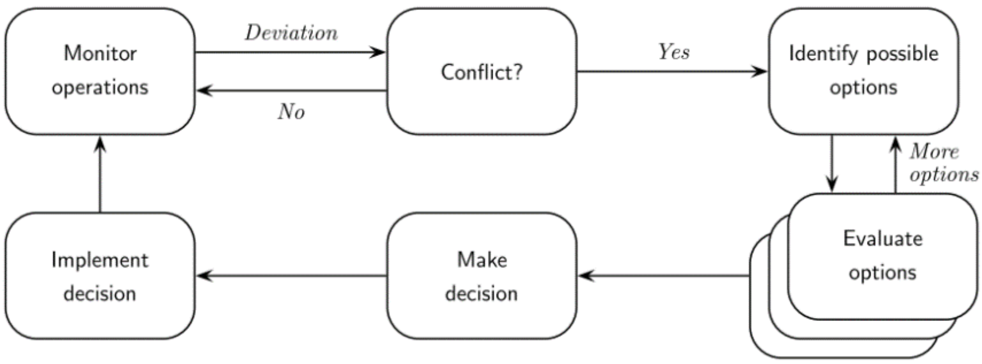



***Figure IV**: Guidelines for operational monitoring.*

Another aspect valuated useful is the use of the technique called *Online combination problem* that, rather than trying to describe the possible outcomes at the occurrence of a disruption by enumerating possible future scenarios, tries to *describe the uncertainty of the situation as an online combinatorial optimization problem.* This approach has been evaluated useful in dealing with the high level of uncertainty and variability that characterizes disruption events.

A last source of inspiration comes from the Decision support system tools that are used by airline industry to help operators in taking the most efficient and effective corrective actions. The ability of this system to process enormous amount of data in a little amount of time providing prompt and useful suggestions to operators leaving them the decisional power to implement them has been evaluated of extreme value also for our case.

## 1.2 Objectives

The level of complexity that characterizes the problem definition is reflected in the objectives of this thesis that are numerous and articulated. In order to be clear and explicative in their presentation we introduce *figure V*. This scheme has the aim to represent the various goals of this work stressing the hierarchy and the relations that there are among them.

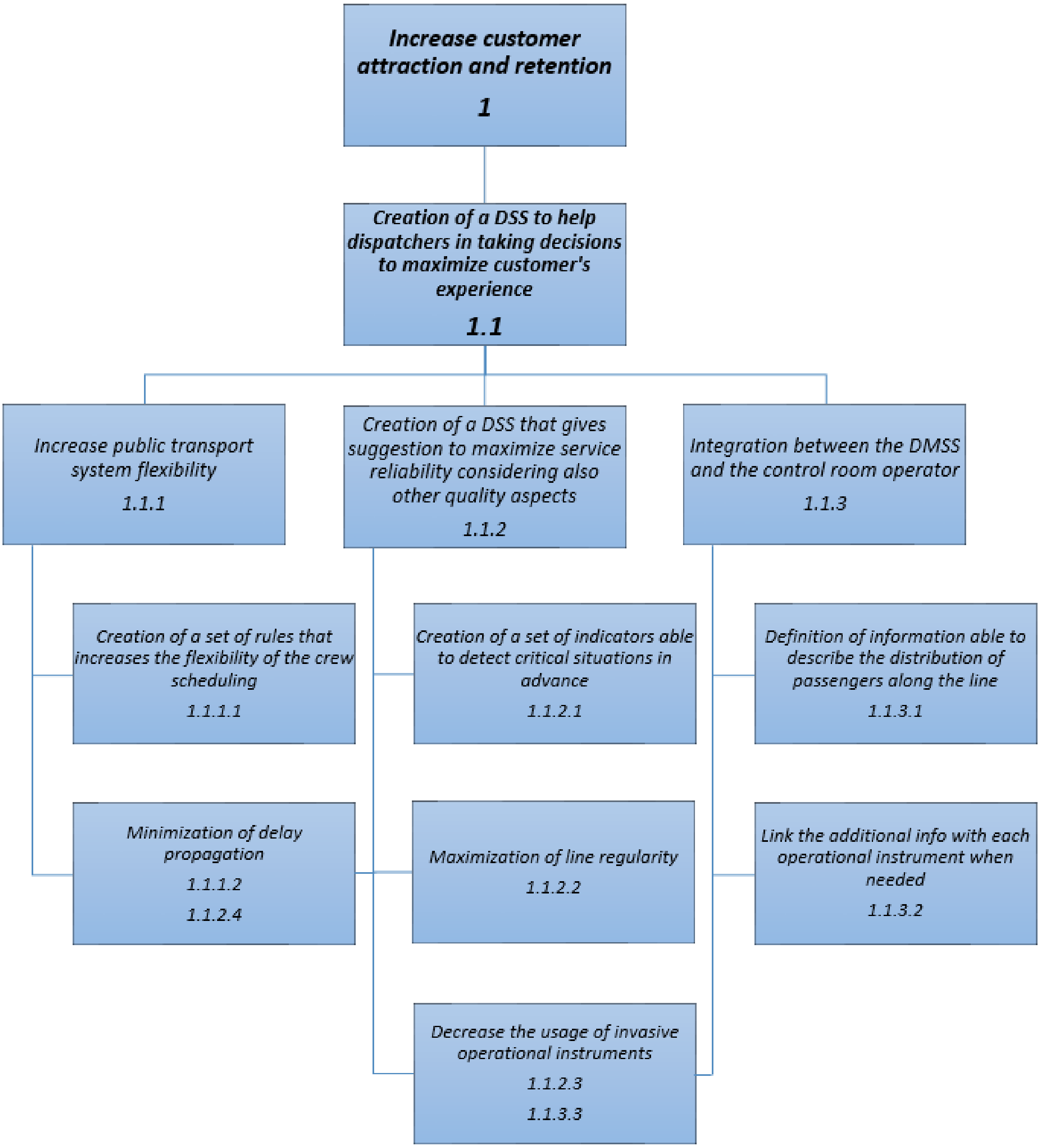



***Figure V***: *Thesis' objective hierarchy scheme.*

## 1.3 Methodology

In this section of the introduction I want to describe the various steps, I and the research groups with which I worked with, went throw to define the details of the new disruption management support system. The entire disruption management project can be divided in two different phases since it has been developed in two different times and places even if the final objective, ***increase customer attraction and retention***, it has always been the same:

1. ***In the first phase,*** I worked for 5 months as an intern at ATM S.p.A. covering the role of *junior risk manager-junior process analyst*. During this period me and the Italian research group created and validated the set of variables, logics and assumption used to generate the support system that aims at minimizing service variability.
2. ***In the second phase*** I worked for six months at TU Delft university faculty of Technology policy and management covering the role of researcher. The first step was writing a document in which I wrapped and translated all the work performed during the internship. After having analyzed and validated the results obtained in the first step with my Dutch thesis adviser and other researchers of the TU we have identified a way to improve the effectiveness of the DMSS. In the end, we decided to create a set of logics and indicators that will provide additional information to control room operators to help them in assessing the impact generated on passenger's quality aspects after the implementation of certain kind of OIs.

The work performed in Milan ca be divided in four main steps that are listed in *table I*.

| ***Step*** | ***Brief description*** |
| --- | --- |
| 1 I (Italy) | *Definition of variables, logics and assumptions used to build the model* |
| 2 I | *Predisposition of the databases*<br>*(definition of variables, logics and assumptions ; simulation and validation)* |
| 3 I | *Simulation on variables and logics* |
| 4 I | *Validation and revision of variables and logics* |

***Table I***: *Methodology's steps list (work performed in Italy).*

Due to time constraints and the massive amount of work to perform my mentors wanted me in the beginning to create a set of logics in order to select the most significant lines and days on which perform the validation phase of the variables, logics and assumptions on which the DMSS will be built. But in the end the actual validation carried out by me was specific on one line, they preferred to have an initial feedback on all the parts of the system instead of having an in depth analysis on few components. The analysis on the other lines it would have been performed by other employees during my absence.

While the approach used to develop the part of the project created in the Netherlands have followed a different scheme (see *table II*).

| ***Step*** | ***Title*** |
| --- | --- |
| 1 N (Netherlands) | *Redaction of a unique document with all the work performed during the internship* |
| 2 N | *Validation of the document created and identification of a way to optimize the effectiveness of the DMSS* |
| 3 N | *Creation of a set of logics and variables to generate the additional information that will optimize the integration between the DMSS and control room operators* |
| 4 N | *Validation of the set of logics and variables generated* |

***Table II***: *Methodology's steps list (work performed in the Netherlands).*

To better explain who did what during the project it is presented *figure VI (figure VI.a; figure VI.b),* it is a scheme in which are listed all the actors that participated in the different phases that brought to the creation of the system.

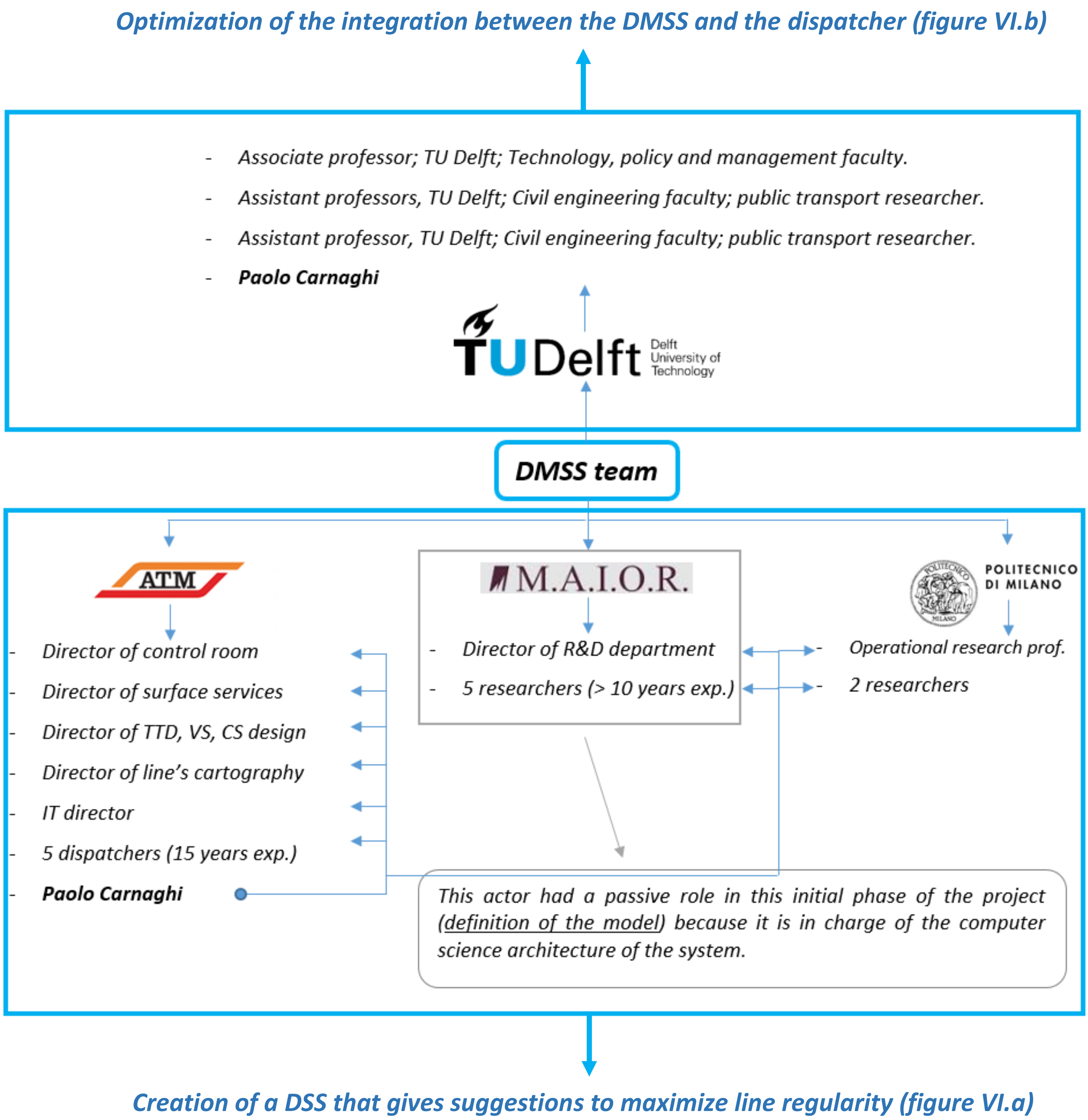



***Figure VI***: *Disruption management team members.*

## 1.4 Principal results

To develop this section we will follow closely the hierarchy presented along the part related to the definition of the objectives (*chapter 1.2, figure V*) to show the achievements obtained in relation to each of them. Now we will list all the main results obtained:

1. Generation of the general architecture of the disruption management support system with the description of the main logics that connect its various components. (*objective 1.1*; see *figure VII*);

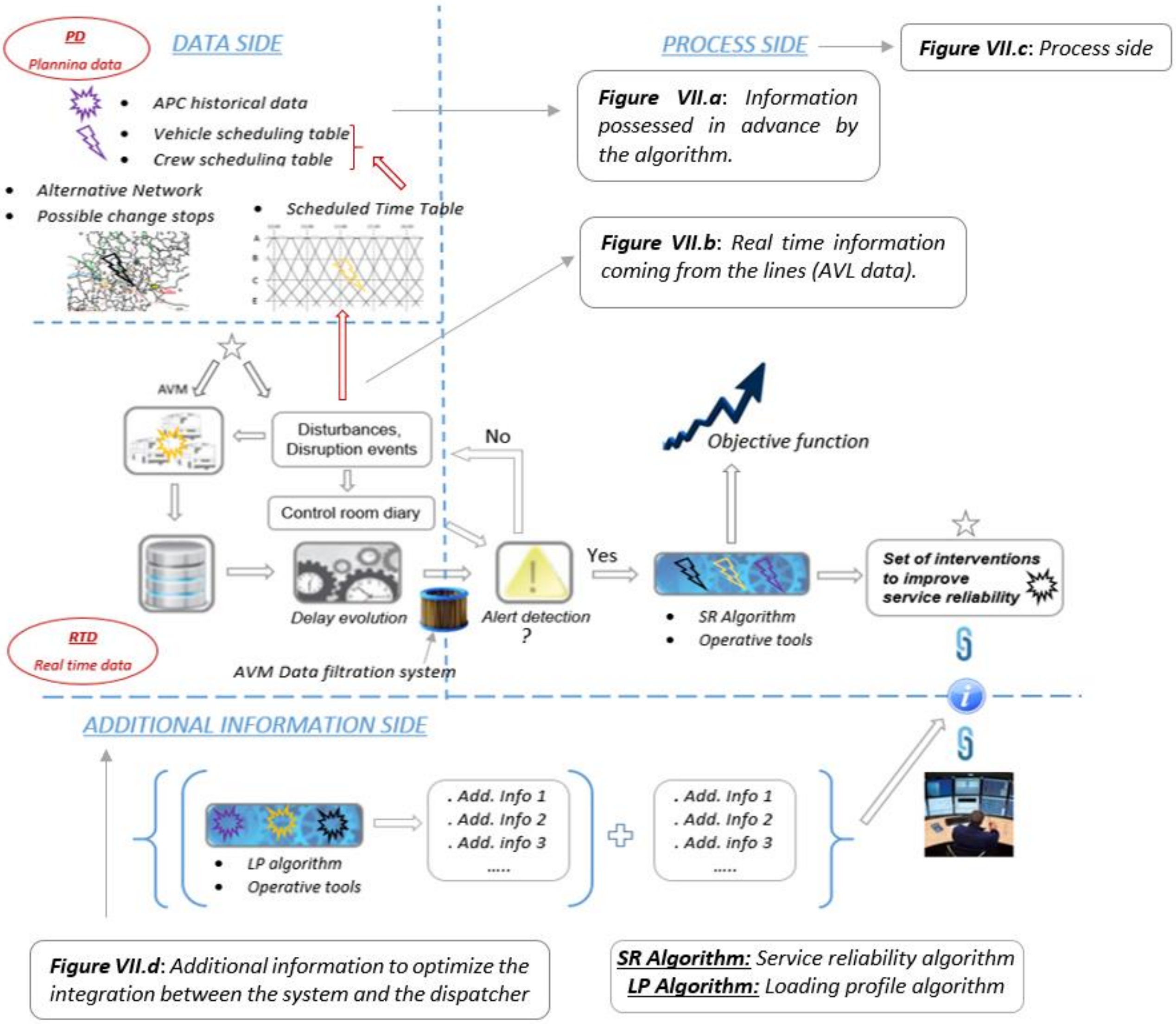



***Figure VII**: Disruption management support system overview.*

2. Generation of the ***AVM data filtration system*** to provide high quality in-put data to the process side of the system. To each data registration that describes the position of each mean on the line is associated a registration code, some of them are usable while other are not. The result has been the creation of a list of codes that has a good quality and that can be used as input to feed the process side of the disruption management support system (see *table III, IV*);

| ***Discarded code*** | |
|---|---|
| ***Error _ code*** | ***Description*** |
| ***Code1*** | *Planned deviation* |
| ***Code 2*** | *No functioning transmission system* |
| ***Code 1024*** | *No transmission in the center of the line* |
| ***Code 128*** | *The mean doesn't transmit during the final 5 stops* |
| ***Code 256*** | *The mean doesn't transmit during the initial 5 stops* |

***Table III***: *list of discarded codes.*

| ***Valid codes*** | |
|---|---|
| ***Error _ code*** | ***Description*** |
| ***Code 0*** | *Correct transmission type a* |
| ***Code 4*** | *Correct transmission type b* |
| ***Code 8*** | *Correct transmission type c* |
| ***Code 16*** | *The mean stops at least 3 minutes at the terminal* |
| ***Code 64*** | *The mean stops at least 3 minutes on the line* |
| ***Code 512*** | …………………………………………………. |
| ***Code 16384*** | …………………………………………………. |

***Table IV***: *list of valid codes.*

3. Creation of the assumptions and logics that constitute the ***alert detection component*** (*Figure VIII*). This is the part of the system that links the "data side" with the core of the DMSS, the "service reliability algorithm". It is composed by a set of rules, variables, indicators an thresholds that have the task to detect in advance possible critical situations on the line that without a prompt intervention can irremediably degenerate and consequently activate the algorithm that will provide suggestions to improve the level of service. *(Objective 1.1.2.1; objective 1.1.2.2; objective 1.1.2.4).*

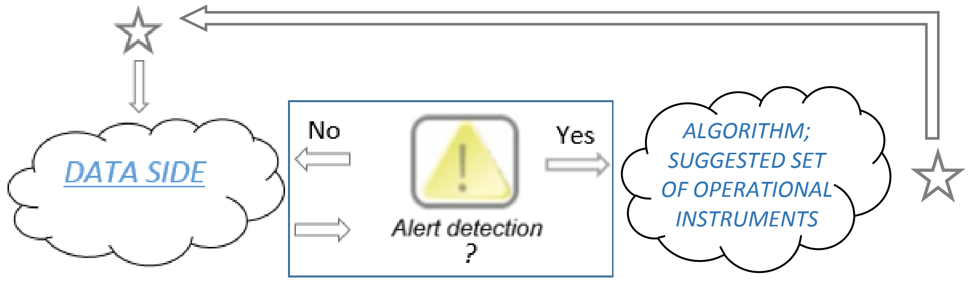



***Figure VIII***: *Alert detection component with context.*

*Table V* recaps the 3 different alerts identified.

| *Alert* | *Description* |
|---|---|
| ***Alert 1*** | *Occurrence of one or more events detected as critical on the risk map* |
| ***Alert 2*** | *Generation of a group of «steps» that overtakes the set of identified thresholds* |
| ***Alert 3*** | *Increasing trend of General deterioration of the line* |

***Table V***: *Alerts presentation with short introductive description.*

4. The creation of a ***new set of operational instruments*** to make the structure of the public transport system more flexible and reactive to disruption events and disturbances that interacting with the operational process increase the variability of the service offered hence decrease the service reliability.

The new set of operative instruments (see *table VI*) will aim at increasing the crew scheduling flexibility. An increasing in the flexibility is fundamental for two main reasons:

*1. To decrease the invasive interventions done by operators to guarantee drivers to arrive on time at the change station even if they lower the service reliability and create discomforts to passengers;*

2. *To reduce the delay propagation.*

*(Objective 1.1.1; objective 1.1.1.1; objective 1.1.1.2).*

| ***Crew scheduling flexibility's operational instruments*** |
|---|
| ***Shift's duration flexibility*** |
| ***Break flexibility*** |
| ***Shift's structure flexibility*** |
| ***Change station flexibility*** |
| ***Stop at the terminals flexibility*** |

***Table VI**: Crew scheduling flexibility's operational instruments table.*

5. ***Creation of a matrix*** (see *figure IX*) that has the aim to prioritize the usage of operational instruments according to the kind of alert activated (the aim is to minimize the usage of invasive operational instruments that have huge solving power but also high impact on service level perception). *(Objective 1.1.2.3).*

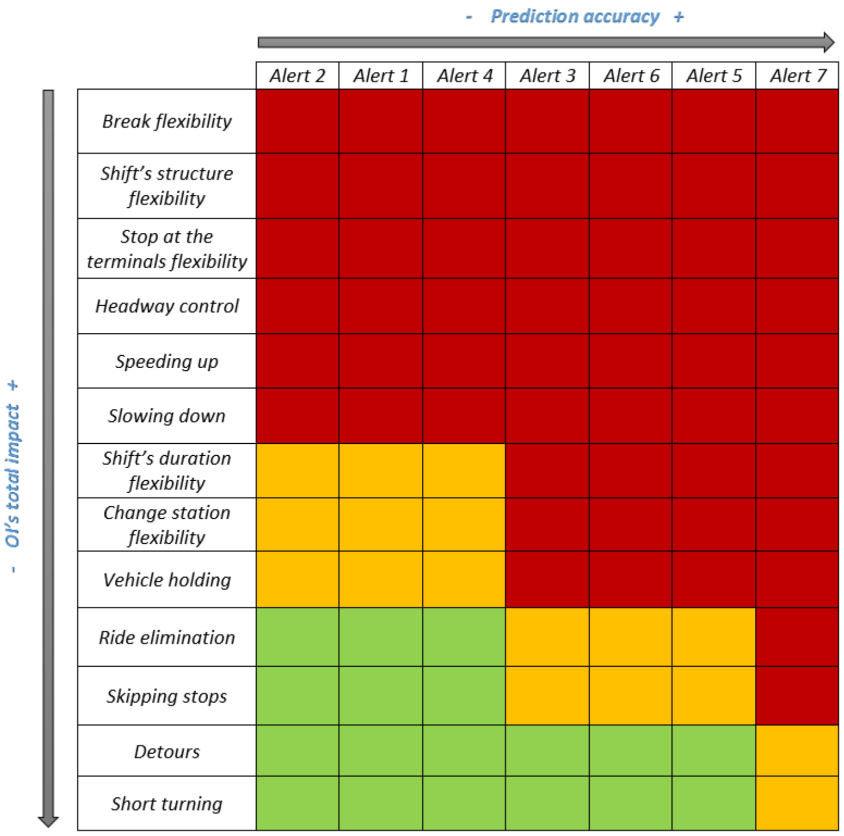



***Figure IX**: Final Alert/OIs matrix with different level of priority usage.*

***Notes:***

- ✓ The different colors of the cells represent the intensity of usage with which a certain OI should be used by the algorithm to solve a critical situation detected by the activation of a certain alert/combination of alerts.

  the process followed by the algorithm to pick the set of OIs to restore the service reliability of the line follows the logic presented below (*see figure X*):

  1. *Alert/s activation;*
  2. *Application of intensive usage OIs (related to the alert/s activated), if with them the algorithm is not able to bring back the line to a good level of regularity it passes to step 3;*
  3. *Application of medium usage OIs (related to the alert/s activated), if with them the algorithm is not able to bring back the line to a good level of regularity it passes to step 4;*
  4. *Application of light usage OIs (related to the alert/s activated).*

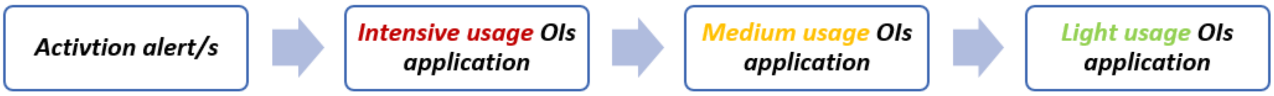



***Figure X***: *Final Alert/OIs matrix with different level of priority usage.*

6. The final big achievement obtained in this thesis it has been the identification of the ***additional information to provide to dispatchers*** in order to make the suggestions generated by the DMSS more complete and effective in maximizing passengers' experience. We have to remember that the last objective is to enable dispatchers to take better decisions in order to increase the overall service quality given to passengers and consequently increase customers acquisition and retention. *Figure XI* shows schematically the components that constitute this part of the DMSS and how it interacts with the rest.

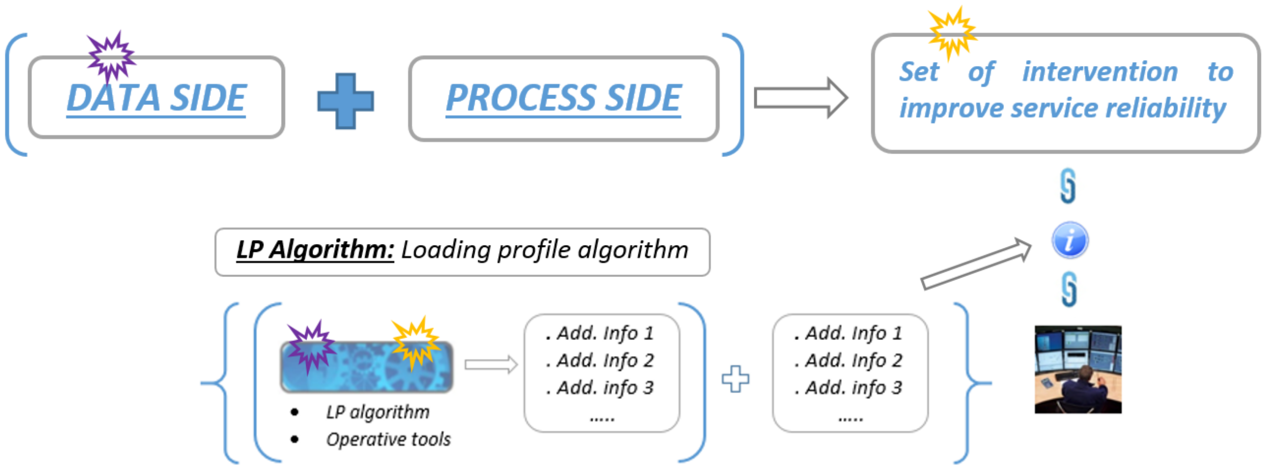



***Figure XI***: *Schematically representation of the components that compose the Additional information side and their interaction with the whole system.*

The additional information identified valuable along this part of the studying has been the following:

1. *Loading profile and number of passenger alighting and boarding*;
2. *Weather condition*;
3. *Cleaning of the vehicle*;
4. *Impact on accessibility*.

After having identified how to generate all the different information that is considered important to support the dispatchers in taking their decisions it is important to relate the specific info with the specific operational instrument.

The auxiliary information will be given only when the system will suggest applying invasive operative instruments that are the ones that generate also negative impact on passengers' quality aspect.

Among all the OIs at disposition of the DMSS we have identified six of them that can be defined critical. Now we will list them reporting the related additional info.

- ***"Group 1 OIs"***
    - *Skipping stop (see table VII) ;*

<table>
<tr><th>Vehicle interested</th><th>Skipped stop</th><th>Quality aspects</th><th>Additional info 1</th><th>Additional info 2</th></tr>
<tr><td rowspan="3">Vehicle J</td><td rowspan="3">Stop i</td><td>Accessibility</td><td rowspan="2">1) Number of passengers boarding at stop i, time k, vehicle j;<br>2) Number of passengers alighting at stop i, time k, vehicle j</td><td rowspan="3">1) Outside temperature [C°] ;<br>2) Weather condition</td></tr>
<tr><td>Comfort 2,<br>Being forced to abandon the vehicle</td></tr>
<tr><td>Cleaning of the means</td><td>Skipped <u>n</u> cleaning operation</td></tr>
</table>

***Table VII**: Table with the additional information needed to dispatchers to understand the impact that the implementation of a **<u>skipping stop</u>** generates on passengers' quality aspects.*

- *Short turning;*
- *Dead heading;* *(see table VIII)*
- *Detour;*

<table>
<tr><th>Vehicle interested</th><th>Skipped stop</th><th>Quality aspect</th><th>Additional info 1</th><th>Additional info 2</th></tr>
<tr><td rowspan="3">Vehicle j</td><td rowspan="3">$\sum_{i=2}^{n} stop\ i$</td><td>Accessibility</td><td rowspan="2">1)Number of passengers on board line section i, time k, vehicle j;<br>2) Average number of passenger waiting for boarding at the various skipped stop, time slot u.</td><td rowspan="3">1) Outside temperature [C°];<br>2) Weather condition.</td></tr>
<tr><td>Comfort 2,<br>Being forced to abandon the mean</td></tr>
<tr><td>Cleaning of the means</td><td>Skipped <u>n</u> cleaning operation</td></tr>
</table>

***Table VIII**: Table with the additional information needed to dispatchers to understand the impact that the implementation of **<u>detour-dead heading and short turning</u>** generate on passengers' quality aspects.*

- ***"Ride elimination"*** *(see table IXI)*;

| *Vehicle interested* | *Skipped stop* | *Quality aspect* | *Additional info 1* | *Additional info 2* |
|---|---|---|---|---|
| ***Vehicle j*** | ***Entire line*** | **Accessibility** ⬆ ⬇ | $\frac{\sum_{i=1}^{n} stop_i \text{ } in\ which\ \frac{average\ load\ \ stop\ i}{capacity\ of\ the\ vehilce\ j} \geq X}{Nuber\ of\ stops\ along\ the\ entire\ line}$ | *1) Outside temperature* [C°]<br>*2) Wheatear condition* |
| | | **Comfort 1,** *Capability to find a seat* ⬇ ⬆ | $\frac{\sum_{i=1}^{n} stop_i \text{ } in\ which\ \frac{average\ load\ \ stop\ i}{capacity\ of\ the\ vehilce\ j} \geq 1}{Nuber\ of\ stops\ along\ the\ entire\ line}$ | |

***Table IX:*** *Table with the additional information needed to dispatchers to understand the impact that the implementation of **ride elimination** generates on passengers' quality aspects.*

- ***"Vehicle holding"*** *(see table X)*;

| *Vehicle interested* | *Stop held* | *Quality aspect* | *Additional info 1* | *Additional info 2* |
|---|---|---|---|---|
| ***Vehicle j*** | ***Stop i*** | **Accessibility** ⬆ ⬇ | ***1) Number of passengers on board*** line section **i**, time **k**, vehicle **j;**<br>***2)Average number of passenger waiting*** *downstream after the held stop at the various stops, time slot **u*** | *1) Outside temperature* [C°] *;*<br>*2) Wheatear condition* |

***Table X****: Table with the additional information needed to dispatchers to understand the impact that the implementation of **vehicle holding** generates on passengers' quality aspects.*

## 1.5. Thesis articulation

### *Literary review:*

- ***Problem definition***

  This section is characterized by the studying of the general situation in which the urban public transportation system (UPTS) has to operate. Here we have analyzed the general trends that describe the share of usage of PTS in the future, all the quality aspects that are considered valuable by passengers and all the problems that contribute in lowering the service level perceived by them. Once depicted this initial scenario our attention moved on disruption events/disturbances and their management, that has been identified as one of the main causes of service reliability scarcity. We studied in deep this phenomenon contextualizing it in the UPTS' environment.

- ***Description of existing useful tools and approaches for disruption management***

  This second part of the literary review has been dedicated to the analysis of the approaches and of the techniques used nowadays by other industries to tackle the disruption management problem. The initial studying has been focused on general control methods that are currently used in different fields as general rules to mitigate output variability; that in our case is the service offered to passengers. After we moved our attention to Airline and Railway industries that have been tackling this issue for years. Their approaches have been a good source of inspiration for certain aspects of the disruption management support system created ad hoc for urban public transport operators.

## *Thesis' framework:*

- ***General systems and logics***

  In this first section we have described the general logics upon which the entire disruption management support system will rely on. We analyzed the aspects of general control method that are of interest for our purposes and we have describe them contextualizing every feature in the specific case of the DMSS.

- ***Disruption management support system skeleton***

  This part is dedicated to the presentation of the DMSS's skeleton showing all the main components that constitute it and all the logical relations that there are among them.

## *Thesis' methodology:*

- ***Creation of a DSS that aims at maximizing line regularity***

  In this this chapter I have described the various steps I and the research groups with which I worked with went throw to define the features of the components that constitute the part of the disruption management support system created in Italy. Furthermore are reported which data and which software have been used to carry out the validation phase of the assumptions and logics identified in the initial phase of the project.

- ***Integration between the DMSS and the dispatcher***

  In this this second section I have described the various steps I and the research groups with which I worked with went throw to define the details of the part of the new disruption management support system created in the Netherlands, during my staying at TU Delft faculty of Technology policy and management.

## *Thesis' Model:*

- **Creation of a DSS that aims at maximizing line regularity**

  In this part of the thesis we have described in detail all the components of the disruption management support system (DMSS) already presented from a broad point of view along the *thesis' framework.* We described all the logics, assumptions and variables that compose each part of the DMSS that aims at *maximizing line regularity* (work developed in Italy).

- ***Integration between the DMSS and the dispatcher***

  In this part of the thesis we have described in detail all the components of the disruption management support system (DMSS) that form the *additional information side*. This section is an in depth description of the part of the work performed in the Netherlands.

## *Thesis simulation*

- ***Data side***

  In this part of the thesis we have carried out the validation of the assumptions, logics and variables that characterize the *data side* of the DMSS. In this section it is reported a numerical case study in which are explained all the passages and the results obtained.

- ***Process side***

  Along this second phase we have carried out the validation of the assumptions, logics and variables that characterize the *process side* of the DMSS. Along this chapter it is reported a numerical case study in which are explained all the passages and the results obtained.

# 2. Literary review

The literary review has the objective to analyze why the disruption management is an important issue and why it is a difficult problem to tackle; this chapter is divided in *two main sections:*

1. ***Problem definition (chapter 2.1):*** We will start with a general analysis on mobility trend highlighting the fact that urban public transport systems are fundamental to ensure a sustainable development of cities. After we will focus our attention in defining what are the aspects that are fundamental for customers in order to identify where it is necessary to bring a change for attracting more passengers and increasing their retention. In the end, we will find that <u>*service reliability*</u> (*travel time reliability* + *travel level of comfort*) is the characteristic of the service they care the most. Once obtained this information we will analyze in detail what is service reliability and the elements that influence it (*service variability, unreliability*). We will conclude this section describing what disruption management is and contextualizing this issue in urban public transport system.

2. ***Description of useful tools and approaches for disruption management (chapter 2.2):*** Along this second part we will analyze the state of art of disruption management in urban public transport system and not only. We will dedicate a part of the section to airline and railway industry and from their studying we will define which aspects can be implemented in our case. In the end we will move our attention on the operation management in urban public transport system describing in detail all the operational instruments that are used nowadays to tackle this problem and the indicators that are used to evaluate operational performances.

## 2.1 Problem definition

Nowadays there is a continuous increasing trend of people moving to urban areas (1990 - 40% → 2030 - 60%; *World health organization*), this combined with a general increase of the welfare have brought to a substantial increase of personal mobility's needs during last years. In the scenario just described public transportation system becomes a crucial mean for a sustainable development. However, the share of public transport (PT) in this increasing of mobility remains steady. A substantial quality leap in this sector is needed nowadays to attract and retain more passengers and increase in this way the usage of PT instead of private means. A decrease in the volume of traffic in the urban areas means an increase in the livability of cities without considering the huge cost due to vehicles circulation that the society could save and invest in other ways. *In this thesis is proposed a decision support system with the aim to help control room operators in optimizing the service level offered to passengers in order to increase their acquisition and retention*. The system will focus principally on the maximization of ***service reliability*** (*travel time reliability + comfort*) with particular attention in not compromising other passengers' quality aspects.

### 2.1.1 Mobility trend and aspects of influence

Let us start this chapter presenting the topics that we will tackle and develop along it (see *figure 1*).

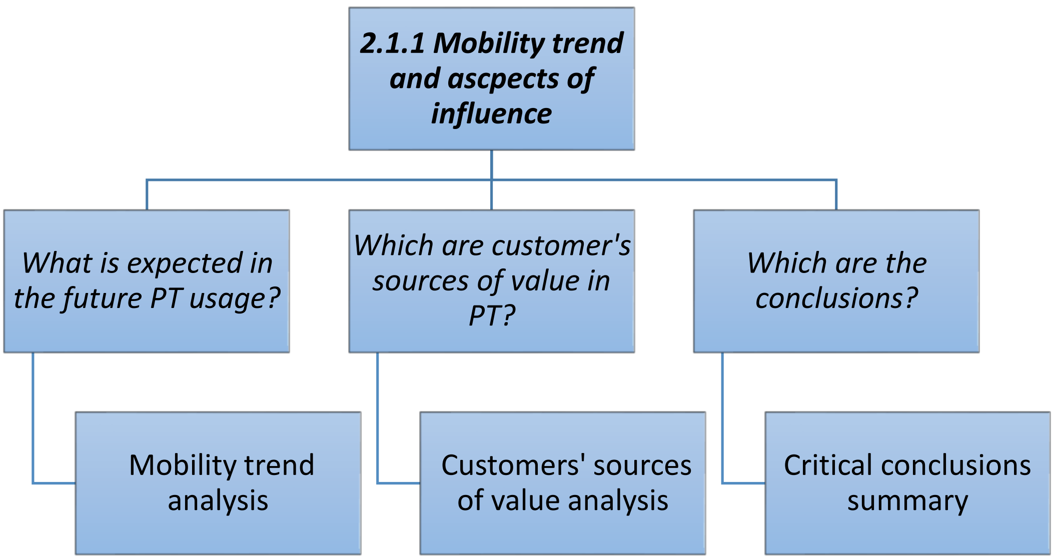



***Figure 1***: *Chapter 2.1.1 structure.*

### *Mobility trend analysis*

Looking at *figure 2 it* is possible to see the travelled kilometers per mode trend in the Netherlands between 1995 and 2008 (*Van Oort 2011*). The chart shows that the share of public transportation has remained almost steady along the years while it is possible to notice an increase in the car usage (*5% from 2000 to 2008*). This trend can be explained considering both the increasing number of people that move to urban areas and the general improvement of the purchasing power of the citizens. Furthermore, there is a constant increase in passengers' demand related to the performance offered by the public transport companies.

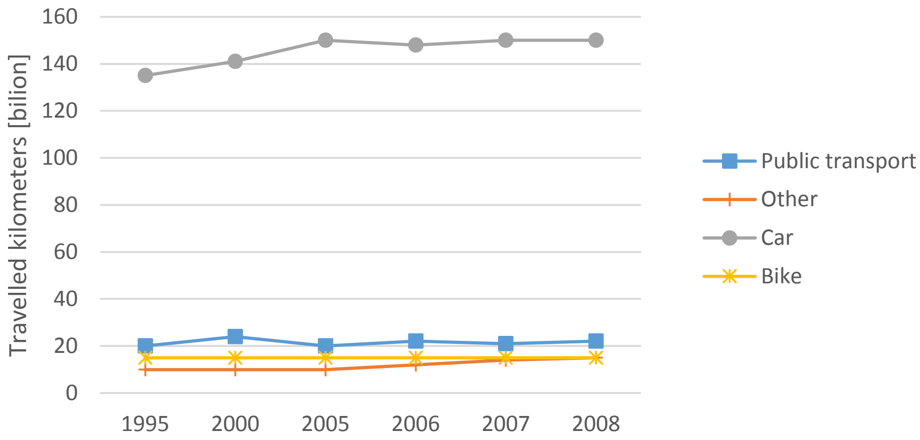



***Figure 2**: (1995-2008) Traveled kilometers per mode in the Netherlands.*

Another aspect that it is important to highlight are the societal costs due to mobility mode's trends. *Table 1* shows the monetary impact of the increasing trend of private transportation means in the Netherlands. In addition to space usage and energy consumption the main aspects to consider are loss of time due to congestion, probability of being injured and the damage generated to the environment due to emissions and noise (pollution).

| Type of cost | Year 2008 |
|---|---|
| **Estimated cost of congestion** | from 2.8 to 3.7 [billion €] |
| **Cost of unsafe mobility** | from 10.4 to 13.6 [billion €] |
| **Cost of environmental damage** | from 2 to 8.5 [billion €] |
| ***Total cost*** | ***from 15,2 to 25,8 [billion €]*** |

***Table 1**: Dutch case, different costs generated by private vehicle circulation in 2008.*

Broadening the view it is possible to see that other countries and continents have similar development trends. *Figure 3* (*Larson 2009*) shows the modal split trend in the European Union from 2000 to 2020. As it is possible to see from the chart the Public transportation system that operates in urban areas (bus, coach, tram and metro) is the one that will suffer the most losing the 3% of the shares while the use of the car will increase of 1%. Looking at *figure 4 (Kenworthy and Laube 2001)* it is possible to notice that the low share of European public transport system can be consider high respect to the American or the Australian one. In the meantime, Asia (especially China) shows a stronger propensity to use alternative way of transport to private motor vehicle.

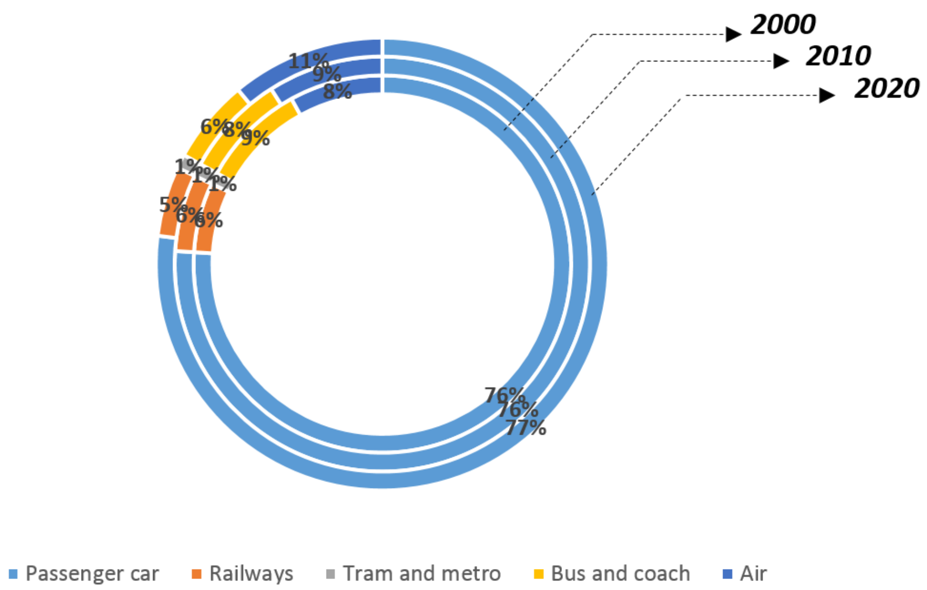



***Figure 3**: Modal split trends (travelled kilometers) in the Europe between 2000 and 2020).*

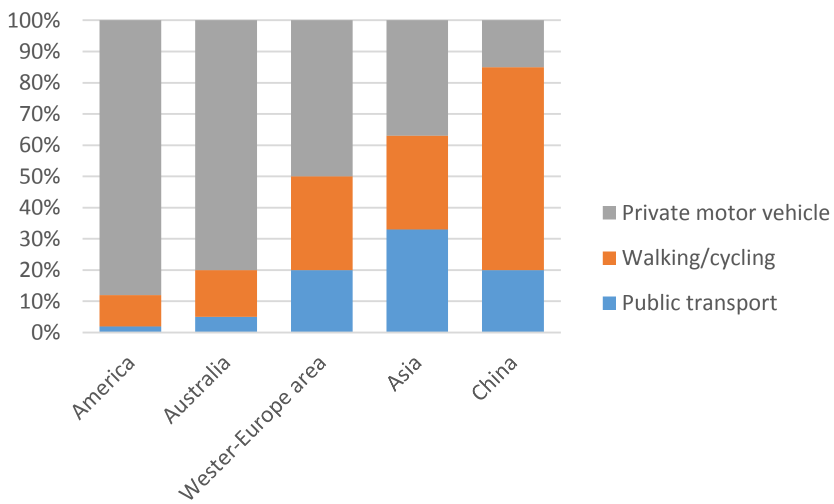



***Figure 4**:* World Modal split in year 2001.

From the situation depicted in the previous pages it is evident *the need for urban public transport companies to  increase passengers acquisition and retention; the idea of this thesis is the creation of a DSS to help dispatchers in taking decisions that maximize the match between the level of service offered and customer expectations.*

As we have already mentioned, customers have constantly increased their expectations for what concern the service level offered by urban public transport systems. The next step is to understand which are the quality aspects that they evaluate more important and the relations that there are among them.

## *Customers' source of value analysis*

Public transport may play an important role in reducing all the external costs listed in *table 1*. In a report done by the Dutch Ministry of Transport in 2004 it is stated that a public transport user causes about half the damage to the environment compared to a car user *(Van Oort 2011).* The policy inside and outside Europe about this issue is to improve public transport to increase the livability and accessibility of cities that are getting more and more populated. In order to guarantee their sustainable development it is necessary an increase in the role of public transport in total mobility.

According to the analysis that we have performed up to now it is evident that public transport is able to improve and ensure accessibility and livability of cities, and since it might invert the increasing trend of car mobility's usage, a leap in its quality is necessary.

In order to understand on which aspects focusing to increase passengers' acquisition and retention it is necessary to understand which qualities characterize public transport. Different authors (*Baker and Cameron 1996, Van Hagen et al. 2007 and Van Oort 2011)* distinguish the following main quality aspects:

- ***Price:*** The main part of the price that a passenger has to sustain is the cost of the ticket. But it is also important to consider the additional costs (the price for parking the car or the bike) that can increase the overall trip cost.

- ***Accessibility:***
  - *a.* ***In time****:* It is the *frequency of the service*, which is the number of possible departures performed in a defined period*;*
  - b. ***In space:*** The distance that separates the passenger from the origin to its final destination.

- ***Travel time:*** This is the total time spent travelling from origin to destination.

- ***Comfort***: Comfort expresses the level of passenger's satisfaction. The level of comfort is a quality aspect and is relevant to both the vehicle and the stop. It can be seen both as the capability to find a seat during the trip and as the possibility to travel without inconvenient that for example force the passenger to leave the vehicle during the service.

- ***Image***: The image of the public transport system determines whether people would like to use it without this reflecting badly on them.

- ***Service reliability:*** Service reliability expresses whether the actual passenger journey meets the expected quality aspects (*travel time reliability+ travel level of comfort)*. *Improve service reliability is one of the objective of this thesis.*

Once listed and described which are the principal quality aspects for passengers identified in the literature, it is important to know if there is a hierarchy among them in order to define which are the values on which it is worth to invest more to increase passengers' share and retention. A tool that can help us in prioritize them is the *"Pyramid of Maslow for public transport"*, (*Peek and Van Hagen 2002*) shown in *figure 5.*

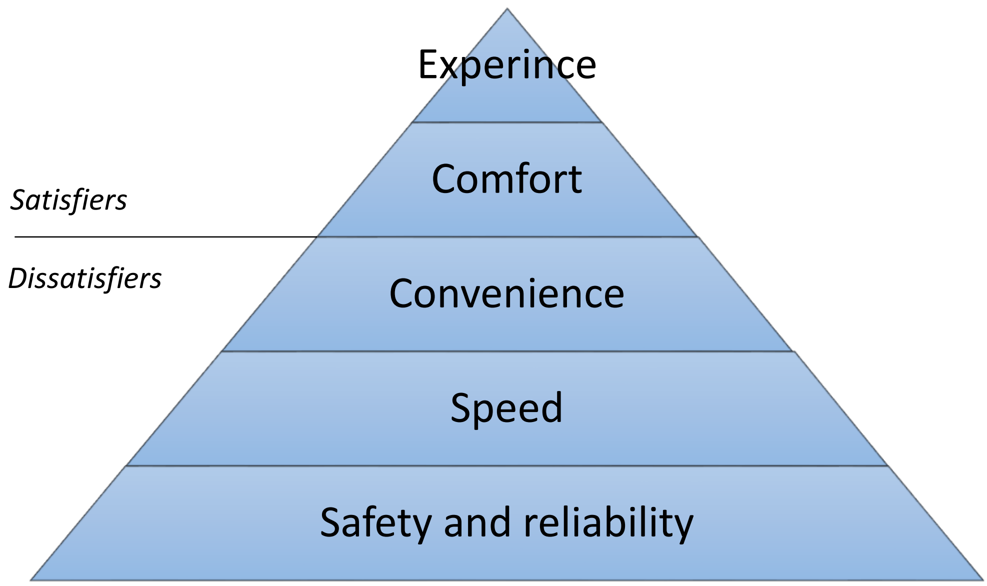



***Figure 5***: *Pyramid of Meslow for public transport.*

The pyramid is composed by different layers that represents passengers' requirements.

The pyramid can be divided in two main parts:

- ***Dissatisfiers*** (*Safe and reliability, speed, convenience*)***:*** These are the first three aspects presented in the pyramid and they have to reach a minimum level of quality otherwise it is probable that passengers change the public transport modality or decide to not travel at all.

- ***Satisfiers*** (*experience, comfort*)***:*** These are the last two aspect presented in the pyramid and are the elements that satisfy the travelers. They enhance the customer's travel experience.

The elements *safety and reliability* that form the base of the pyramid stress the importance to guarantee a high level of service reliability. It is important to highlight that all the layers are bonded one another and low performances in one of them have negative repercussions on others. For this reason *it is not effective focusing in maximizing only one of them forgetting the others, in fact the DSS that we will propose will help the operators in understanding the overall repercussions that their decision will have on passengers.*
Now we want to go more in deep in understanding passenger's appreciations related to different quality aspects in public transport (*Van Oort 2011, Jackson and Jucker 1981, Black and Towriss 1991 and König and Axhausen 2002)*. The aspect that is commonly the principal driver that leads passengers in their decision about transportation modality is ***service reliability*** *(travel time reliability + level of comfort)****.*** *Brons and Retvel* (2007) built a graph (*figure 6*) in which show their findings about the perception that *passengers* have on public transport quality aspect (they evaluate both *level of satisfaction* and *level of importance*). *Figure 6* demonstrates that travel *time reliability* is consider one of the most important aspect for passengers, while their appreciation of it is limited.

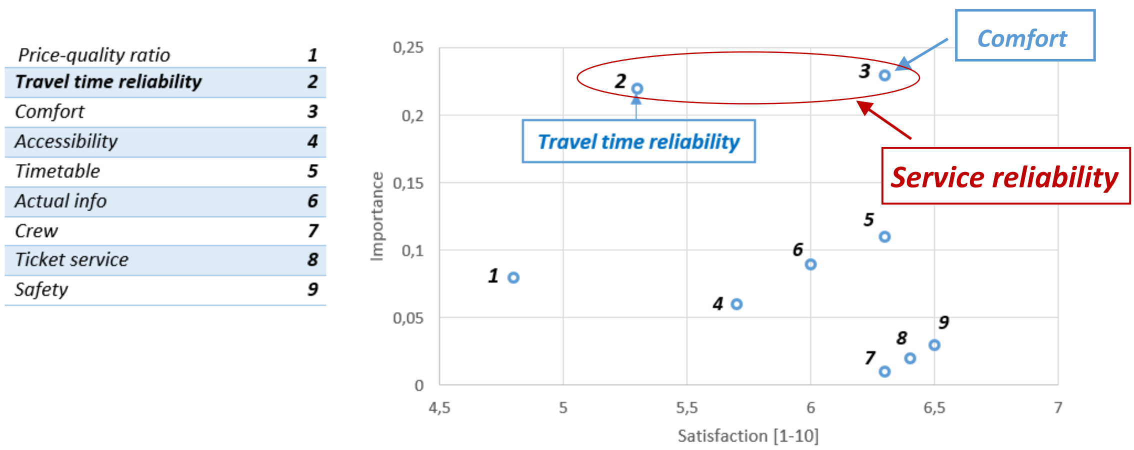



***Figure 6***: *Importance of quality aspects for passenger; (Brons and Retvel 2007).*

A lot of studying confirm that ***service reliability*** is one of the principal aspects that influences customers behavior in deciding which kind of modality of transport use. The European union is trying to increase the share of people that use public transportation system and in order to achieve this result are investing a lot of capitals to make the PT system more attractive alternative.

*Figure 6* shows the high importance of *travel time reliability (TTR)* and *level of comfort* for customers. The fact that these quality aspects has both high importance and low level of satisfaction suggests that in order to change the mobility trends (*figure 3, 4*) it is necessary to focus on them for improving significantly the quality of service offered by public transport. This does not mean that it is possible to ignore completely the other quality aspects (QAs); otherwise, they will became a future issue. *The final objective of the support system introduced in this thesis will be to maximize the critical QAs (travel time reliability and level of comfort) without lowering the level of the others.*

We conclude with a critical analysis of the all the material reported along the chapter.

### *Critical conclusions summary*

In *chapter 2.1.1* we started presenting the actual situation in which public transport has to operate; cities are getting more and more crowded and the need of personal mobility is continuously increasing. In the scenario just described public transport systems (PTS) play a fundamental role in assuring a sustainable development of urban areas.

Unfortunately, the generic trends that describe the choice of transportation modalities made by passengers do not go in favor of PTS. This is also due to the fact that nowadays the standards to meet customer requirements are getting higher and higher, they do not care only to be transported from a point A to a point B inside the city but they pay a lot of attention also in the experience that they have along the trip.

In this situation it is evident the necessity of a quality leap in the level of service offered by public transport companies. *The main objective of this thesis will be the creation of a system that will help control room operators in maintaining a high service level to meet passengers' expectations and consequently increase their acquisition and retention*. In order to understand on which aspects it is necessary to invest for improving the level of service offered we have analyzed passengers' quality aspects and their level of appreciation.

What found is that travel time reliability (TTR) and the level of comfort during the travel are the aspects more valuable for them. Particular attention it is worth to be put on TTR because it is the aspect that has the main importance and the lower level of satisfaction. Another important thing that we have discovered is the presence of a strict relation between all the QAs, this means that will be fundamental consider all of them. Now that we know which are the aspects evaluated important by passengers it is worth to understand why some of them, also if considered fundamental, have such a low level of satisfaction and which are the causes that pose them in this status.

### 2.1.2 Process/service reliability, variability and unreliability

What we have seen along *chapter 2.1.1* shows the importance that public transport system has in guarantying a sustainable development of urban areas. Furthermore, we have identified the different public transport's quality aspects and the importance that they have for passengers, highlighting the critical ones (*High importance, low satisfaction*). The core of this thesis is the creation of a decision support system that will help control room operators in *maintaining a good regularity of the line, hence a good level of service reliability, without compromising the other quality aspects*. Along this section we will analyze in detail service reliability and variability to understand what they are, the relations that there are among them and the impact that they generate on riders. *Figure 7* briefly presents the contents of this chapter.

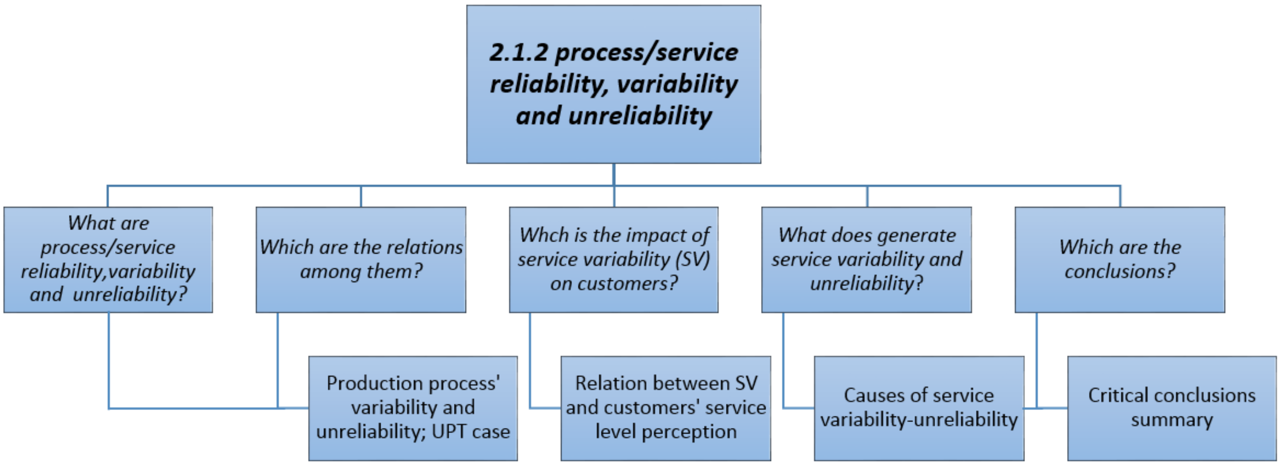



***Figure 7**: Chapter 2.1.2 structure.*

*"**Service reliability** is defined as the certainty of service aspects compared to the schedule (such as travel time (including waiting), arrival time and seat availability) as perceived by the user. (Van Oort 2011)*. The level of reliability depends on the variability of the system itself and on the customers' expectations of this variability. When variability overtakes certain limits it becomes unreliability that is perceived as poor service by passengers.

Now it is important to understand the interaction that exists between passengers' service reliability perception and the variability of the service offered by public transportation companies. Van Oort in his studying on service reliability suggests to analyze the interactions between the *demand and the supply side* of the public transport to clarify the relation between service variability and reliability. Let us start this section with a general overview about the concepts of variability-unreliability in a generic production process, after we contestualize import them in the urban public transport case.

### *Production process' variability and unreliability; urban public transport case.*

*Figure 8* (*Heylighen and Joslyn 2001*) presents a generic process that transforms input into output as if it works in a black box (*Cybernetics' theory*). However, since processes operate in the real word it is necessary to consider also the interactions that there are between the operations and the external environment, these interactions are called *disturbances/disruption events* and are the main causes of variability.

Due to them the process is not able to perform always as planned, this fact has an impact on the final output that is subjected to variability along the time. Introducing the interactions with the real world the process cannot be consider deterministic anymore, it becomes stochastic.

If this variability is not desired or more than expected, it results in unreliability. Unreliability means that the actual output is not equal to the promised (or expected) one. If we relate this concept to the PT it is possible to say that passengers will suffer from this because they experience a reduction of the service quality. In addition, also the operator may suffer since it may need additional resources or instruments to reduce or mitigate the effects caused by the variability. To tackle this issue it is necessary to improve the process and the way it is managed to mitigate the effects that disturbances generate on the final output.

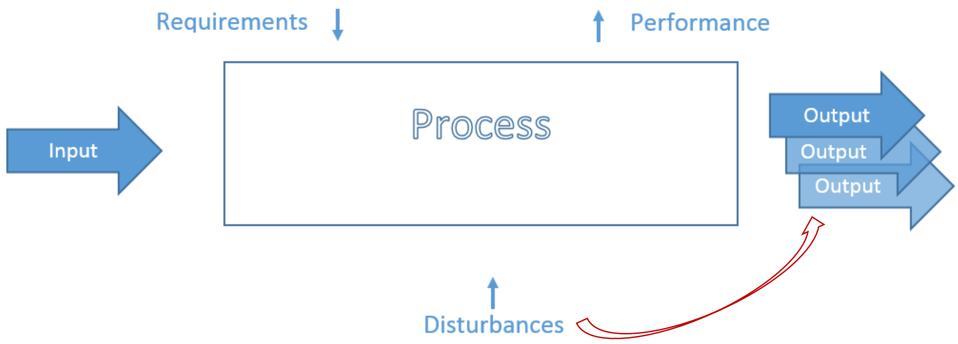



***Figure 8:*** *General production process including output variability.*

Now that we have an overview, we can contextualize the concepts just explained in the urban public transport process (UPTP). UPTP is composed by all the operations that allow passengers to move from one point to another within a determined period of time that can vary according to disturbances/disruption events that interact with the operational process and that generates output variability.

The ***input*** of the process is a network, consisting of *infrastructure and service lines*, a *schedule*, *crew* and *vehicles*.

The ***output*** of the process are actual vehicle trips from stop to stop, including actual departure and arrival times. In order to assess the level of output variability it is necessary to compare the actual service with the scheduled one (planned output in term of *time, vehicles and general performance of the service*).

However, the actual output is often not exactly as the planned one due to disturbances that interact with the process (*human behavior, weather, other traffic,…*) and generate output variability.

***Service variability** in public transport is defined as the distribution of output values of the supply side of public transport, such as vehicle trip time, vehicle departure time and headways (Van Oort 2011)*.

The variability of the system affects dramatically the level of quality perceived by passengers: "*In transportation **service reliability** may generally be defined as the probability that a transport service will perform a required function under given environmental and operational conditions and for a stated period of time"* (*Iida and Wakabayashi 1989*).

Once described what is service reliability, variability and unreliability in urban public transport it is necessary to broaden the view on the UPT process to better understand what just explained.

Before the operations there is the ***planning process*** in which are specified the timetables that define the planned service that is performed on the lines by the various means during the operations (scheduled service). The planning process is composed by the ***strategic*** and ***tactical level***. *Figure 9* shows the entire process.


***Figure 9**: Public transport system management stages.*

*Van Oort (2011)* explains that in the beginning the network (*strategic level*) and schedule (*tactical level*) are designed since they are input for the *operational level* that represents the actual service provided to the passengers. Variability of the actual service (*operational level*) respect to the scheduled one (*strategic-tactical level*) occurs due to the interaction of the operational process with the external environment, this generates service unreliability that impacts badly on customers' service level perception. *In order to increase passengers' level of satisfaction it is necessary to focus at operational level that is where inefficiencies occur and try to mitigate the variability caused by disturbances.*

In this first part we have analyzed the general principles of the reliability's concept and how it is related to variability and unreliability. Now it is necessary to understand and analyze it more in detail.

Concerning service reliability in public transport, both the *supply side* and the *demand side* of the system are important since service unreliability perceived by passengers is caused by the interaction of the two sides.

- ***The supply side*** consists of the service provided by the operator.
- ***The demand side*** is the passenger side including their behavior and experiences.

In order to better understand why the output provided by the process is subjected to such an extent of unreliability and in this way being able to understand how to mitigate it, it is important to analyze in detail the variability coming from the *supply and demand side*.

### Supply side

The public transport system supply side is composed by all the trips performed on the lines along the day. The number of means serving the line and its length determine the frequency of departure offered to the passengers. The frequency determines also the headways among different means that are an aspect to keep in consideration to guarantee a good service level. *Part of the DSS that we will present during this thesis focuses on the generation of suggestions to optimize the regularity of the line hence maintaining regular headways.*

During the *planning phase* the schedule is built in a deterministic way without considering the possible variations that occurs due to the interaction of disturbances with the operational process. In an ideal situation, vehicles depart on time from the terminal and drive perfectly according to the schedule. Unfortunately, deviations and variations of the supply side happen frequently. *Van Oort* identifies two different kinds of variability that can appear at operational side:

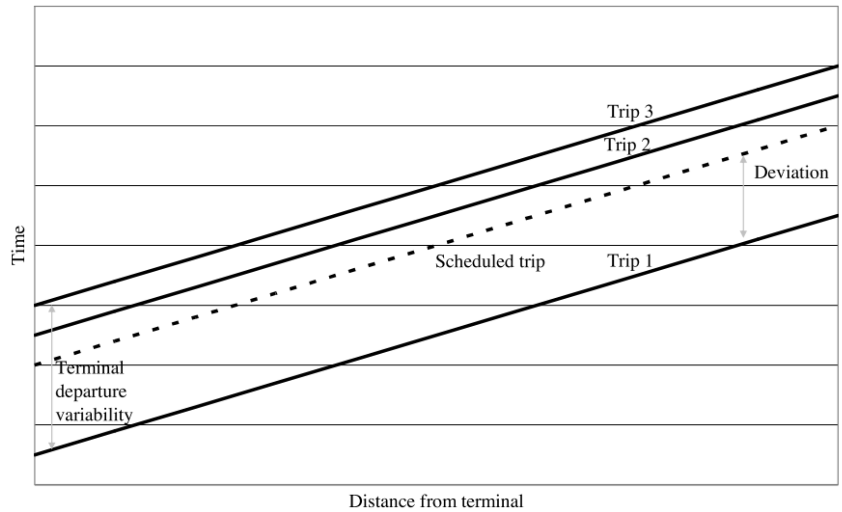
1. ***Terminal departure time variability***: This is the misalignment between the actual and the scheduled departure time at the terminals.

2. ***Vehicle trip time variability***: This is the misalignment between the actual and the scheduled trip times along the route.

It is fundamental at this point understanding in depth how variability works in order to intervene effectively and control it.

1. ***Terminal departure variability***

If we assume that the actual trip is stick to the planned one and the only aspect that varies is the terminal departure time, it is possible to assume a misalignment between actual and scheduled operations as shown in *figure 10.*




*Dotted line represents the scheduled service, straight lines represents actual trips that vary according to the departure time.*

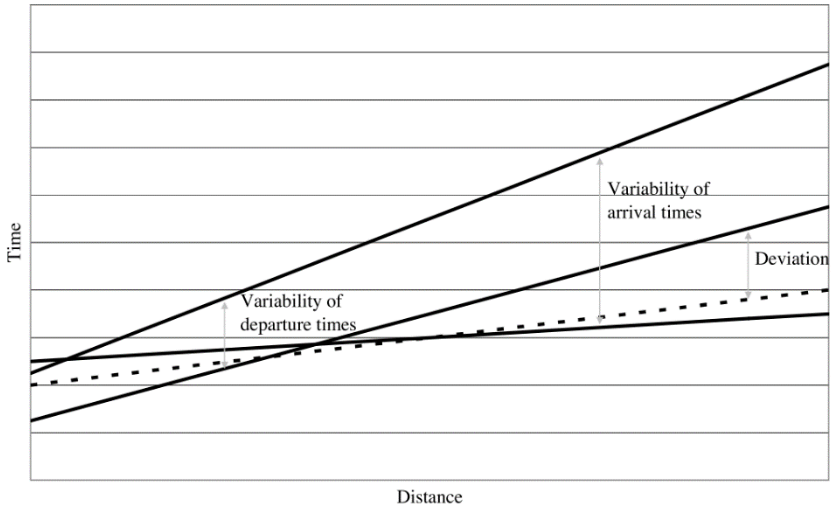
***Figure 10***: *Variability of service causes terminal departure time variability; (Van Oort, 2011).*

2. ***Vehicel trip time variability***

According to Van Oort to describe *trip time variability* it is necessary to consider both *Driving time* and *Dwell times:*

***Driving times*** are composed by the actual driving time that is needed to cover the route between two stops, this time is inclusive of all the unplanned stops during the route that don't generate any boarding or alighting. The unplanned stops are one of the major causes of trip time variability. The length of the line is directly proportional to the trip time variability.

The other part of vehicle trip time is ***dwell time***, which is the time used for boarding and alighting at a stop. This element variability is positively related with the number of stops that there are on a line. *Figure 11* presents the trip time variability considering *the single mean*.




*The dotted line represent the scheduled service, the straight lines represent the actual service. In this case we are considering both variability in departure times and variability in vehicle trip times.*

***Figure 11****: Variability of service: example of variability of departure (at stop n) and arrival times (at stop n+x); (Van Oort, 2011).*

If we consider the *relation among different vehicle*, it is possible to notice that ***headways*** between successive vehicles at stops are not constant as well. The misalignment of headways between different means is shown in *figure 12*.

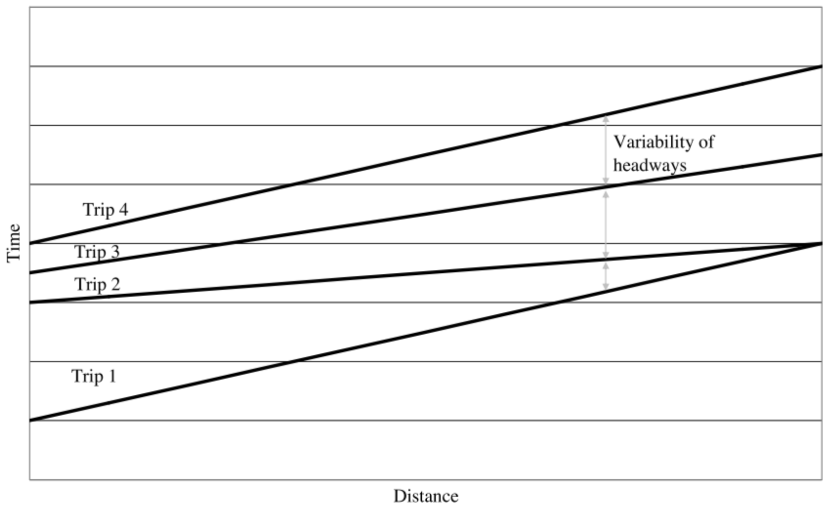



***Figure 12***: Variability of headways between successive trips at diff. stops along the route; (Van Oort 2011).

Now it is important to introduce another concept of extreme importance for the development of this thesis, the ***propagation of variability***. This is a common and harmful aspect that affects public transportation system. <u>*The DSS we are going to present along this research will have also the objective to mitigate the propagation of delay hence variability.*</u> This issue affects service performances principally in two ways:

***a. Propagation of delays at the terminal***. A late arrival at the terminal, if not absorbed by the slack inserted in the scheduled timetable, generates a delay on the successive departure. In this case it is considered only the *single mean*.

***b. Deviation propagation on the line itself***. If trip time variability affects *more than one vehicle* it triggers a mechanism called bouncing. This mechanism brings to dilate headways until it generates queuing between two consecutive vehicles. The mechanism of bunching is illustrated in *figure 13* (*based on Chapman 1978*).

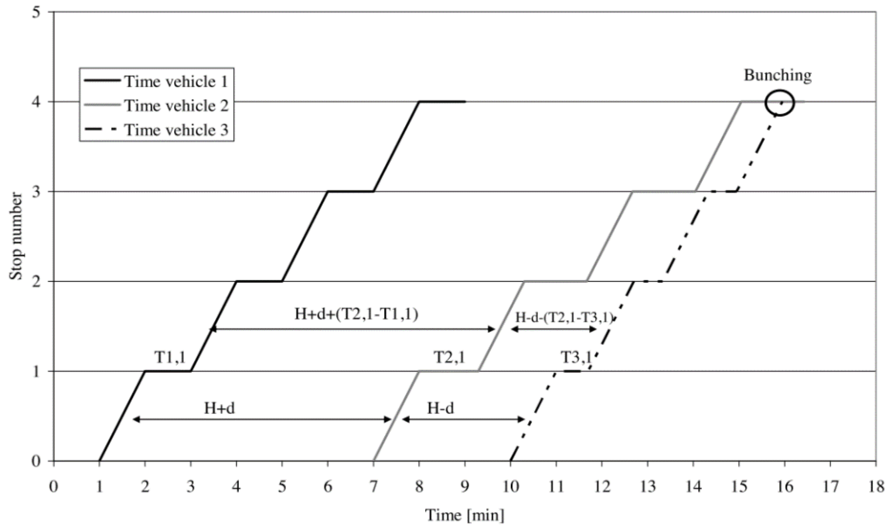



***Figure 13**: Bunching illustrated in a time-space diagram; (Van Oort 2011).*

*Van Oort* explains bouncing as follows: *"If a vehicle suffers from an initial delay (d), the actual headway between this vehicle and its predecessor increases (and will equal the scheduled headway H plus initial deviation d). Due to this longer headway, the number of passenger at the stop, waiting for this vehicle will be increased. Due to this larger number of people, dwell time will be extended (T2,1 >T1,1). The extended dwell time will create even more delay and thus the headway ahead will increase even more (H+d+(T2,1-T1,1)). This process will enforce itself and will lead to larger delays.*

*When we look at the headway between a vehicle and his successor, this mechanism works the other way around. Due to the initial delay, the headway shrinks (H-d) and the number of passengers waiting for the successor will decrease. This enables shorter dwell times (T3,1<T1,1), which decreases the headway even more. This loop will enforce itself as well, resulting in bunched vehicles. The successor will reach the vehicle and they are bunched"* (at stop 4 in *figure 13*).

## Demand side

Now our attention is moved to the demand side, here the subject of the analysis is no more the operations but the passenger. *Figure 14* shows the different components that describe the demand side

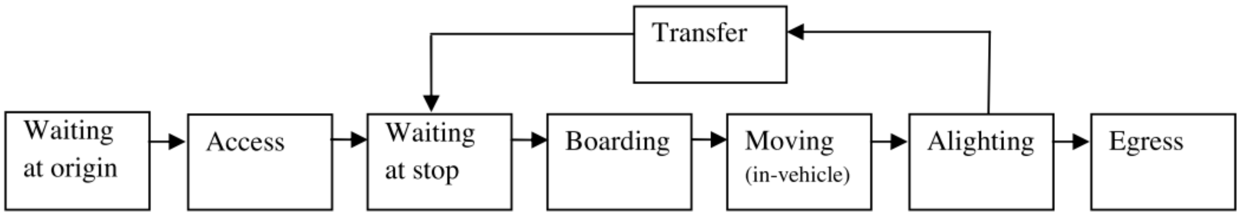



***Figure 14****: Passenger travel time components; (Van Oort 2011).*

- ***Access time****:* This is the time needed to the passenger to get to the departure stop;

- ***Waiting at the stop:*** This is the time that passes between the arrival of the passenger and the departure of the vehicle. Passengers may arrive randomly (*typical behavior adopted by passengers during peak hours → high frequency service*) or they may plan their arrival according to the schedule (*typical behavior adopted by passengers during soft hours → low frequency service*). During the development of this work our attention will go on pick hours, these are the parts of the day in which the highest number of inefficiencies happen, there is the highest demand and the highest frequency of service;

- ***Boarding:*** It is the time needed by the passenger to get on the vehicle once arrived at the stop;

- ***Moving:*** This is the in vehicle time that passes between the boarding and the arrival at the destination stop;

- ***Alighting:*** It is the time that passes between the arrival at the stop and the moment in which the passenger get off the vehicle.

At this point if the passenger needs to get another mean to reach the final destination it enters in a loop that restarts form *waiting at the stop* and finishes when it gets to the *final destination stop.*

- ***Egress:*** It is the time needed to get from the final destination stop to the final destination.

The passenger's travel time components over listed and described generate the ***total travel time of a passenger***. It is important to highlight that in case of transfers, *waiting time* and *in-vehicle time* occur for every service line used and that in addition *transfer time* may arise.
The *expected value of passengers' travel time*, that with the *travel comfort* is one of the two aspects that compose ***service reliability***, is one of the most important drivers that determines the travel choices made by people *(Allin and Wright 1974, Schmöcker and Bell 2002)*.

Now, in order to understand how service variability in the supply side affects passengers' service unreliability perception, it is necessary to relate the elements that generate variability during operation with the passengers' travel time component. This passage is fundamental to understand how the variability of the operational process and the perception of customer service unreliability are connected.

### Variability on travel time components; relation between supply side and demand side

*Van Oort (2011)*, with *figure 15*, shows the relation between the demand side's components and the supply side's components. The graph explains how variability in operations, generated by the interaction between the service and the external disturbances, influences the variability of the customers' expected travel time hence the level of service unreliability.

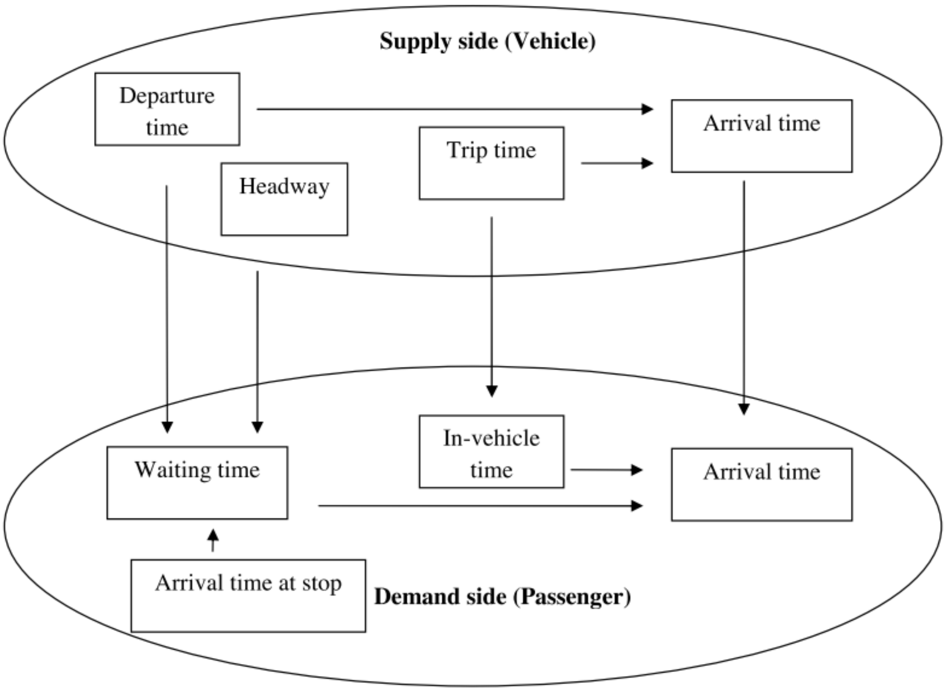



***Figure 15***: *Interaction between demand and supply sides' components; (Van Oort 2011).*

In the graphic are illustrated the different existing relations between demand and supply side. *Passenger waiting time* is determined by *actual headways* and *departure times* of the means (*supply side*) and by the passenger arrival time at the stop (*demand side*). In addition it is possible to notice that passenger in-vehicle time is equal to the trip time. In the end, the arrival time of the means and of the passenger is the same.

The analysis just performed shows and analyzes in detail the relations that there are between supply side's variability and passengers' side unreliability (demand side). *Table.2* recaps the main aspects analyzed in this section.

| ***Production process' variability and unreliability; urban public transport case*** | |
|---|---|
| *Step 1* | Presentation of the general concepts of variability and unreliability in a generic production process following cybernetics' principles. |
| *Step 2* | Contextualization of the concepts presented along step 1 in urban public transport systems. |
| *Step 3* | Analysis on how variability acts at public transport supply side level (Operational level). |
| *Step 4* | Analysis on how variability acts at public transport demand side level (Passenger level). |
| *Step 5* | Relate the components that constitute the supply-demand side. |
| *Objective* | *Description of the concepts of process' variability, reliability and unreliability and their contextualization in the urban traffic transport process* |

***Table 2:*** *Summary table of section "Production process' variability and unreliability; urban public transport case".*

Starting from what obtained up to now it is possible to increase the level of detail of this analysis to understand and describe the relation between service reliability and customer's service level perception.

## *Relation between service variability and customers' service level perception*

In the previous section It has been shown that the level of service reliability is generated by the interaction of the supply side with external disturbances that generate variability in the process hence unreliability for customers. *Now we want to demonstrate the impact of service variability on passengers, with a special focus on travel time reliability and variability to find an available seat*. This passage is fundamental to describe and understand on which aspects of the process we will need to focus on in order to optimize the level of service offered to passengers.

Passengers, due to the variability and the uncertainty of the service offered, experience the two negative effects introduced below *(Noland and Small 1995, Noland and Polak 2002, Van Oort and Van Nes 2004)*. Note that due to the stochastic nature, the impacts on individual passengers may differ from average values.

1. ***Variability of travel time components with consequent impact on trip time duration;***
2. ***Impact on probability of finding a seat and vehicle's crowding level*****,** which affects the level of comfort of the journey.

This demonstrates that the variability of the process lowers sensibly the level of service reliability that passengers experience. This confirms that in order to offer a more appealing service to customers it is necessary to focus on *operational variability mitigation*. Now we will analyze in detail the two aspects just mentioned.

### 1. Variability of travel time components with consequent impact on trip time duration

Passengers are strongly influenced in taking their decision by the travel time that the public transport system offer them. Furthermore the misalignment between the expected travel time (*scheduled service*) and the actual travel time (*actual service performed*) it is one of the main reason that discourage people that live in urban areas to use PTS. At this point it is important to highlight that *irregular transport services* influence both *in-vehicle times* and *waiting times*, now we will explain the reasons.

*Figure 15* shows the presence of a direct connection between the *trip time performed by the vehicle* and the *In-vehicle trip time* of the passenger. This means that if there is variability in the trip time also the passenger will be directly affected.  As we have seen trip time variability triggers bouncing mechanism (*figure 13*), this will result in longer in-vehicle times for a part of the passengers as well as shorter in-vehicle times for other ones. The effect just described is mainly due to the irregularity of headways generated by disturbances that creates turbulence in operations; <u>*from here, it is possible to understand the importance of having a system that will help dispatchers in keeping regular headways between different means.*</u>

An important aspect to consider is that in case of bunching the *average in-vehicle time* and the *average waiting time* at the stop will be extended. More passengers will suffer from the delay than the number of passenger benefiting from the speeding up of the successive vehicle, because the slowest vehicle will collect more passengers (since it will take more time to arrive at the stop there will be an higher number of people waiting for it.)

When passengers arrive randomly at their departure stop and services are regular, *average waiting time per passenger will be equal to half the headway of the departing vehicles (Welding 1957, Osuna and Newell 1972, Heap and Thomas 1976)*. In theory, half of the passengers will have a shorter waiting time and half of them will encounter more.

*However, when headways are irregular, the average waiting time per passenger will increase*. Headways will be both longer and shorter than scheduled, but the number of passengers benefiting from shorter headways will be smaller than the number of suffering from longer headways and longer waiting times.

As analyzed in chapter 2.1.1, service variability produces an increase in the trip time due to an increase in the variability of its components. This is a critical aspect because trip time variability is one of the aspects on which customers care the most (see *figure 6*), so are needed systems and approaches able to mitigate it, in fact this will be one of the main objective of this thesis.

### 2. Impact on probability of finding a seat and vehicle's crowding level.

Public transportation's vehicle trip variability not only increases the passenger trip time but it also decreases the travel comfort of the passenger.  The variability generates irregular headways that triggers bouncing mechanism. This brings some vehicle to be almost empty and others to be overcrowded, in the second case the passengers are obliged to travel in uncomfortable conditions since it is difficult to find a seat and in the worse cases it is also impossible to get on the mean because there is no room available inside it.

*Van Oort* (*2011*) illustrates this mechanism in *figure 16*. A similar problem can be generated also if a departure is canceled because the successive vehicle will have to load a higher amount of people than normally expected. In the end there are other two aspects that it is important to highlight:

1. *Crowded vehicles are one of the causes/effects that increase the headways irregularity and produce vehicle queuing;*

2. *Crowding is one of the aspect that affects the most the dwell time variability, so it increases also trip time variability*.

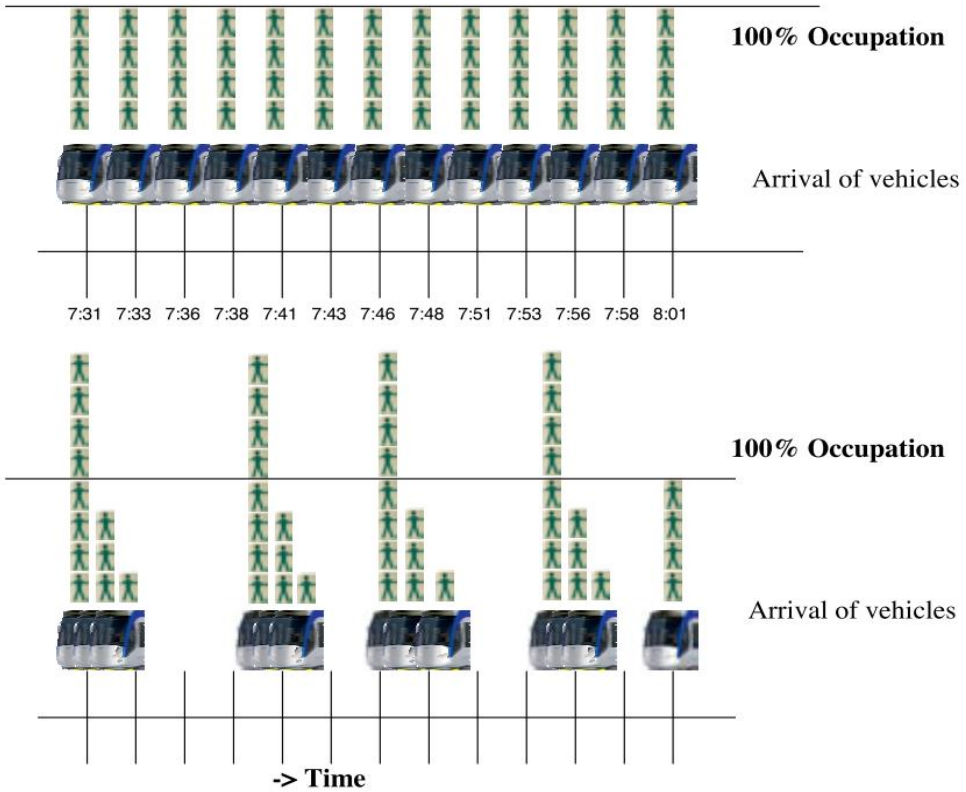



***Figure 16***: *Distribution of passengers in case of regular headways (upper part) and in case of irregular headways (lower part); (Van Oort 2011).*

Concerning to what we have seen up to now the level of service variability affects negatively passengers in different ways. This fact decreases public transportation attractiveness, especially if we consider the relative attractiveness compared to other travel options that can be for example private means.

A low level of service reliability affects also the appreciation of public transport in general. A low level of service damages the image of the public transport system, which may determine a future further decrease in the use of PT services.

The extension of average travel time, the variability of travel time and the decrease of the travel level of comfort may all lead to changes in passengers' choice behavior that can decide to change modality of transport because not satisfied by the service offered.

What just said highlights the potentiality to gain customer consensus improving service reliability. *Vrije* claims that people are likely to change their mode of transport in case of changes in the level of service reliability. *Table 3* shows the results of his researches, looking at the figure presented under it is possible to claim that service unreliability (*expressed as standard deviation of travel time*) has a great impact on the mode choice of travelers. Especially occasional travelers seem to be very sensitive to changes in unreliability. From the results coming from this research it is possible to see that an eventual decrease of trip time reliability it can have devastating effects on the passenger's appreciation of public transport services

| | *Regular travelers* | *Occasional travelers* | *Non trevelers* |
|---|---|---|---|
| *Decrease of unreliability* | 9%[1] | 22%[1] | 9%[1] |
| *Increase of unreliability* | 17%[1] | 44%[2] | - |

*$X^1$:Part of travelers that will travel more often by public transport.*

*$X^2$:Part of travelers that will travel less often by public transport.*

***Table 3**: Effect of change in unreliability in the mode of transport.*

*Table 4* recaps the main aspects analyzed in this section.

| ***Relation between service variability and customers' service level perception.*** | |
|---|---|
| *Step 1* | Analysis of the impact generated by variability on travel time duration (trip time + waiting time) |
| *Step 2* | Analysis of the impact generated by service variability on passengers' travel comfort |
| *Step 3* | Analysis of the sensibility of passengers in relation to the extent of service unreliability |
| *Objective* | *Analysis of the discomforts generated to customer due to service variability* |

***Table 4**: Summary table of "Relation between service variability and customers' service level perception".*

## *Causes of service variability and unreliability*

In the first part of the literary review we have introduced the situation in which the public transport has to operate. First describing the mobility trends expected for the future then analyzing the customer sources of value focusing particularly on the service reliability that is the quality aspect on which passengers care the most. Now that are well known the aspects that need to be improved in order to have a considerable leap in the quality of the service offered by public transport companies (*where to intervene*) it is important to understand which are the causes that generate inefficiencies (*how to intervene*).

As we have seen previously there are two main types of service variability:

1. ***Departure variability***

2. ***Trip time variability***
    a. *variability in driving time;*
    b. *variability in stopping time;*
    c. *variability in dwelling time.*

Several causes are responsible for deviations and variability, now it is fundamental identify and analyze all of them in order to understand how to intervene in order to reduce in the end service unreliability. First it is necessary to distinguish if they are *internal* or *external*, this fact determine the possibility for operators and public transport authorities to deal with them. In order to identify the causes it is necessary to analyze the literary review concerning the relation between planning, operations and service reliability offered *(Nelson and O'Neill 2000, Cham and Wilson 2006, Veisseth et al. 2007). Figure 17* summarizes the relation between trip time variability, internal causes and external causes***.*** The graphic shows the main causes of service variability and indicates which elements of the trip time variability are affected.

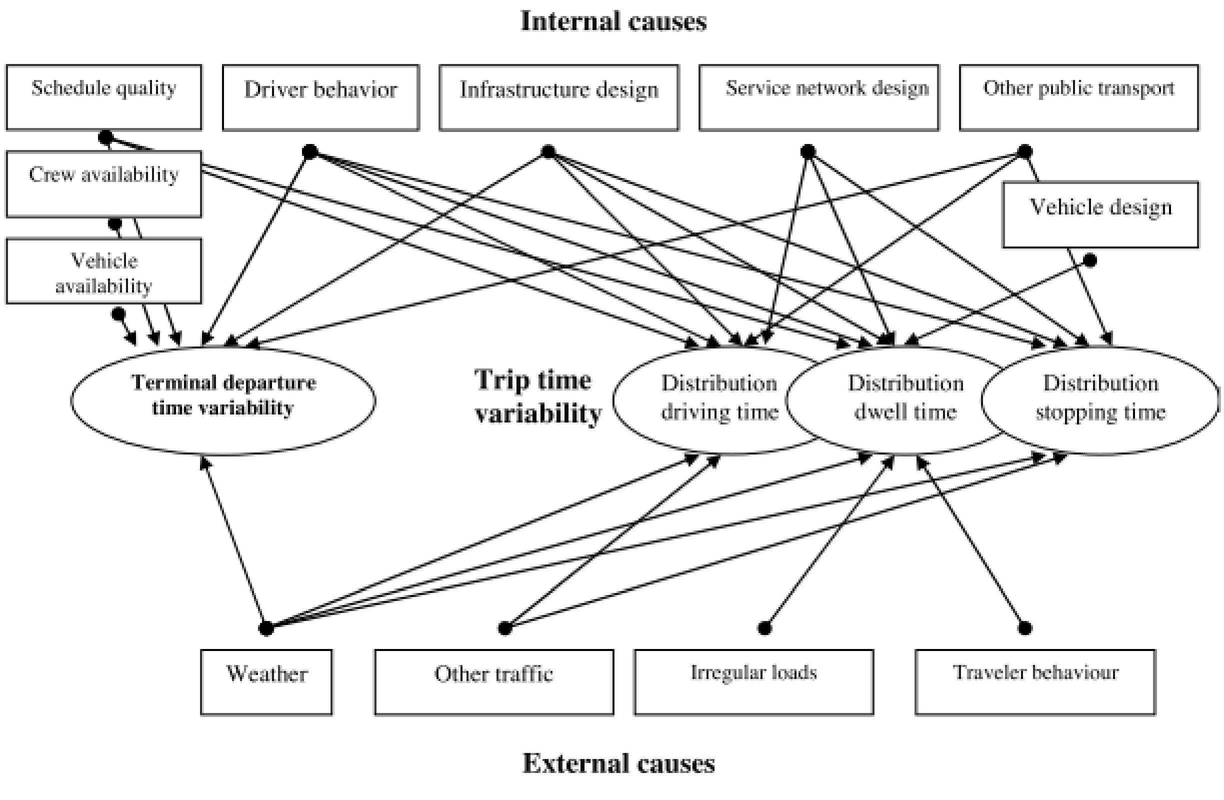



***Figure 17:*** *Main causes of service variability in urban public transport.*

Now we will analyzed in detail the causes that generates ***terminal departure time variability*** and the ***trip time variability*** *(driving time + dwell time +stopping time)*. We will make a distinction between internal and external causes in order to better identify on which arears focus to make the DMSS an effective tool.

## Causes of terminal departure time variability

As seen previously departure variability can generate a misalignment between actual and scheduled operation that produces trip time variability for the passenger hence a decrease of the service reliability offered. Now let us focus on the causes that leads to the generation of this particular variability:

***Internal causes:***

- *Crew availability*: This is a necessary resource to guarantee an on time departure. An important aspect to consider is the possibility of delay propagation, if a driver arrives late at the change stop the driver that has to start his duty inherit the delay of the first one.

- *Vehicle availability*: As for crew availability the vehicle have to be ready to depart otherwise it generates a delay in the departure. Delayed departures can be spread on more means if there are failures in the loop mechanism to turn vehicles or there is traffic congestion at the terminal.

- *Terminal infrastructure configuration:* In case of errors in the infrastructure design (*insufficient capacity)* delays have to be expected due to traffic congestions that can be easily generated and that make the departure process slower. In this case and in presence of a tight schedule with high frequency, it is very easy to spread departure delays among different means (*Kaas and Jacobsen 2008*).

- *Schedule quality:* If the schedule is loose (too much trip time in the schedule than actually needed), drivers tend to depart late (depending on their attitude and driving style). The other way around a tight schedule leads to an early departure. Another issue of schedule quality is the amount of slack planned; it determines the possibility to recover from an arrival delay.

- *Driver behavior:* How a driver adjusts his departure time if delays are expected (e.g. in case of road works).

*In dealing with variability propagation the arrival of the precedent trip at the terminus is fundamental*. If vehicles tend to arrive late and the slack is minimized, departures will be delayed as well. Since this aspect it is so fundamental in order to provide a regular service we will focus a lot in order to mitigate this aspect

## Causes of trip time variability

Trip time variability is one of the elements that has the highest impact in reduction of service reliability. Now we will describe the causes that contribute in generating this kind of variability in order to understand which are the aspects on which we have to focus to make the decision support system that we want to create a useful tool. To do this it is necessary to distinguish between internal causes and external causes. This distinction is needed to clarify if the variability are generated by internal inefficiencies or by the interaction between the process and external disturbances.

Trip time variability can be divided into three components:

1. ***Driving time;***
2. ***Stopping time;***
3. ***Dwelling time.***

*Shelby, 2001* studied which are the aspects that influence the variability of trip time. He says that not only the length of the line but also the number of intersections passed, the number of stops along the line and the number of vehicles that serve it in relation with the frequency are factors that strongly influence operation's performances hence the service quality offered to the passengers

Now we will consider the trip time components individually, this will allow us to analyze in detail the vehicle trip process and it will give us the possibility to gain insights into the causes of total trip time variability.

***Driving time + Stopping time (1;2)***

The first process analyzed is the ***driving between stops***, including accelerating, braking and unplanned stopping. Since the causes of ***stopping*** may also be responsible for slowing down vehicles these two components can be treated uniquely. The *causes presented below are responsible for actual driving time and stopping time variability*.

***Internal causes:***

- *Driver behavior*: Drivers' driving style affect the variability of the trip time, because there are drivers that drive faster and other ones that tend be slower. The driving style influences also the approach in presence of slowing down or in case of completely stop.

- *Other public transport*: Both on the same route as on junctions, other public transport may affect the driving and stopping time variability. In case of signalized sections this influence is most of time even larger, especially when frequencies are close to the theoretical capacity of the system. The probability of delays will then increase, also resulting in service variability (*Goverde et al. 2001, Van Oort and Van Nes 2009a, Landex and Kaas 2009*).

- *Infrastructure configuration*: The infrastructure design (stops, junctions, lanes, crossings) is another aspect that strongly influences the trip time variability. We have to consider that the public transport has to operate in an environment in which the external factors that influence its variability (e.g. traffic) are constant, so the infrastructure configuration is an important aspect that can strongly influence the level of service reliability.

- *Service network configuration*: The configuration of the service network may be of influence on service variability. Examples are the number of lines or stops on the same route and the length of lines.

- *Schedule quality*: It is an aspect that strongly influences drivers' behavior and generates variability. A tight schedule can have different influences on drivers. On one hand there are drivers that feel the pressure and want to follow the schedule so they drive faster on the other hand there are drivers that do not change their driving style and are more focused on safety. The difference of reactions increase line irregularity, hence variability.

***External causes:***

- *Other traffic*: This is one of the main causes of service variability and unreliability because public transport's companies do not have any control on it. Furthermore the traffic gets worse during pick hours when there is the highest frequency of the service and the highest demand so the possibility to increase the variability is very high.

- *Weather conditions:* Different kinds of weather and the different driver behavior accordingly may result in variability (*Hofmann and Mahony 2005*). This mainly occurs when the weather is not in the regular state.

***<u>Dwell time (3)</u>***

As mentioned before *dwell time variability* is an important factor that generates service variability and unreliability. Having long lines with many stops are two factors that increase the impact of this element on service reliability.

According to what presented in *figure 17*, it is possible to distinguish the following causes for dwell time variability :

***Internal causes:***

- *Driver behavior*: It influences also the dwelling time. The speed with which it opens and closes the doors, the use to wait late arriving passengers and the approach used to brake and to accelerate to get back on the line are aspects that increase service variability.

- *Vehicle design:* The number and position of vehicles' doors influence the dwell process, a good design generate a positive influence on service reliability (*Weidmann 1995, Lee 2008 and Fernandez 2010*). Vehicles and platforms that facilitate the boarding and the alighting of passengers allow saving a lot of time because they enable people to do the process faster. The variability of the service generated by a sub-optimal design is higher during pick hours (many people waiting at the stops and crowded vehicle). On the other way around a good design can help in keeping a good service level.

- *Platform design*: The platform design affects the variability of dwell times by affecting the passenger behavior. The design leads the distribution of passengers over the platform enabling an optimal dwell process. Width, length, location of sheds and other facilities are important elements and in case of sub-optimal design, variability may arise.

***External causes:***

- *Passenger behavior:* Several types of passengers have different boarding speeds (speed differs for instance due to age, experience, luggage) resulting in variability in dwell times. In any case this aspect is strongly related to the platform and to the vehicle design that influence the behavior of passengers during dwelling process. A platform and a vehicle that facilitate people with difficulties in movement can save time that otherwise would impact on service variability.

- *Irregular loads:* The elimination of a ride and irregular headways can generate irregular loads. Naturally, the dwell time has a positive relation with the number of people that have to board and to alight. Due to these reasons irregular loads increase trip time variability.

In this analysis we have presented the main causes of service variability categorized by ***terminal departure variability*** and ***trip time variability*** considering both internal and the external causes. Now it is possible to say that the main internal causes are *vehicle availability, crew availability and other public transport* while the external causes are the *other traffic, irregular loads and passenger behavior*. *Table 5* recaps the main aspects analyzed in this section.

| ***Causes of service variability and unreliability*** | |
|---|---|
| *Step 1* | Analysis of causes (*internal*) that generate *terminal departure variability* hence service unreliability |
| *Step 2* | Analysis of the causes (*Internal-external)* that generate *trip time variability* (*driving time, stopping time, dwell time)* hence service unreliability |
| *Objective* | *In detail understanding on how the different causes of variability interact with the process in order to have an initial idea on how to intervene to improve the reliability of the process.* |

***Table 5****:* Summary table of “causes of service variability and unreliability”.

### *Critical conclusions summary*

Along *chapter 2.1.2* we have analyzed in detail process/service reliability, variability and unreliability. In a generic system variability is due to the interaction of disturbances with the process that as consequence deviate from what scheduled, when the misalignment between actual and planned performance is too high variability of the process results in unreliability. The same principles can be applied in the public transportation system, we have disturbances/disruption events that interact with the service offered to customers generating variability that, overtaken a certain extent, becomes service unreliability for passengers that experience a lowering of service quality level. *Figure 18* resumes the concepts of service reliability, variability and unreliability in urban public transport systems.

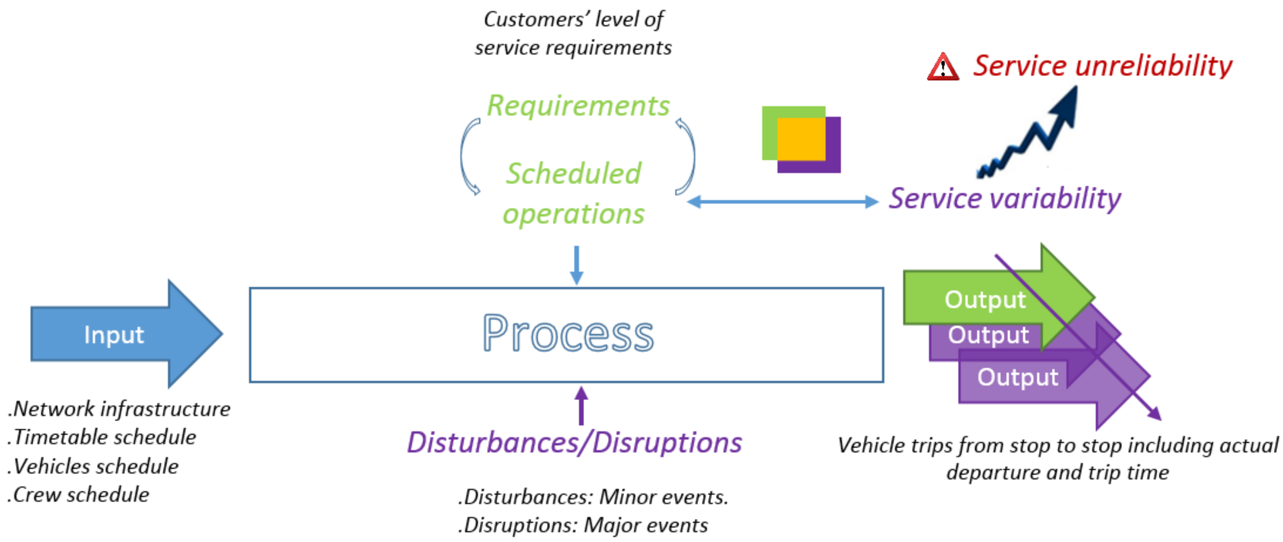



***Figure 18***: *Scheme that shows the concept of service reliability, variability and unreliability in UPTS.*

To understand better how all of this process works in public transport we have analyzed the ***supply side*** (*service provided by the operator*), the ***demand side*** (*passenger side*) and the interactions among them because unreliability of the service perceived by passengers is the results of the interactions between the two sides.

On the *supply side* we have principally two types of service variability:

3. *Terminal departure variability;*
4. *Vehicle trip time variability (driving time + stopping time + dwell time).*

We have discovered that two aspects that are cause and effect of the variability of these two components are the *propagation of delays* and headway irregularity that, among others, trigger the bouncing effect that in the end brings to queuing between different means.

While, concerning the *demand side*, after having analyzed the entire passenger travel process, we have found the existence of a strict relation between the variance of the expected value of passengers' travel time and the level of service reliability perceived by them.

In the end relating the two sides, we have identified and analyzed the links that there are between variability in the operations and the service unreliability perceived by passengers. A conclusion is that having an irregular line (irregular headways) is one of the main causes of service unreliability for passengers because it increases their expected travel time and decreases their level of comfort (the two most important quality aspects for customers). Another aspect to take care of is the propagation of delays that is also a main cause of variability of the service hence unreliability for customers. <u>*Two main objectives of the DSS that will be proposed in this thesis are the maximization of line regularity and minimization of delay propagation*</u>.

Once identified which are the main aspects that lower the level of service reliability we focused our attention on the causes that generates them making a distinction between *terminal departure time-trip time variability* and *internal-external causes*. What found in the end is that the main internal causes are *vehicle availability, crew availability and other public transport* while concerning external causes we have identified *other traffic, irregular loads and passenger behavior*.

All the material analyzed along this chapter taught us that the main aspects to enhance in order to provide to passenger a service that meets their expectations are *the level of the expected trip time'* and a *good level of comfort.* These aspects are heavily influenced by *"headway irregularity"* and "*delay propagation*" that are generated mainly by problems with *vehicle availability, crew availability and other public transport.* Now we know which are the aspects on which intervene for improving customers' satisfaction.

### 2.1.3 Disruption management; UPTS current approaches, criticalities and limitations.

In chapters 2.1.1 and 2.1.2 we have described the situation in which the urban public transport systems (UPTS) operate defining and analyzing all the different causes that contribute increasing the variability of the service offered. Now the Focus is shifted on the *disruption management* and *rescheduling* that are the approaches (operational level) used by transportation companies to manage disturbances and disruption events that affect the quality and reliability of outputs. The structure of this chapter is shown in *figure 19.*

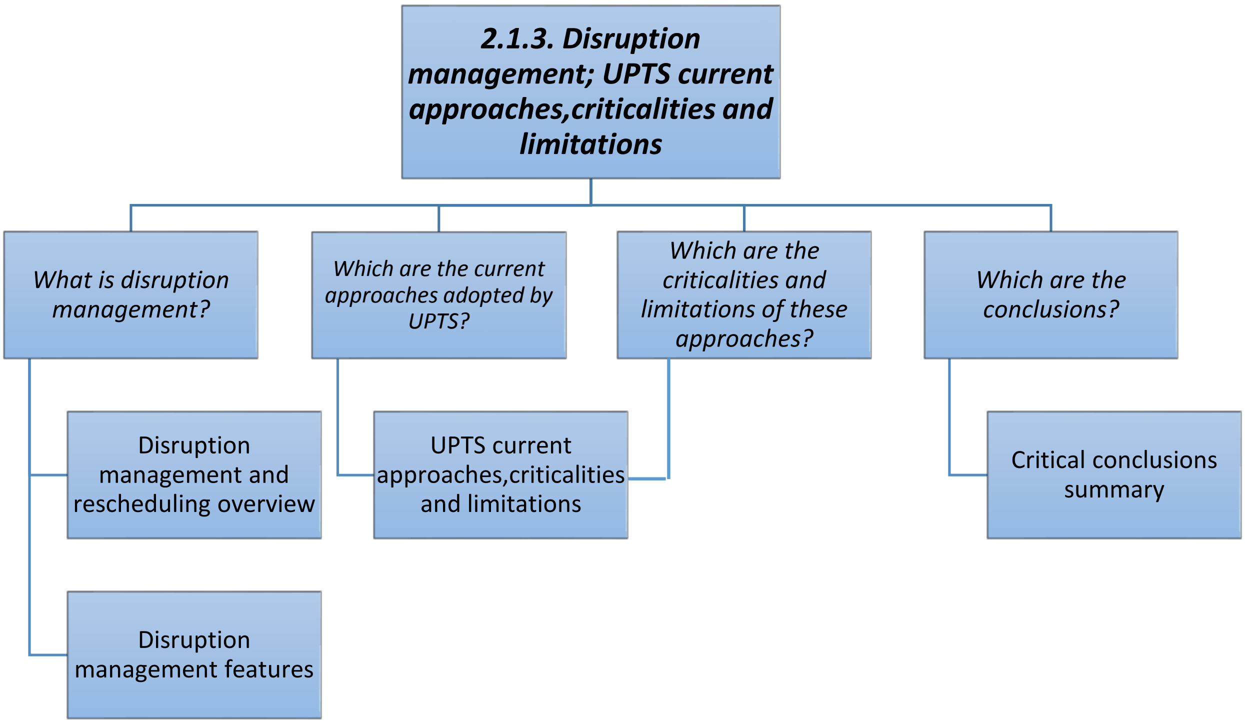



***Figure 19***: *Chapter 2.1.3 structure.*

#### *Disruption management and rescheduling overview*

Let us start this section introducing the concept of *rescheduling: "Rescheduling is the task of adapting an existing schedule to a modified situation." (Lars Nielsen 2011)*

Naturally, two questions rise from this definition; first, *what is a modified situation*? And second, *when is rescheduling preferable over pure scheduling*?

*For the first question* we define a modified situation as a change in the system for which the existing schedule was planned; the change makes the existing schedule either infeasible or suboptimal.

One or more of the following properties may characterize the modified situation:

- a *change in availability of resources or infrastructure*;
- a *change in demand*;
- a *change in the system environment*.

*For the second question* we note that there is no strict consensus on when rescheduling is preferred over pure scheduling, but we give a number of informal reasons that explain why a problem should be considered a rescheduling problem rather than a scheduling problem:

- The existing schedule is feasible (or even optimal) for most, but not all, of the modified situation. If the modified situation concerns a geographically or temporally restricted modification we may want to limit our response to the affected parts of the schedule only.

- There is only limited time available for creating a new schedule. If the problem exists in a time-critical environment, we may want to limit our efforts to rescheduling the subset of resources that cause infeasibilities.

- There may be costs associated with deviating from of the existing schedule. In order to be more efficient as possible the final choice might be tackle the problem rescheduling rather than make a schedule from scratch.

The rescheduling problem studied in this thesis is referred to public transportation system *(urban areas)* management problem and it is the problem of rescheduling an existing schedule to a modified situation dictates by disturbances that affect the process and create variability in the level of output hence discomfort for passengers that are unhappy with the service.

The execution of public transport operations involves monitoring the positions and movements of all resources, and reacting to any unexpected deviations from the plans. Deviations from the operational plans may require *rescheduling* of some resources.

Naturally, some deviations are more serious than others. In practice, there is a distinction between minor and major incidents. *Minor incidents are called disturbances and major incidents are called disruptions*. The distinction is purely practical and not well defined, but it depends on the impact on the operations. As a rule of thumb, ***disruptions*** require significant changes of the pre-set resource schedules, a ***disturbance*** is an event that causes part of the operations to deviate from the operational plans.

For example, at a station the boarding of passengers may take longer than planned for a certain mean leading to a delay in departure. Disturbances are usually absorbed by the slack in the system or can be handled by small changes to the resource allocation.

More serious incidents are known as disruptions and these incur major deviations from the planned operations. Disruptions may be caused by various internal or external factors such as a faulty switch on a busy track, broken down vehicle, or damaged overhead wires. Disruptions generally cause serious timetable changes where several departures are canceled or rerouted. The timetable changes invalidate the planned resource schedules so they will have to be updated to take the actual situation into account.

*"**Disruption management** refers to the process of dynamically revising an operational plan to obtain a new one that reflects the objectives and constraints of the actual situation* (*see Yu and Qi (2004)*)". Disruption management refers to the task of adapting the three main entities, the *timetable*, the *vehicle in circulation* and the *crew schedules*, to the actual situation.

When there are problems, it is necessary to intervene at operational level in order to bring back stability in the system, when destabilizing events occur the disruption management process starts. When a problem is detected the following three steps are necessary to recover the situation. Each step is related to updating one of the three mentioned entities (*timetable, the means circulation and the crew schedule*).

In the ***first step***, the *timetable* is updated by canceling or changing means departure. Depending on the nature of the disruption, dispatchers manually (this is a great limitations) decide which services are affected by the disruption and update the timetable accordingly.

In the ***second step***, the *vehicle schedules* are adapted to serve the updated timetable. The vehicle circulation has to be updated to conform to the actual situation while fulfilling a number of operational constraints. It is generally a goal in this process to minimize the changes from the existing plans.

In the ***third step***, the *crew schedules* are updated so that the correct number of qualified drivers and conductors are assigned to each vehicle in the updated timetable. The Crew Rescheduling Problem is subject to a number of constraints as crews are entitled to breaks, there are limitations on the allowed length of duties and crews have to get back to their crew bases at the end of their duties.

The proposed changes to the crew schedules are negotiated with the affected crews to ensure they can be realized in practice.

The three steps are interdependent in the sense that if it is not possible to assign vehicle or crew in the second or third step the timetable from the first step may have to be revised again. Furthermore, the process takes place in a dynamic environment that continuously affects the available options in the process.

## *Disruption management features*

A disruption in a public transport system, as described previously, is an event or a series of events caused by external or internal factors that leads to substantial deviations from planned operations. In either case, new restrictions are imposed on the system. These restrictions may involve resources, infrastructure components or both. Now the focus moves to two aspects that aim at describing a disruption in a more detailed way:

1. *Characteristics of the impact generated by disruptions;*
2. *Disruption's extent of uncertainty.*

### 1. Characteristics of the Impact generated by disruptions

Regardless of the cause of a disruption it has an impact on the PT system. That impact is generally in the form of a change in the system settings, a change in resource availability, or both. We here discuss some overall aspects of the impact of disruptions.

A disruption may cause a ***change in the environment*** in which the system operates. The effect may be decreased maximum speed of vehicle or even prevent vehicle from running on certain parts of the network. Closing a stop temporarily is another example of a change in the system environment that affects the system's ability to operate.

Disruptions may also involve a ***change in resource availability***. This is the case when vehicle breaks down or when crew calls in sick. The response to a change in resource availability is to re-plan the current operations applying only the available resources that may include giving up some of the planned services. A change in the availability of resources may be the cause of the disruption or a consequence of the disruption.

As mentioned, the disruption may indeed be caused by vehicle breakdowns, or a lack of crew, or a blockage may prevent vehicle and crew from being at the right place. Additionally, some resources may be taken out of service to undergo preventive maintenance or to build up a buffer of additional resources for an upcoming event. For example, some vehicle may be removed from circulation if a snowstorm is expected to ensure that certain amounts of functional vehicles are available when the weather conditions have settled.

Another important aspect that have to be taken into account is the ***unpredictability of events*** that leads to a disruption, and when an event is anticipated the consequences are even harder to forecast. Some events are completely spontaneous and strike without warning. This is generally the case with collisions with other traffic. Other events are predictable to a certain extent such as adverse weather conditions. Another example is during a flu epidemic where a given share of the population is sick. Then we would expect a similar share of the personnel to be sick too. However, the exact shortage of staff is not known beforehand as well as whether. The sick share of the personnel may also include key personnel that cannot be replaced on the short term.

In the end the ***decision making process*** associated with disruption management exists in a ***time-critical environment***. After the occurrence of a disruption, the first decisions on how to adapt the system must be made within a few minutes.

It is very important to be reactive in this kind of situation because with the passing of the time also the magnitude of the disruption increase affecting other lines until it is reached the complete blockage of the system. Time is critical in this kind of situation, but it is important to understand that another crucial issue is the restoration of service stability after that the critical event has been solved (the lines interested are still deviate). In order to accomplish this objective it is necessary to intervene on the three elements mentioned before to bring back the line close to its equilibrium (constant headways between consecutive means.)

## 2.Disruption's extent of uncertainty.

One of the main features of disruptions is the related ***uncertainty***. We have already mentioned uncertainty, namely the unpredictability of the events that lead to disruptions. In addition, the uncertainty of the impact is an important characteristics of the disruption.

Generally it ***is difficult, if not impossible, to forecast the exact impact of a disruption*** when it occurs. However, for some localized disruptions it is possible to know from experience what are the likely outcomes of the situation.

Consider the example of a *failing switch at a busy railway node*. First, a problem with the switch is detected. Then, a repair crew is dispatched to assess the state of the problem and repair it. When assessing the damage the repair crew determines how much time is needed before the switch is again functional. However, this estimate of the time needed for repair may be given as an interval such as two to four hours, adding uncertainty to the situation.

Another example is the *occurrence of accidents*. In such an event, the police must conduct an investigation. Independently of the outcome of the investigation the involved infrastructure is blocked for an uncertain amount of time. From experience the operators know the relation between the length of a blockage and its repercussions on the line, but since the amount of time it is not know in advance also the extent of the repercussion is uncertain.

In addition to the uncertainty of the impact of the disruption ***some details of the state of the system may be uncertain*** as well. For example, exact information on the positions of all vehicles and crew may not be available in real time. Also, since traffic control and vehicle dispatching are conducted by different operators the intention of each dispatcher may not be clear to the others. This is largely due to the locality of information or even miscommunication. In recent years the introduction of new applications have enhanced dispatchers' coordination.

In the end it is also important to consider the ***uncertainty related to available countermeasures***, in a disrupted situation the dispatchers attempt to react for stabilizing the line. However, any decisions on changes to the pre-set allocation of resources have to be implemented in practice by the involved personnel. But the dispatcher may not have full information on personnel and vehicles availability. A dispatcher may come up with a possible solution to the problem that seems elegant, but he may not know if it is implementable. Fully evaluating all options manually during a disruption event is time consuming and therefore generally not possible.

Literature does not show cases in which disruption management has been applied in urban public transport systems (UPTSs) that operate in urban areas. The reason why this kind of approach has not been experimented yet is the level of complexity that characterizes the environment in which PTSs has to operate. Other industries such as ***airline industry*** and ***railway industry*** have studied this issue for years, but we have to consider that they operate in an environment with a lower extent of uncertainty respect to the UPT one. Let us think about a modern city in which heavy traffic, accidents, road traffic, road maintenance (ordinary/extraordinary) and maybe also an inadequate infrastructure to sustain heavy traffic streams are constant variables of the system, all these aspects affect heavily the operations' quality that is lowered due to the high level of unreliability and uncertainty.

Thanks to experience gained during the internship done at ATM S.p.A. and to the support of professors and researchers of TU Delft specialized on public transport issues we have been able to describe the current disruption management approaches adopted by urban public transport companies identifying their main criticalities/limitations.

## *UPTS current approaches, criticalities and limitations*

In urban public transport system the operation is the service that is carried out to passengers and allows them to move inside the urban area, it is the implementation in the reality of the scheduled time tables defined in the design phase (tactical *level*). *Van Oort (2011)* summarizes the characteristics of this level in *table 6,* after we will explain more in detail the concepts mentioned in the table.

| *Level* | *Time window* | *Input* | *Output* | *Actors* |
|---|---|---|---|---|
| - Operations | - Days-Real time | - Network<br>- Schedules<br>- Available crew<br>- Available fleet | Public transport service (*actual trips in time and space*) | - Passengers<br>- Drivers<br>- Dispatchers |

***Table 6:*** *Public transportation operational level characteristics; Van Oort 2011).*

The operation is the actual service that is provided to the customer, it is a real time process that operates in a variable and unpredictable environment. Due to this, dispatchers strive in order to make actual operations as close as possible to what defined in the scheduled time table. They control the service of part of the network (*10-15 lines*) having the possibility to adjust the operations if deviations occur. Recent developments enable better communications between dispatchers and drivers in addition to real-time monitoring tools (*Van Oort and Van Nes 2009a*) even if the process to tackle and mitigate output variability is still principally manual. Operational level is fundamental because it is the product that passengers evaluate and buy, for this reason it is important to offer a service that meets passengers' expectations because it is based on their experience that they choose the modality of transport to adopt. If the final objective of public transport companies is to increase customer retention and acquisition it is fundamental to invest to offer high-quality service.

In literature it is possible to find different studies that aim at monitoring the service level and customer satisfaction (enabling reporting and optimizations of the operations). It is possible to distinguish two main type of measurements and surveys that are conducted at the operational level:

1. ***Supply monitoring***:
   *Muller and Furth (2001)* and *Strathman (2002)* describe and analyze in their researches the use of *Automated vehicle location system (AVL)* that generates *activity vehicle monitoring data* (AVM). This technology consists in a computer in the vehicle that registers all the activities performed by the mean during its service and sends this information to the central

control room where it is saved in DBs. The dispatchers use this data to control the level of lines' performances and they intervene when notice that the service level is getting lower. Furthermore this data is used by authorities to check if the quality of the service performed respects the parameters set during contractual phase, and according to them are assigned to transportation companies prizes or penalties.

2. ***Customer satisfaction***

   Once measured the performances of the line it is important to relate them with the passengers' satisfaction. It is important to inquire the passenger in order to understand how they perceive the service offered in order to understand where to intervene for increasing customer experience and satisfaction. Through these surveys it has been found that there are more aspects on which customer care besides punctuality as *tidiness, safety and comfort*. And it is thank to this information that during last years have been done a lot of researches about quality aspects evaluated important by passengers (*Brons and Retvel 2007; see chapter 2.1.1)* . In fact, one of the main characteristics of our support system will be a constant attention for all the quality aspects considered valuable by passengers.

Besides customer satisfaction, surveys are used to find out how many passengers travel on each link (manually or automatic, using Automated Passenger Counters (APC)) and what the origins and destinations are. The results of these surveys are useful to optimize both strategic, tactical and operational design and service*. Furthermore, we will use the historical data coming from the APC in order to build a set of additional information. It will have the aim to help dispatchers in understanding what is the real impact generated on passengers by the application of certain kind of operational instruments that will be defined "critical" because they have side effects on passengers.* *Drivers* and *dispatchers* have a fundamental role at operational level, because they are the one that have the power to intervene and mitigate the disturbances that interact with the service offered that increase the unreliability hence the quality of the service offered to the customers. Looking at the entire picture it is possible to say that also the interaction of the passengers with the process has a relevant effect on the fluctuations of service reliability offered (see chapter 2.1.2). Passengers have to be considered as external disturbances, but transport companies have the possibility to mitigate the variability that they produce. An example is the fact that is possible to reduce variability of dwell time caused by passenger optimizing the design of transportation means (position and numbers of doors) and the design of the stops' platforms (length, width, positioning of the shelters).

Now that we have a general idea on how the operational monitoring process is carried-out we want to analyze more in detail the different methods used by dispatchers in order to understand where are the inefficiencies that make the current control process not efficient and effective as it should be. We have identified five main area of improvement:

1. *Decision taken manually;*
2. *Not critical usage of operational instruments;*
3. *Reactive approach;*
4. *Narrow-short sight approach in solving disturbances;*
5. *Stiff structure focus on punctuality.*

In the continuation of this section we will perform an in depth analysis on each of them.

### 1. Decision taken manually

The monitoring and control process is carried out manually and no decision support system are given to the dispatchers to facilitate their work. They use their experience to solve critical situations.

An important aspect to stress is that operating manually is impossible to consider all the thousands of variables that are involved when there are criticalities on the line and consequently the actions taken to tackle them is usually not the optimal one. This kind of approach have ***three main disadvantages:***

1. *The quality of the decision vary accordingly to the experience and to the capability of the dispatchers*;

2. *The quality of the decision cannot be considered sufficient since a manual process deny the possibility to consider all the variables in the systems;*

3. *The operators are not able to identify the degradation of the system performances caused by disturbances. This process is very difficult/impossible to detect without the help of a support system because it is slow and degenerates suddenly during change hours.*

## 2. Not critical usage of operational instruments

Dispatchers have at disposition different instruments to recover an inefficient situation on the line *(see table 7).* All the operational instruments will be analyzed and described in detail in *chapter 2.2.2*.

| ***Operational instruments*** |
|---|
| *Skipping stops* |
| *Deadheading* |
| *Headway control* |
| *Speeding-up* |
| *Slowing-down* |
| *Detours* |
| *Short turning* |
| *Vehicle holding* |

***Table 7:*** *Operational instruments currently in use by control room operators.*

Currently operators consider in the same way all the operational instruments (OIs). The problem is that they should take into account that certain instruments, even if they have a high power in solving inefficiencies, hide side effects since impact negatively also on passengers. This highlight the need to understand which is the impact on different passengers' quality aspects (decisional drivers) generated by the implementation of the different OIs, in this way dispatchers will be able to apply them in a more critical and useful way. *The DSS proposed in this thesis will both have the task to help operators in limiting as much as possible their usage and to show them the impact that they have on passengers when there is no other choice but implementing them.*

- ***Example***

*Considering skipping stops:*

*This instrument has a great power to recover a delay but at the same time it impacts negatively on the passengers because the customers that want to get to the skipped stop have to alight the vehicle and wait for the passage of the following one.*

It is important to consider also the negative effects generate by these OIs because the final objective is to promote and improve the usage of public transportation. Utilizing indiscriminately operational instruments that impact badly on passenger quality aspects put distance between PT companies and the objective to increase passengers' acquisition and retention.

## 3. Reactive approach

Another limitation of the approach currently used is that the interventions to solve disruption are always taken after that the inefficiency occur even if sometimes it would be possible to foresee it. Surface PT companies use exclusively *reactive approaches* to deal with critical situations, they intervene to restore line service level when it is already compromised.

It is important to say that it is possible to identify two different types of inefficiencies *(figure 20)*:

1. ***UNFORSEABLE INEFFICIENCIES*** *that are caused directly by one or more disruption events that cannot be foreseen;*

2. ***FORSEABLE EFFICIENCIES*** *that are caused both by the* ***manual interventions*** *made in order to recover the regularity of the line that has been lost due to unforeseeable inefficiencies (disruption event) and by the slowly degradation of the line that it is usually produced by* ***little disturbances*** *that slightly affect the operations.*

Now we introduce a fictitious example to better explain these concepts.

- ***Example***

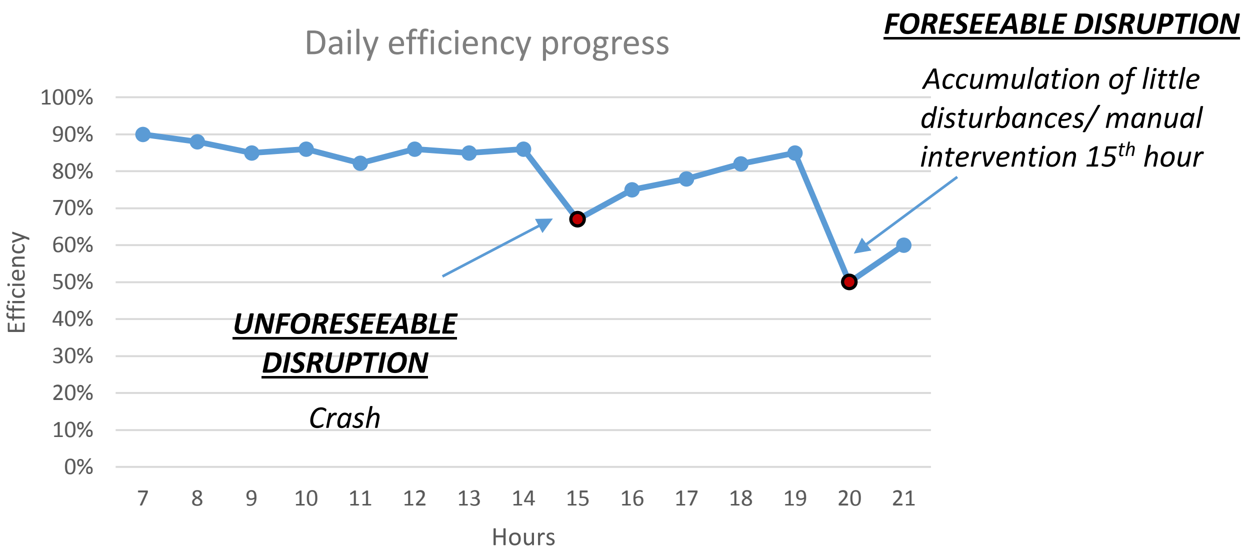



***Figure 20***: *Daily efficiency progress with Foreseeable/Unforeseeable disruptions, fictitious example.*

*The inefficiency generated by the first kind of disruption (15th hour) cannot be predicted because it is impossible to foresee (for example an accident between a vehicle and a private car). However, it is possible to foresee the second one (20th hour) since it is due to crew scheduling issues generated by the recovery actions taken to solve the initial problem.*

*It would be helpful to have a system that monitors the situation on the line analyzing concurrently the different position of the means on the line and the different drivers' shift change hours and places and suggests to the dispatchers how to intervene before the situation degenerate.*

*Part of the DSS proposed along this thesis will be constitute by a set of alerts that will have the task to foresee a critical situation before it degenerates in a grate inefficiency.*

*Figure 21* represents how could change the situation if the first disruption would have tackled considering also crew scheduling issues.

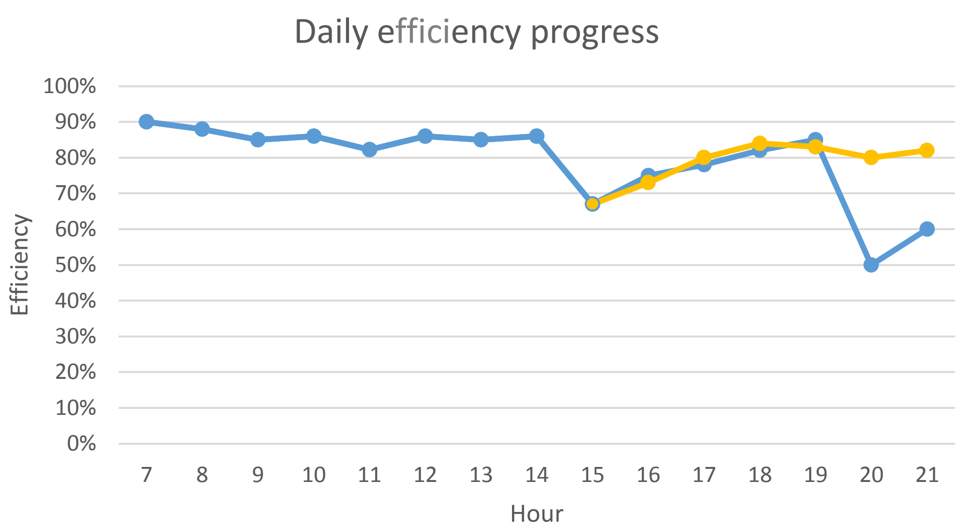



***Figure 21**: Daily efficiency progress considering crew-scheduling issue and without considering crew scheduling issue example.*

## 4. Narrow sight approach in solving disturbances

To analyze this issue is important to explain how disruption events affect the PT's system operations. When a disruption event occurs there is an initial inefficiency that is tackled promptly by the dispatchers in the control room, but other problems usually appear during peak hours and during shift change hours *(see figure 22)*.

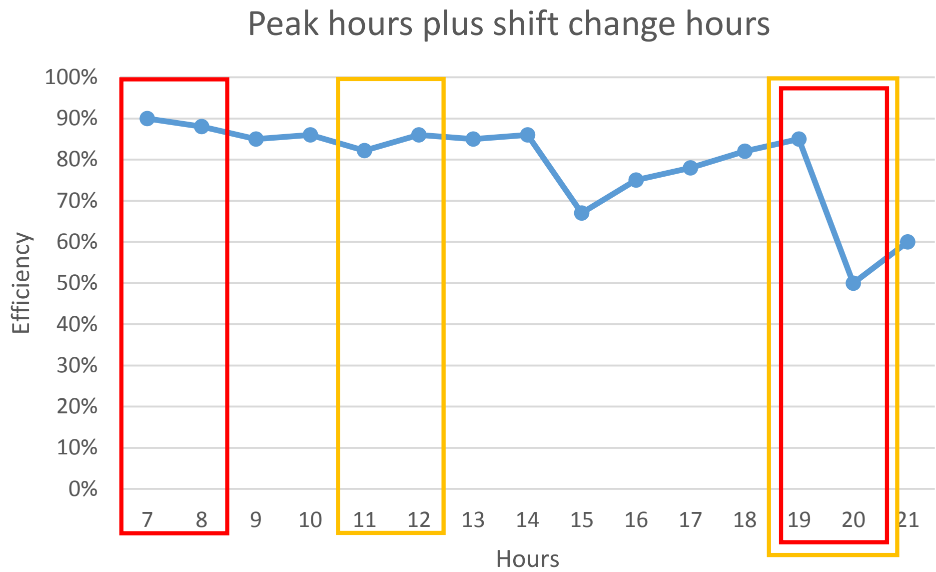



***Figure 22***: *Peak hours* plus *shift change hours*.

In these parts of the day there are two main criticalities:

1. They are the parts of the daily service where there is the highest demand (*high frequency service → in certain lines there is a frequency of 20 passages/hour per stop*);

2. It is fundamental the position of the different means on the line (punctuality with the schedule) because the places and the hours in which drivers can change-finish their shifts are predefined and they are a strict constrain to be followed *(actual system).*

The fact that dispatchers decide manually how to intervene generates more problems because they are not able to foresee how their decisions to restore service reliability after a disruption will change the position of the different means on the line in the future respect to their schedule. Due to this the actions taken to recover the inefficiencies caused by the first disruption event will create more inefficiencies when the operator will have to intervene again with invasive operational instruments (e.g. skipping stops) to to allow drivers to reach the change stops on time.

The concept is better explained by *figure 23* where is visible that the misalignment between schedule and actual position of the mean obliges an invasive intervention to respect the crew scheduled change also if the regularity of the line is good (constant headways between means). The consequence of this intervention is a decrease in the regularity hence a decrease in service reliability. I could have a line in which all the means running on it are half an hour late respect to the schedule but have constant headways hence perfect regularity. Consequently, a decision aimed to realign a vehicle accordingly to its schedule could worsen line's performances. Furthermore, these interventions generate discomfort for some passengers that are obliged to get off the mean.

As explained, the short sight approach applied to solve these problems generates more inefficiencies than benefits. Anyway, this is not fault of the dispatchers because they are not equipped with any tool that helps them in managing this kind of situations and the variables that they can consider and process manually to take decision are limited.

The structure of the inefficiencies' propagation process is well explained by *figure 23.*

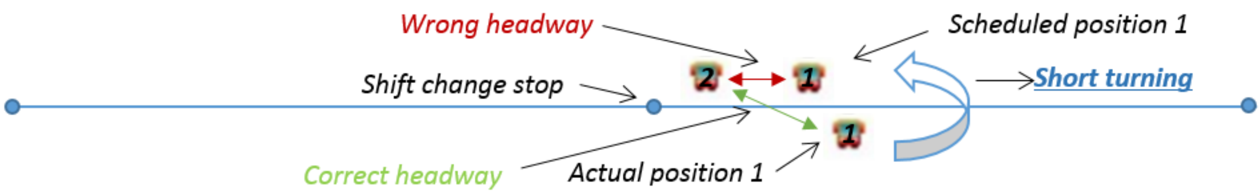



***Figure 23:*** *Misalignment between scheduled and actual position with consequent invasive instrument.*

## 5. Stiff structure, focus on punctuality

Another problem that is evident is the stiffness of the surface public transport system. The fact that shift hours and shift change stations are rigid entities create huge problems at the operational side. Usually happens that even if the system is performing well (there are constant headways between means) are needed interventions to restore the punctuality of the means in order to respect crew scheduling (*figure 23*), these interventions always produce an inefficient service.

As seen along chapter 2.1.1 during peak hours what is important for passengers is frequency and not punctuality. We have also seen that service with inconstant headways generates problems both for passengers and for the management of the service.

The possibility to have a more flexible system that will allow focusing more on the improvement of frequency rather than on the maintenance of punctuality will bring huge benefits in the management of the system and in the improvement of service reliability. Another important aspect is to find a way to deal with crew scheduling because its stiffness perturbs the system also if it is performing well.

The main issue is that operating with a rigid system in an environment in which the extent of uncertainty and variability is extremely high produces a lot of inefficiencies and output variability. In order to improve the level of service it would be necessary make the system more flexible.

- ***Example***

*Consider a generic line X and a generic day Y, let us assume that the progress of the efficiency of the line (indicator related to the capacity of the system to maintain constant headways between means) during the day is presented by the figure 24.*

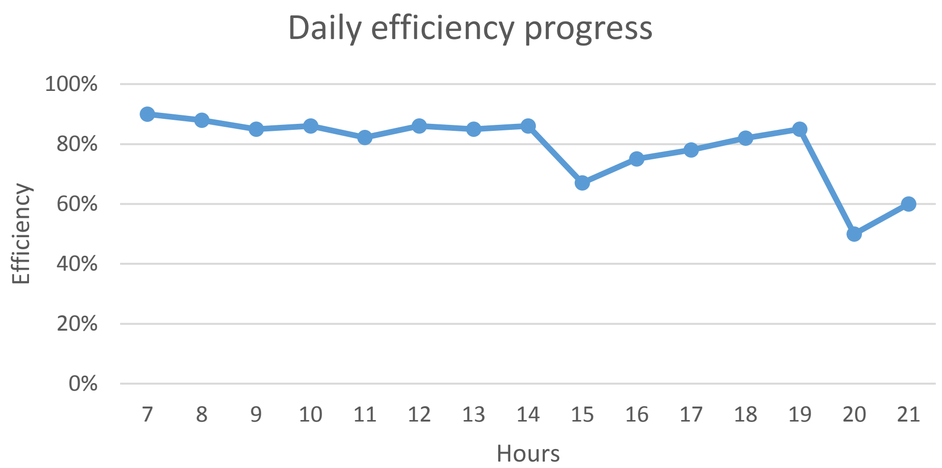



***Figure 24****: Daily efficiency progress of line x, day y.*

*As presented by the chart above the line performed quite well along all the day apart from the 15$^{th}$ and the 20$^{th}$ hour of the day. In Fact during the 15$^{th}$ hour occurred a disruption event (crush between a bus and a car) that created an efficiency problem on the line (efficiency 68%) but, as it is possible to see from figure 24, because of the decision taken by the dispatchers the service level of the line has been restored up to 85%. But the situation during the 20$^{th}$ hour get worsen (efficiency:50%) even if no conventional disruption event occurred.*

*The problem is that the interventions made to solve the disruption event (15$^{th}$ hours) set the line out of schedule. This combined with the increase in the frequency of the service (peak hours) and with the need to have the means at the change stations at certain hour (shift change hour) in order to respect crew schedule generate the huge inefficiency of the 20$^{th}$ hour. The main issue here is that dispatchers intervene on the line to solve the crew-scheduling regardless the negative effects that such intervention would have brought on the level of service.*

The process that brings to the great inefficiency is explained in *figure 25.*

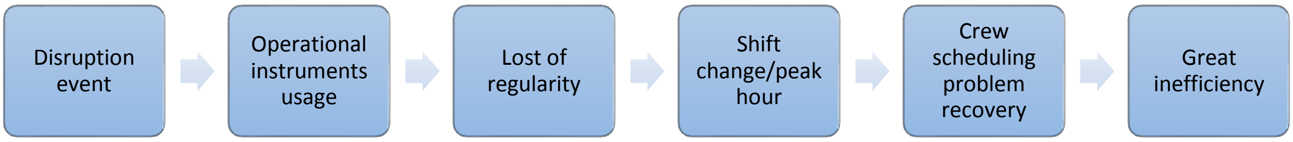



***Figure 25****: Disruption event-great inefficiency problem.*

## *Critical conclusions summary*

During this chapter focused on disruption management, we tried to describe how public transport companies that operate in urban area tackle this issue. We performed also a detailed analysis in which we have highlighted the criticalities and limitations of the current approaches.

An important aspect discovered, analyzed and described also in the previous chapter is that public transport operations have to deal daily with disruption events (major incidents) and disturbances (minor incidents). The interaction of the process with these events generates a misalignment between scheduled and actual operation, therefore it is necessary to reschedule resources inside the system in order to be able to provide a service that meets customers' expectations.

**Disruption management** refers to the process of dynamically revising an operational plan to obtain a new one that reflects the objectives and constraints of the actual situation. It refers to the task of adapting the three main entities, *timetable*, *vehicle in circulation* and *the crew schedules*, to the actual situation.

When a disruption event occurs, it generates a huge impact on the entire system and it is characterized by a high level of uncertainty that is translated in difficulty to find a proper solution to relocate the available resources to the new status of the system.

We have analyzed in detail also how disruption management is performed in public transport companies. Even if there is scarcity of material on this topic we have been able to perform a detailed studying on this aspect thanks to the internship done at ATM S.p.A. and the support of professors and researchers of TU Delft that have a great experience in this field. In the end we have identified the following criticalities that characterize the actual process relating them to the objectives of this thesis.

1. ***Decision taken manually*** → *Objective*: Creation of a DSS to help dispatchers in taking decisions to maximize customer experience;
2. ***No critical usage of operational instruments*** (operational instruments are used without evaluating the side effects that they generate on passengers) → *Objective*: Integration between the DSS and the control room operator; Decrease the usage of invasive operational instrument;
3. ***Reactive approach*** → *Objective*: Creation of a set of indicators able to detect critical situations in advance;
4. ***Narrow-short sight approach in solving disturbances*** → *Objective*: Creation of a DSS that gives suggestion to maximize service reliability considering also other quality aspects;
5. ***Stiff structure, focus on punctuality*** → *Objective*: Creation of a set of instruments to Increase system flexibility.

# 2.2 Description of useful tools and approaches for disruption management

We start this chapter with the description *of general control methods* to diminish variability and consequently increase reliability of processes. We will find that this approach is applicable also to public transport system that operates in urban areas. Then we will move our attention to analyzing how two other industries (airline and railway), in which the problem of disruption management has been studied for years, tackle this issue. In the end we will highlight which are the aspects used in other industries that can be useful and the one that cannot be used for our purposes.

Then we will perform a detailed description of all the operational instruments that are used by control room operators nowadays and that will be used also by the algorithm of the DMSS as tools to improve its objective function *(Maximization of service reliability)*. We will also analyze the different indicators used nowadays to express punctuality and regularity. In the end we have highlighted the *Percentage regularity deviation mean* (PRDM) as the most appropriate KPI to use as guideline for the creation of the objective function of the service reliability algorithm's objective function (task performed by the operative research department of Politecnico di Milano).

## 2.2.1 Disruption management tools and approaches

As analyzed in deep along *chapter 2.1.1 and 2.1.2* improving service reliability it is necessary to satisfy passengers requirements and increase in this way their acquisition and retention. Along this chapter we will analyze and describe the state of art of disruption management tools and approaches trying to understand which of them can be implemented in our case and which not. *Figure 26* briefly presents the contents of this chapter.

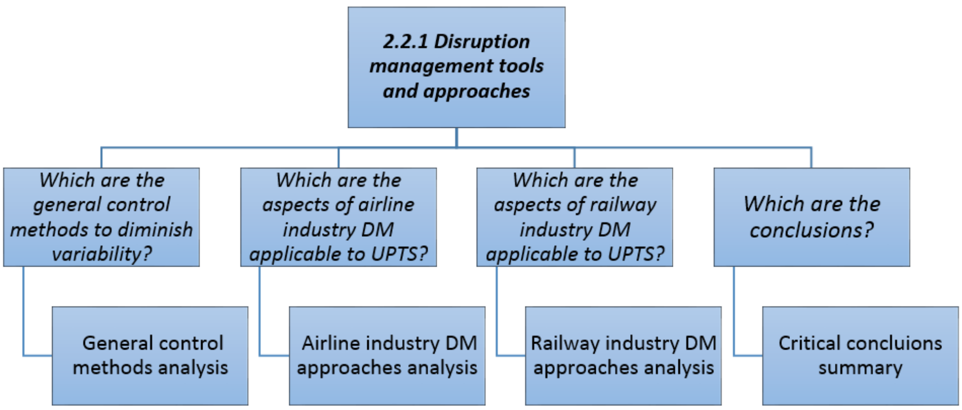



***Figure 26:*** *Chapter 2.2.1structure*.

### *General control method analysis*

Improve service reliability it is necessary to maximize the match between scheduled and actual operations as shown in *figure 27*. *Van Oort* in his research valuates suitable applying general control methods as guidelines to control operation's variability caused by the interaction of the process with disturbances that distance the planned service from the actual one. In this section three major general control types are analyzed, later on special attention will be dedicated to control methods used to improve service reliability in airline and in railway industry.

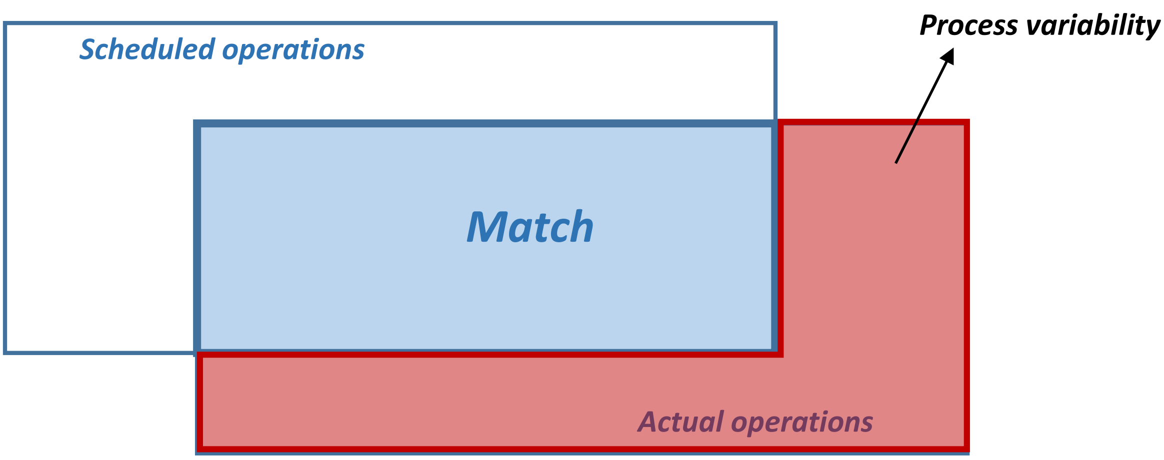



***Figure 27****: Mismatch between scheduled operations and actual ones that it is cause of process. variability.*

In the previous analysis (*chapter 2.1.2*) we have found that variability and unreliability may arise due to both internal and external factors. General Control methods provide indications on how to tackle disturbances (*internal or external*) that interact with operations and in this way reduce the process variability.

Cybernetic, that is the general science of controlling system, focuses on function and information flows rather than on the nature of the system itself. For this reason its principles are suitable also for process control theory and for describing and mitigate variability of the systems (*Van den Top 2010*; *Heylighen and Joslyn 2001)*. The final objective of both cybernetic and process control theory is to maximizing the production maintaining at the same time a process that is reliable and economically convenient (*Hahn and Edgar 2002*).

Now are introduced the basic notions of cybernetic and production control theory that, accordingly to the reasoning in the introductive part of this section, are suitable to mitigate the variability of public transport service.

- *The desired output:* This is the planned result of the process.

- *Disturbances*: These are internal and external factors that interact with the process and generate variability of the output.

- *The regulator*: This is a tool or a control system that helps in mitigate/eliminate the variability of the output.

- *The buffer*: A buffer is an addition of resources (for instance time, crew or production measures) that enable absorbing the variability generated by disturbances that do not produce mismatch between scheduled and actual output.

In *Ashbly (1956*) are presented the three main control methods that are illustrated in *figure 28 – 30*. These control methods have been ideated with the aim to mitigate the negative effects that disturbances generate on the process allowing to obtain the desired results also in their presence.

- ***Using a buffer***: This passive method does not allow any kind of adjustment after the design phase and it is available independently by the interaction of disturbances in the process. The logic on which this method is built is to have redundant resources available that allow absorbing the variability without generating repercussion on the desired output.

- ***Feedback***: In this method a regulator tracks output variability and in case of a non-acceptable misalignment between planned and actual results it intervenes in order to re-bring the situation in a stable state. This is a reactive approach.

- ***Feed-forward:*** The approach used by this method is anticipatory. The regulator, instead of tracking the out-put variability trends, checks the evolution of the process. When it detects a situation that can degenerate producing a mismatch between actual and planned results it intervenes re-stabilizing the process.

All the three approaches have their own specific advantages and disadvantages. In practice, they are used in combination as well.

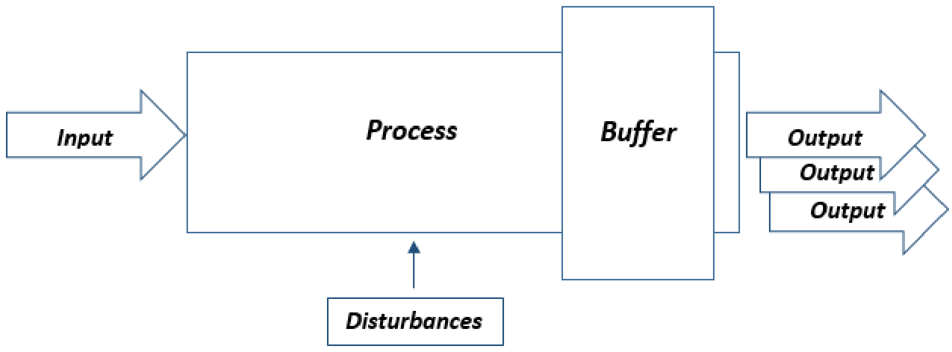



***Figure 28***: *Control methods: Buffer.*

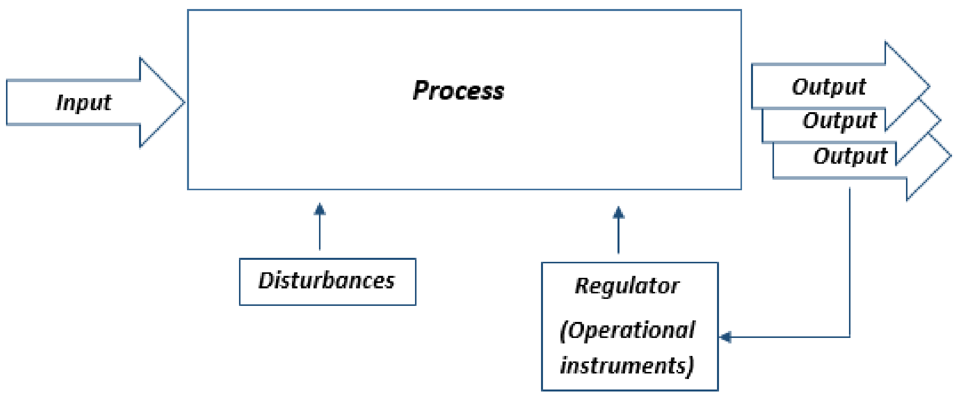



***Figure 29***: *Control methods: Feedback.*

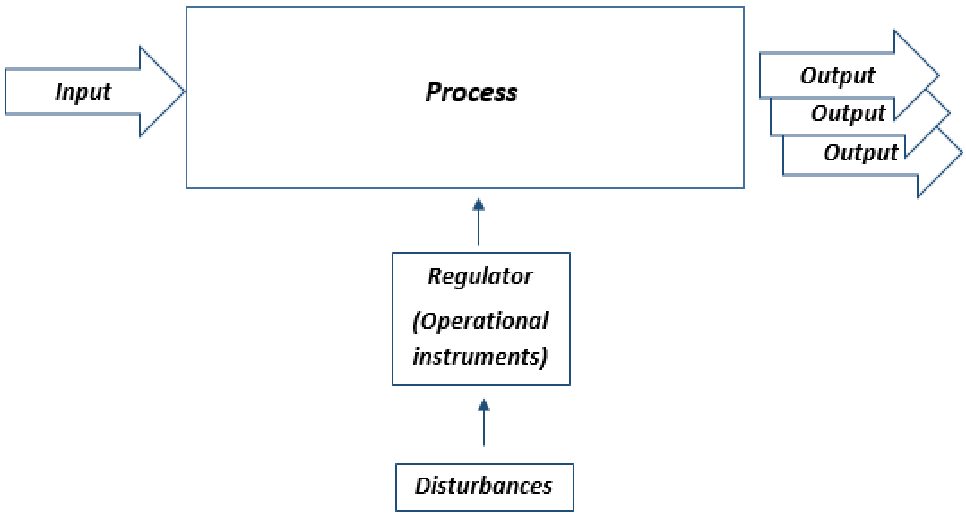



***Figure 30***: *Control methods: Feed-forward.*

The control types mentioned above are applicable to public transport as well. As analyzed in *chapter 2.1.2* urban public transport is composed by two parts: *operation and planning* (the latter consists of network and timetable design). Regarding the improvement of reliability, most attention is paid to the operations but there is not an approach that really has the power to significantly improve service reliability yet. Mainly Feedback approach is used to check the actual performance and to adjust the operations accordingly but without a great success. This thesis wants to introduce a new way of thinking in order to overcome the inefficiencies of the procedure adopted nowadays.

Before analyzing in detail the operative instruments used by urban public transport companies in managing disruptions it is worth to see how other modalities of transport face this problem. Airline and railway industries are the ones selected because this subject have been studied deeply during last years in this two fields. The objective in the following sections will be analyze the models applied by them in order to find the aspects that could be implemented also in PT's system case.

### *Airline industry disruption management (DM) approaches analysis*

Control the operation is one of the most important tasks that an airline company has. It does not matter to produce an optimal or near-optimal schedule of flights if, later, during the execution of the operational plan, the changes to that plan caused by disruptions are too far from the original schedule. Unfortunately, the majority of the disruptions are difficult to predict (for example, those caused by meteorological conditions or by aircraft malfunctions). Airline companies developed a set of operations control mechanisms to monitor the flights (and crewmembers) to check the execution of the schedule. During this monitoring phase, several problems may appear related with aircrafts, crewmembers and passengers. According to Kohl, disruption management is the process of solving these problems. To be able to manage disruptions, airline companies have an entity called *Airline Operations Control Centre* (AOCC). This entity is composed of specialized human teams that work under the control of an operations supervisor. Although each team has a specific goal (for example, the crew team is responsible for having the right crew in each flight), they all contribute to the more general objective of minimizing the effects of disruptions in the airline operational plan.

In this section we introduce the ***airline operations control problem*** – AOCP (*also known as airline disruption management problem*). To contextualize, we start by briefly introducing the AOCP preceding problem known as the ***Airline Scheduling Problem (ASP)***. Then we explain what is an airline operational control centre (AOCC). We will also introduce the approaches adopted in this industry to tackle the problem of disruption management and in the end we will present a classification of tools and systems currently used.

According to *Kohl (2004)* the ***scheduling process of an airline company*** is composed by the long and short-term phases presented in *figure 31*. The scheduling process has three main dimensions or views: (1) *passenger view*; (2) *aircraft view* and (3) *crew view*. The first one represents the seats available to be sold to the airline customers. The other two views, represents resources that will be allocated to perform the service.

The ***airline scheduling problem (ASP)*** is composed of all the initials phases and steps and ends some hours or days (depends on the airline policy) before the ***day of operation***. The global objective of the ASP is to maximize the airline operating profit *(see Grosche 2009).*

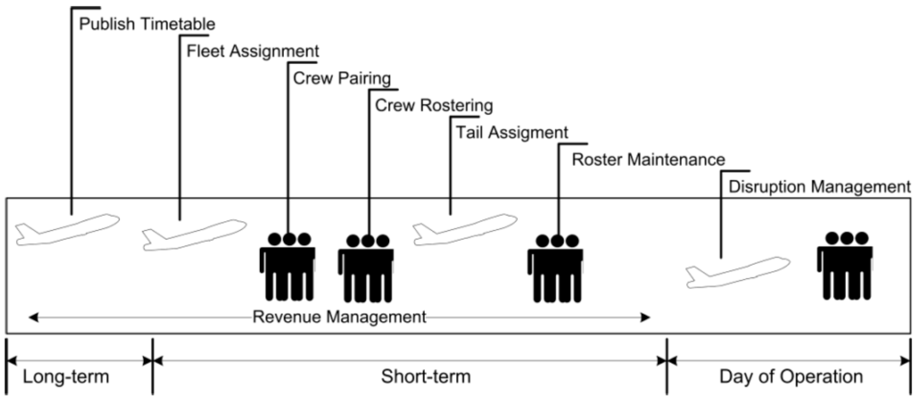



***Figure 31****: Airline scheduling problem; (*Grosche 2009*).*

The ***airline operations control problem (AOCP)*** starts when the airline scheduling problem finishes. If everything goes as planned the airline just needs to monitor the execution of the plan. Unfortunately, several unexpected events appear during this phase that can disrupt the plan. To monitor those events and solve the problems that arise from these, it is necessary to define and follow a disruption management process. Airline companies have an entity called ***Airline Operations Control Centre (AOCC)*** that is responsible for the disruption management process.

*In Figure 32* it is presened the organization of a typical Integrated Operational Control Centre. It is important to point out the role of the supervisor, a characteristic that makes this organization hierarchical and, also, the operation time-window that marks the responsibility boundaries of the AOCC. This operation time-window is different from airline to airline but, usually, ranges from 72 to 24 hours before to 12 to 24 hours after the day of operation.

The roles or support functions more common in an AOCC, according to *Kohl 2004* are the following:

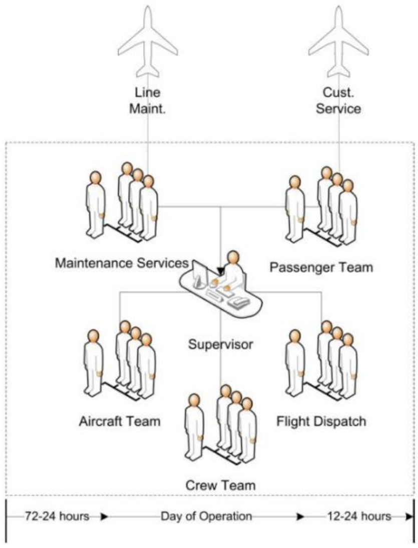



***Figure 32****: integrated control center; (Castro e Olivera 2011).*

We have just presented the typical AOCC organizations and the roles that exist on those organizations. Now, it is important to understand the ***typical problems that appear during the execution of the airline operation***. *Kohl & Karisch (2004)*. An important issue that they have found during their studying is that the problems might propagate due to the relation between them and generate new problems on different flights. This propagation characteristic makes the problem more difficult to be solved optimally in a real time and dynamic environment. There is a strict *relation between Flight Arrival Delays and Flight Departure Delays,* we saw the same issue in urban public transport companies that operates in urban area (*chapter 2.1.2*). Most of the flights are performed by aircrafts that are used in previous flights so if there is an arrival delay and the aircraft turn-around time at the airport is not enough, then, if the AOCC does not find an alternative solution, we will also have a departure delay.

The main reasons for flight arrival delay (besides the delay on departure) are: *En-route air traffic, en-route weather, en-route aircraft malfunction and flight diversion*. In the previous cases and to minimize the arrival delay it is necessary a cooperation between the pilot and the AOCC. Regarding departure delays, the main reasons are: *crew delays, cargo/baggage loading delays and passenger delays as a consequence of an arrival delay*. *Crew members that do not report for duty, air traffic control reasons, aircraft malfunctions and weather conditions* (at departure or at arrival) are the other main reasons for departure delays.

Several problems might cause flight delays. AOCCs have a process to monitor the events and solve the problems, so that flight delays are minimized with the minimum impact on passenger and, preferably, with the minimum operational cost. In *figure 33* is presented the current disruption management process in use at most of the airlines. This process has five steps:

***1. Operation Monitoring:*** In this step the flights are monitored to see if everything is going accordingly to the plan. The same happens in relation with crewmembers, passenger check-in and boarding, cargo and baggage loading, etc.

***2. Identify possible options:*** If an event happens, like for example, a crewmember is delayed or an aircraft malfunction, a quick assessment is performed to see if an action is required. If not, the monitoring continues. If an action is necessary than we have a problem that needs to be solved.

***3. Evaluate options:*** Having all the information regarding the problem the AOCC needs to find and evaluate the candidate solutions. Usually, a sequential approach is adopted when generating the solutions. First, the *aircraft problem* is solved. Then, the *crew problem* and finally, the *passengers*. It is understandable that the AOCC adopts this approach. Without good computer tools, it is difficult to take care of the problem, considering the three dimensions (aircraft, crew and passengers) simultaneously. Although there are several costs involved in this process, we found that the AOCC relies heavily on the experience of their controllers and in some rules- of-thumb (a kind of hidden knowledge) that exist on the AOCC. A same process leads the operations in urban public transport control rooms. The main difference is that in airline industry operators are often provided with decision support systems that help them in taking the best decisions.

***4. Make decision***: Having the candidate solutions a decision needs to be taken.

***5. Implement decision:*** After the decision the final solution needs to be applied in the environment, after the operational plan needs to be updated accordingly.

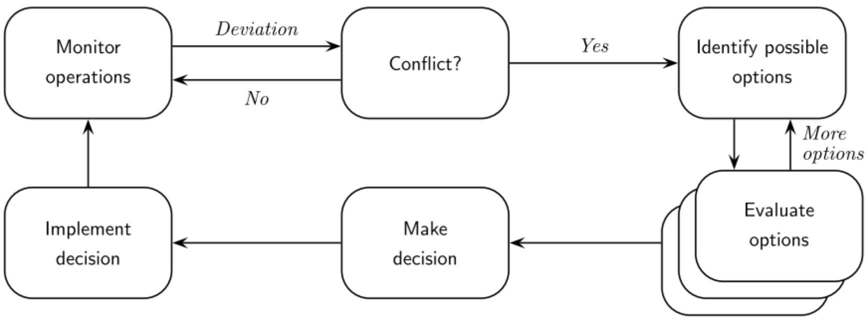



***Figure 33****: Disruption management process in airline industry.*

In the end it is important list which are the tools currently used by airline companies to facilitate the disruption management process (*Khol 2004, Castro 2011*):

1. *Database Query Systems* ***(DBQS)***

2. *Decision Support Systems* ***(DSS)***

3. *Automatic or Semi-Automatic Systems* ***(ASAS)***

The ***DBQS*** – Database Query Systems (the most common situation at airlines) allows the AOCC human operators to perform queries on the existing databases to monitor the airline operation and to obtain other data essential for decision-making. These systems are useful and relatively easy to implement and/or acquire but they have two main disadvantages:

1. *The solution quality is dependent on knowledge and experience of the human operator and;*

2. *Due to the usual difficulty of the human being in leading with large volumes of data simultaneously, they do not use all the necessary information (variables) to take the best decision.*

These two issues are also the biggest limitations of the procedures and of the systems that public transportation companies that work in urban areas have nowadays. But the breakthrough brings by this industry are the two more complex support systems described below.

The ***DSS*** - Decision Support Systems, besides having the same characteristics of the DBQS, also include additional functionalities to support the human operators on the decision-making. For example, after a request made by a human operator, these systems are able to recommend the best solution to solve a problem related with a delayed aircraft. DSSs eliminate some of the disadvantages of the DBQS systems. Namely, they are able to analyze large volumes of data and, because of that, proposed solutions take into consideration more information (variables). The decision-making still is on the human operator side but, now, he is able to take better decisions. Unfortunately, one of the big problems with airline companies is the absence and/or complexity of the computerized information system keeping all the operational information. These are of paramount importance for the success of the decision support tools*. This tool is similar to the one we will present along the thesis. Our final objective is to increase passenger acquisition and retention providing dispatcher with a powerful support system that is able to analyze both planning data and real time data and in the end to suggest the best set of intervention to apply on the line to increase the service level reliability.*

The goal of the third type of systems, ***ASAS*** – Automatic or Semi-Automatic Systems, is to automate as much as possible the AOCC, replacing the functional part by computerized programs. Specifically, these systems try to automate the repetitive tasks and also the tasks related with searching for the best solution (problem solving). In a totally automatic system, decision-making is also taken by the system. In a semi-automatic system, the final decision is taken by the human operator. In ASAS type of systems, the AOCC does not need as much human operators as in the previous ones, to operate correctly. Roles or functions related with operation monitoring, searching for solutions related with aircraft, crew or passenger problems and re-allocation of resources, are performed by machines that replace the human specialists. The final decision regarding the application of the solution found by these systems on the environment (for example, making the necessary changes on the airline operational plan database) depends on the human supervisor. *This just described it is not our case, the aim of the decision support system that we will develop along this thesis is not to substitute the dispatcher but is to give to him a valid support in taking his decisions.*

Now, after having analyzed which approaches are used to tackle disruption management by airline industry we want to analyze which aspects can be useful for our purposes and which not.

## Limitations of airline industry approach

- *Environment and system*

The first difference between airline and UPT industry is the *extent of the environment's unreliability and uncertainty*. PTS is obliged to operate in a context in which the variables out of its control are a lot of more respect to airline industry. The main extern variables that can influence the performance of the airline system are related to the *weather***,** while if we analyze the PT there are also *other traffic, working site on the street, inadequate infrastructure.*

The main difference between the two is *other traffic*, this factor is of extreme importance and it is the one that disturbs the UPTS operations the most. While a plane, once in flight, can perform its service without being influenced by external factors.

The main issue of *other traffic* is the extent of impact on the quality level of the service because it is a constant disturb and it gets worse during the part of the day in which the demand is higher and hence perturbing the level of service is easier and it produces an high impact on passengers. See *figure 22.*

- *Incompatibility AOCC (airline operational control center) - CRUPTS (control room urban public transportation system)*

The AOCC is the organization in charge of managing disruption events in the airline industry. *Figure 32* shows its structure. The AOCC is a fragmented organization; there are different teams in charge to deal with the different problems that a disruption event can generate. In the end the choices taken by the single entities are checked and coordinated by a supervisor.

While CRUTPS's structure is completely different, in this organization a single operator has to deal with a part of the network (*sub-network composed by 10-15 lines that are clustered following geographical drivers*) and he manages all the issues of the sub-network. The decisions to solve critical and extended problems that affect multiple areas are coordinated by a supervisor.

These two organization have very different structures. For urban public transport companies CRUPTS is evaluated to be the best solution because the disturbances that interact with the operational process are strictly related with the geographical position of the lines. Due to this is more effective to have an operator that controls some lines an all the different aspects rather than having a fragmented structure like AOCC that would be more stiff and less reactive organization because it needs coordination that is a time consuming activity.

### Useful aspects of airline industry approach

- *<u>Disruption management approach</u>*

The macro-approach to deal with disruption events used by airline industry (*figure 33*) is evaluated effective also for the PTS.

The first aspect considered valuable is the fact that there is a ***continuous monitoring*** of the operation and interventions are taken as soon as some discrepancy is detected between the scheduled and the actual operation. Currently also urban public transport companies adopt this approach, but the main problem is that all the process is performed manually and due to this are generated a lot of inefficiencies. Also the ***hierarchical approach*** on how the interventions are created is considered suitable for the UPTS. The solutions generated are linked to the two entities that compose and guarantee the service plus the one that receives the service:

- *Aircraft (Vehicle);*
- *Crew ;*
- *Passengers.*

The decisions are taken hierarchically following in the order the three entities just mentioned. This means that when a misalignment between scheduled and actual operation is detected first of all it is tackled the aircraft problem then, once the time table design of the different vehicles has been restored crew is assigned to the single vehicle and in the end the passengers are informed of the changes.

In the UPTS the entities are different but the ***continuous monitoring*** and the ***hierarchical approach*** in generating solutions are considered valuable also for the case of our concern.

- *Tools and system used*

Airline industry utilizes systems that make the disruption management process more computerized even if in the end the final decision to implement or not an action is up to the dispatcher. Among the tools used the one that is judged more suitable for the PTS is the ***decision support system***.

The goal of a ***DSS*** (Decision Support Systems) is to support the human operators in the decision-making. For example these systems are able to recommend the best solution to solve a problem related with a delayed aircraft. DSSs are able to analyze large volumes of data and, because of that, the proposed solutions take into consideration more information (variables). The decision-making still is on the human operator side but, now, he is able to take better decisions

## Conclusions

In this section we have analyzed the airline industry's disruption management approach. Summarizing what discussed previously it is possible to claim that there are some aspects from which it is possible to get inspired for the creation of a model applicable to the UPTS. *Table 8* resume schematically what said above.

| ***Useful aspects*** | ***Limitations*** |
|---|---|
| *Disruption management macro-approach* | *Different environment* |
| *Tools and systems used* | *Control center structure incompatibility* |

***Table 8****: Summary table "useful aspects-limitations" of the airline disruption model.*

Now the focus goes on railway industry and on how it tackles the disruption management problem. Most of the consideration done for the airline industry are valid also for the railway, this is due to the fact that the RI's disruption approach is inspired to the one applied by the AI that was the first in studying this kind of issues. In the following section we will analyze which are the aspects that ca be considered valid also for UPTS's model.

## *Railway industry disruption management approaches analysis*

For airline operations, *Kohl et al. (2007)* describe the disruption management process by *figure 34*. The macro approach is similar to the one used by passenger railway system. The disruption management process can be called also *operational process* since the core of its process, namely the monitoring of the resources, continuously takes place also when no disruption has occurred. The process involves monitoring the resources and evaluating possible conflicts whenever the process deviates from the planned operations. If a conflict is indeed detected, an iterative process of identifying and evaluating possible options is performed. when an appropriate decision is reached appropriate countermeasures are implemented.

When the operational plans are carried out in practice, they are monitored closely. The performances of the system are monitored carefully to ensure that it is providing the service as planned. Taking into account that any deviation between the planned and the actual position of a resource may cause a conflict in the resource assignment. The first step when a ***deviation is detected*** is to determine whether this will result in a conflict. Predicting upcoming conflicts requires knowing the propagation of delays and resources' availability into the future. Also, the passenger flows are monitored to determine whether station and train capacities are sufficient.

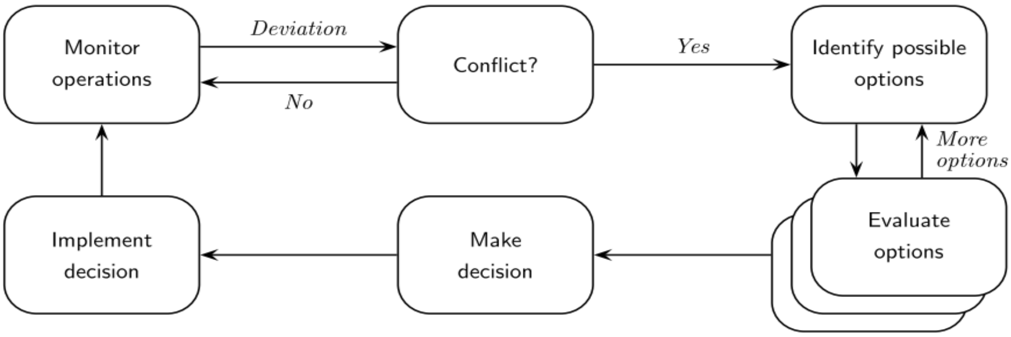



***Figure 34***: *High-level view of the operational monitoring process based on Kohl et al. (2007).*

A conflict can for example be a delayed train that blocks the arrival platform of another train in a station, or a delayed driver that is needed for driving the next train in his duty. More serious conflicts result from failing infrastructure and malfunctioning rolling stock. When a conflict is detected the process of identifying possible options begins.

In case of a conflict in the timetable or in the assignment of resources the dispatchers must decide ***how to react to the conflict***. In case of small deviations it may be relatively simple to assess the possible options, but in case of a more involved disruption there are often numerous possible alternative countermeasures with different impacts on the system performance.

A further complicated part of the decision process is to ***estimate the duration of a conflict***. Possible options primarily involve canceling trains, changing the routes of trains between stations and inside stations, changing the timetable according to (expected) delays, cancelling passenger connections, changing the order of trains, and changing the assignment of resources to trains.

Once the overall framework of how to react to a conflict has been outlined, the ***decisions are implemented*** in practice. The practical implementation consists of two major tasks:

1) *Updating the appropriate information in the systems and;*
2) *Communicating the changes to the proper parties.*

The changes in expected arrival times of trains are automatically recorded in the information systems, while changes to the assignment of resources are entered into the information systems manually. In addition, rerouted and canceled trains need to be recorded as well as the routes of trains inside stations. Updating the information systems allows the dispatchers to query the system for details on how the resources are utilized in the adapted situation. Thereby the new decisions are monitored rather than the originally planned operations. In practice the timetable is updated before the resource schedule since the timetable forms the basis for the tasks to be performed by the resources.

A crucial part of the implementation is to communicate the changes to the proper parties. Especially, the crew needs to know any changes to their duties, and shunting and cleaning personnel should be informed about changes in the rolling stock duties.

### A model for disruption in rolling stock

To develop a decision support system for disruption management it is need a way to represent the *occurrence of the disruption*, the *development of the situation*, and the *accompanying uncertainty*.

In this section will be briefly discussed how disruptions are modeled and how uncertainty can be represented explaining how disruption system in railways works.

In several studies of disruption management in various time-critical settings, the associated problems are described as pure ***recovery problems***, in which the problem is to reassign the available resources to a new situation. *Teodorovic and Stojkovic (1990), Thengvall et al. (2001), Bard et al.*

*(2001)* offer examples of recovery models in various settings in the airline industry that are applied also in the railway industries.

Strictly speaking such models consider a plan for normal operations, but if a disruption occurs it poses new constraints that make the current plan infeasible. The problem is then to adapt the plans considering the new constraints while minimizing a number of metrics such as operational cost, delays and cancellations. In general, recovery models consider the disruption as an event that leads to a new situation and do not explicitly consider the dynamics of the disruption.

A disruption is namely a developing situation where the knowledge of the state of the system only gradually becomes available. Consider the case of a failing infrastructure component; at first the repair crew may estimate it takes 1.5 hours to repair. However, after one hour the repair crew concludes that their first estimate was too optimistic and provide a new estimate that the total repair time is likely to be one hour longer. This suggests ***considering the disruption as on-online problem rather than a one-time recovery problem***.

- ***Example***

*A disruption could develop as sketched in figure 35: The train services are planned according to the timetable shown as a time-space diagram in figure 35(a). At time 12:45 an infrastructure malfunction is reported at a point between **B** and **C**. The repairs are expected to be done at time 14:15 where-after the tracks are again opened for train traffic.*

*According to the pre-computed handling scenario the trains are turned at the closest major stations on either side of the blocked section of infrastructure. For this line these are **B** and **C**. This turning pattern and the expected duration of the blockage results in the timetable shown as a time-space diagram in Figure 35(b).*

*At time 13:45 it turns out that the problems with the infrastructure are more complicated than first assumed. The repair crew provides a new estimate of the duration of the blockage; it will now last until 15:15. This leads to a new update of the timetable as shown in figure 35(c).*

*Note that the paths of some of the trains in the time-space diagram are changed both when the disruption occurs and at the moment information about the duration of the disruption is updated. For the train following the bold path in the diagram it means that any changes along the path will have to be rescheduled after the occurrence of the disruption. But when it becomes clear that the blockage lasts longer than first estimated those composition changes have to be rescheduled again.*

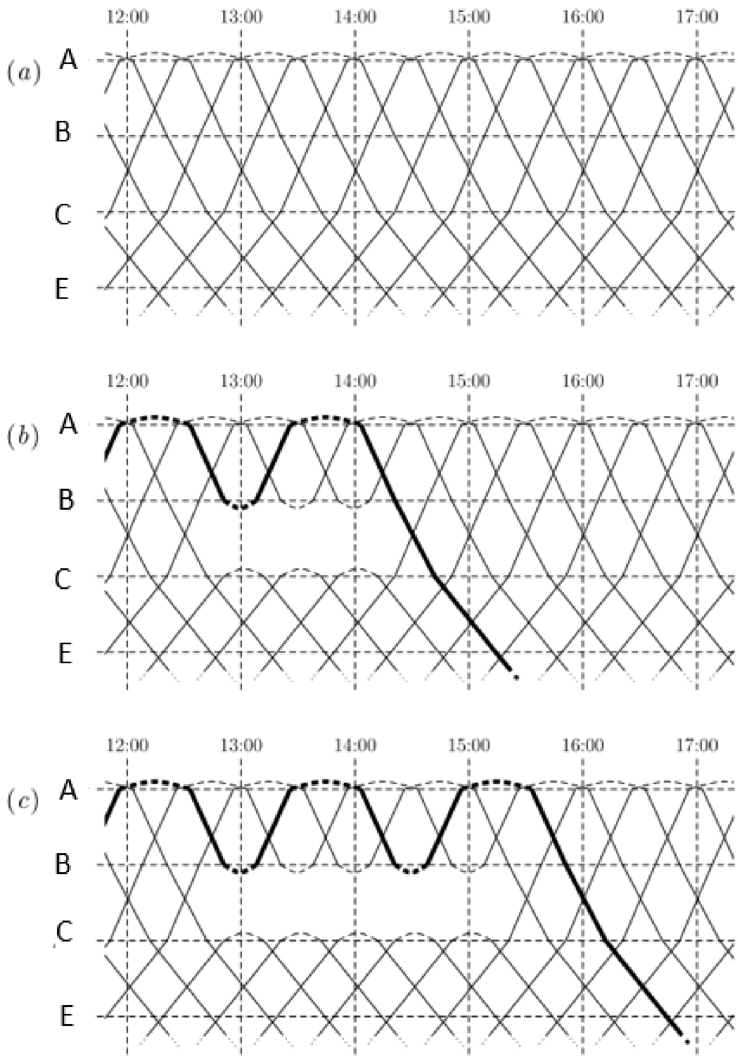



***Figure 35****: (a) Time-space diagram for part of some line. (b) Adapted timetable after the occurrence of a disruption between B and C. (c) Adapted timetable according to updated information on the disruption.*

The above example shows how a disruption may evolve. First, a blockage is detected and the impact of the disruption is estimated. Then, a number of countermeasures are taken, i.e. the timetable is updated and the planned travels of some trains are revised. Later still, the situation develops and the blockage is estimated to last one hour longer. This shows the extent of uncertainty that is brought in the system by a disruption event.

### Scenario-based modeling

One way to accommodate the uncertainty of a disrupted situation is through ***scenario-based modeling*** where the concept of scenarios is used to model each possible state of the system. If the repair crew in the example in *figure 35* concluded that it would take between one and three hours to repair the infrastructure malfunction, then it would result in different scenarios.

Classically, two classes of approaches to decision making under uncertainty rely on the concept of scenarios; ***Robust Optimization*** *(see Kouvelis and Yu (1997) and Ben-Tal et al. (2009))* and ***Stochastic Programming*** *(see Ruszczynski and Shapiro (2003)*).

- ***Robust Optimization*** attempts to find a solution that in some sense is feasible in all scenarios while minimizing the cost of the worst one.

- ***Stochastic Programming***, on the other hand, rely on probability distributions on the outcome of the scenarios, and then the expected outcome is optimized according to the known probability distributions.

There are both pros and cons for such scenario-based approaches. ***Robust Optimization*** offers a guaranteed lower bound on the quality of the performance in the given scenarios whereas ***Stochastic Programming*** offers an optimal expected performance. There is, however, a number of problems with the applicability of such approaches in a real-time setting; first of all it may be difficult to enumerate all scenarios in a more extended disruption than the example above. Second, even a limited number of scenarios may result in computationally challenging models which are time consuming hence not suggested for a time critical situation like the one taken in consideration. Third, it is difficult to estimate the probability distributions of the scenarios in practice as needed for the Stochastic Programming approach.

To overcome these shortcomings it has been introduced a new approach that solves the problems over listed, this technique is known as ***Online combination problem***.

Rather than trying to describe the possible outcomes at the occurrence of a disruption by enumerating scenarios, it tries to *describe the uncertainty of the situation as an online combinatorial optimization problem (see Borodin and El-Yaniv (1998)).* The occurrence of a disruption and the development of the situation can be describe by the following elements.

- The undisrupted scenario $S_0$;

- A finite list of updates ($t_1$,$S_1$) , . . . , ($t_n$,$S_n$).

Here, the scenario $S_0$ describes the state of all parameters in the system in the undisrupted situation. An element in the list is composed by two elements one is the instant $t_i$ and a scenario $S_i$ that describes the system at time $t_i$. The element ($t_i$,$S_i$) denotes that at time $t_i$ the system changes to $S_i$. The list thus represents the uncertainty of the development of the situation.

The task is then at time instant $t_i$ to re-plan the resources in the system so that the new plan is feasible under the constraints described by scenario $S_i$. At this time there is no knowledge of future changes in the system, i.e. the rest of the list ($t_{i+1},S_{i+1}, . . . ,t_n,S_n$) is not known. Also, the number of updates $n$ is not known.

In the context of *disruption management* of rolling stock in a passenger railway system, the scenario $S_i$ describes the updated timetable, the rolling stock availability, passenger demand, and all parameters on shunting possibilities (the assignment of platforms to trains and the routing of trains inside railway nodes). The disruption in *figure 35* can be modeled by letting $S_0$ describe the ordinary timetable of *figure 35 (a)* and letting the list consist of two updates (***t1,S1***), (***t2,S2***).

The first element is ($t_1,S_1$) where $t_1$ = 12:45 and $S_1$ describes the timetable update in *figure 35 (b)*. Similarly, the second element in the list is ($t_2,S_2$) where $t_2$ = 13:45 and $S_2$ describes the timetable update in *figure 35 (c)*. This way of modeling the progression of a disrupted situation is known in practice as a ***wait-and-see approach*** (*see Wets (2002)*). In this approach, no assumptions are made on the probability distribution of the occurrence of the possible scenarios. This approach is valid because overtakes the problems of scenario-based approaches.

Now it is interesting to understand and analyze which railway industry's disruption management approaches are useful for our purposes and which not.

### Railway industry approaches limitations

- *Environment and system*

The environment in which railway companies operate is different respect to UPTS because the level of uncertainty in this case is lower, there is more control on the environment since railway are dedicated only to rolling stocks passage. The fact that the system is not shared with other modality of transport reduce de level of disturbances that can perturb the operational process. While UPTS systems has to deal with other traffic that is a constant that has an high impact on the service level offered by the company.

- *Decision are taken manually*

The decision process to detect and to deal with critical situation is carried out manually, as explained in *chapter 2.1.3* using this approach brings many limitations because it denies to take the optimal corrective action, furthermore the entire process is slower respect to one in which is implemented some decision support system.

## Useful aspect off railway industry

- *Disruption management approach*

The disruption management approach is the same of the airline industry because RI gets inspiration from AI's model. But here there is a breakthrough respect to the AI model related to the entities considered in the disruption management process. The three entities are:

  - *Timetable;*
  - *Vehicle scheduling;*
  - *Crew scheduling;*

The hierarchical structure of these three entities are presented in *figure 36:*

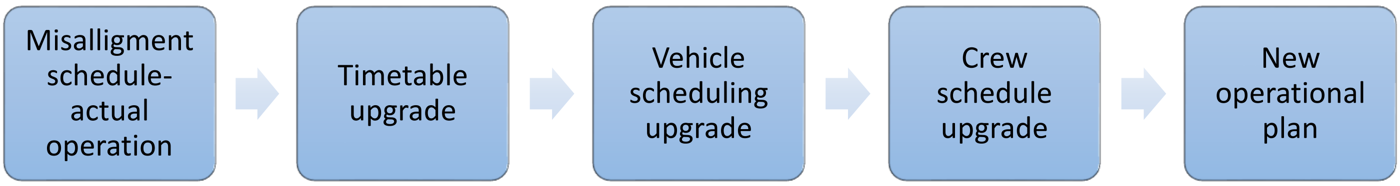



***Figure 36****: Hierarchal structure to implement corrective actions.*

- *Online combination problem*

Railway model introduces this kind of approach that rather than describe the possible outcomes at the occurrence of a disruption by enumerating scenarios tries to describe the uncertainty of the situation as an online combinatorial optimization problem. The occurrence of a disruption and the development of the situation can be describe by the following elements.

  - The *undisrupted scenario* $S_0$;
  - A *finite list of updates* $(t_1,S_1), \dots, (t_n,S_n)$.

Here, the scenario $S_0$ describes the state of all parameters in the system in the undisrupted situation. An element in the list is composed by two elements one is the instant $t_i$ the other is the scenario $S_i$ that describes the system at time $t_i$. The element $(t_i,S_i)$ denotes that at time $t_i$ the system changes to $S_i$. The list thus represents the uncertainty of the development of the situation. The model is based on creating new solutions for the current situation without looking at the future, if a change happens it will be found solution for the new situation. This has been evaluated a good approach because in a context in which the extent of uncertainty is so high and the number of variables to consider concurrently is so numerous that is worthless and expensive try to build possible future scenarios on how the system will perform in the future.

### Conclusions

In this section we have analyzed the railway industry's disruption management approach. Summarizing what discussed previously it is possible to claim that there are some aspects from which it is possible to get inspired for the creation of a model applicable to the UPTS. *Table 9* resumes what said above in a schematically.

| ***Useful aspect*** | ***Limitations*** |
|---|---|
| *Disruption management macro-approach* | *Different application environment* |
| *Online combination problem method* | *Decision are taken manually* |

***Table 9***: *Summary table "useful aspects-limitations" of the railway disruption model.*

The objective of the last section of this chapter is to resume all the principal aspects that we have found during this analysis.

## *Critical conclusions summary*

During *chapter 2.2.1* we focused on disruption management and we tried to describe the state of art of the approaches used nowadays to tackle this problem. We started analyzing General control techniques applied by cybernetics and we found that the three approaches on which they are based (Using a buffer; feedback; feed-forward) are useful also for our purposes.

After we focused on how disruption management is tackled by other industries (*railway and airline*) that face problems comparable to the one tackled by urban public transport system.

The logics explained in general control methods are used by both airline and railway industries that have been trying to improve the way of tackling disruption events for years. We have found interesting and adaptable to our case the general approaches used by them to tackle critical situations. The disruption management process starts with a continuous monitoring of the operations that has the aim to trigger an iterative process that has the objective to identify, evaluate and then implement corrective actions when a conflict between actual and planned operations is detected.

*Figure 37* shows the approach schematically.

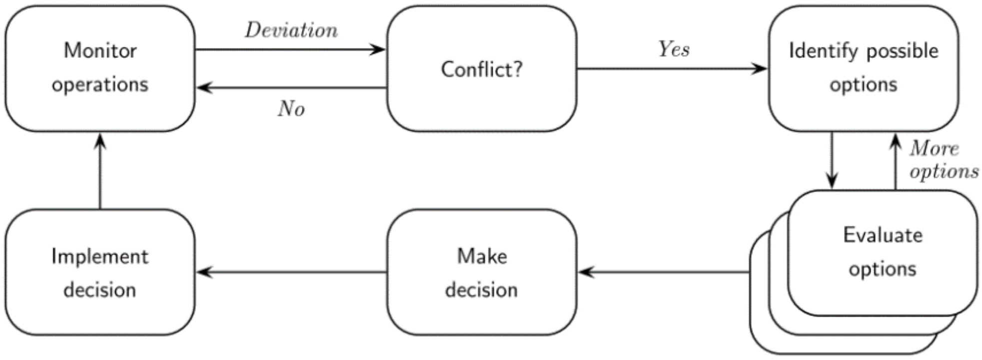



***Figure 37****: Guidelines for operational monitoring.*

Another aspect valuated useful is the use of the technique called *Online combination problem* that, rather than trying to describe the possible outcomes at the occurrence of a disruption by enumerating possible future scenarios, tries to *describe the uncertainty of the situation as an online combinatorial optimization problem.* This approach has been evaluated useful in dealing with the high level of uncertainty and variability that characterizes disruption events.

A last source of inspiration comes from the Decision support system tools that are used by airline industry to help operators in taking the most efficient and effective corrective actions. The ability of this system to process enormous amount of data in a little amount of time providing prompt and useful suggestions to operators leaving them the decisional power to implement them has been evaluated of extreme value also for our case.

After having built a general knowledge about disruption management and having understood how it is tackled by other industries that have to face similar problems to the one of our concern, our focus shifted on public transport that operates in urban areas.

## 2.2.2 Operational management in urban public transportation system

In this last chapter our attention moves on *operational level in urban public transport system (UPTS).* After having outlined how UPT companies tackle the disruption management issue our main objective is to analyze the operational instruments at disposition of control room operators. In the end we will verify which are the indicators that are currently used to evaluate performances and we will identify which of them can be utilized as guideline for the identification of the service reliability algorithm objective function. ***Figure 38*** briefly presents the content that we will tackle along this chapter.

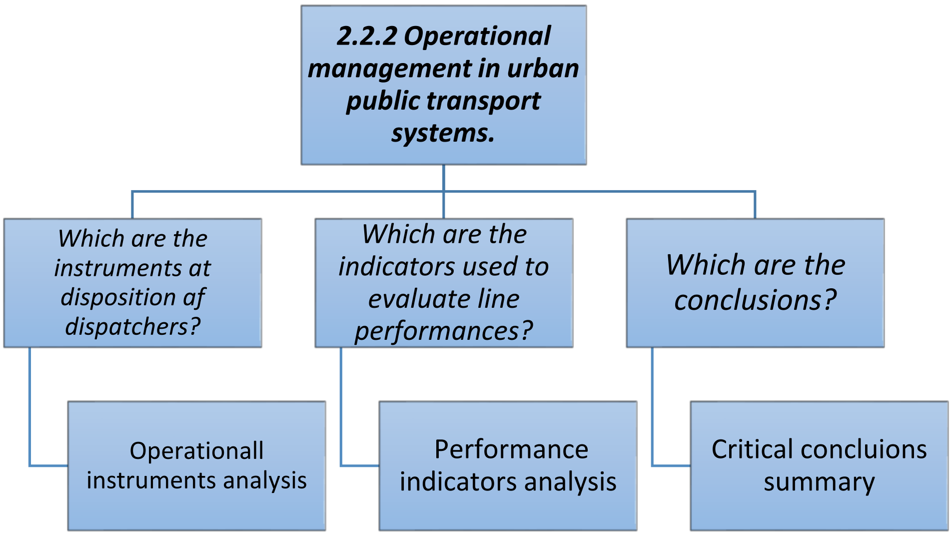



***Figure 38:*** *Chapter 2.2.2 structure.*

### *Operational instrument analysis*

Now we will perform an in deep analysis on the operational instruments at disposition of dispatchers to mitigate service variability and consequently increase the service level offered to passengers. *Van Oort (2011)* during his research about service reliability analyses carefully the work done by *Cham and Wilson (2006)* that separates the instruments at disposition of public transport companies in two different categories:

1. ***The first category*** of instrument are also called ***responsive remedying instrument*** because they try to solve inefficiencies in a reactive way.

2. ***The second category of instruments*** are also called ***preventive instrument*** because they try to be proactive in tackling inefficiencies.

At the operational level, the *main applied instruments are of the responsive type.*

*Van Oort (2011)* presents the relation between responsive operational instrument and the requirements that they need in order to be implemented at strategic and tactical level in *figure 39*. Later we will analyze in detail all the operational instruments (divided in *responsive* and *preventive* instruments) listed in *figure 39*.

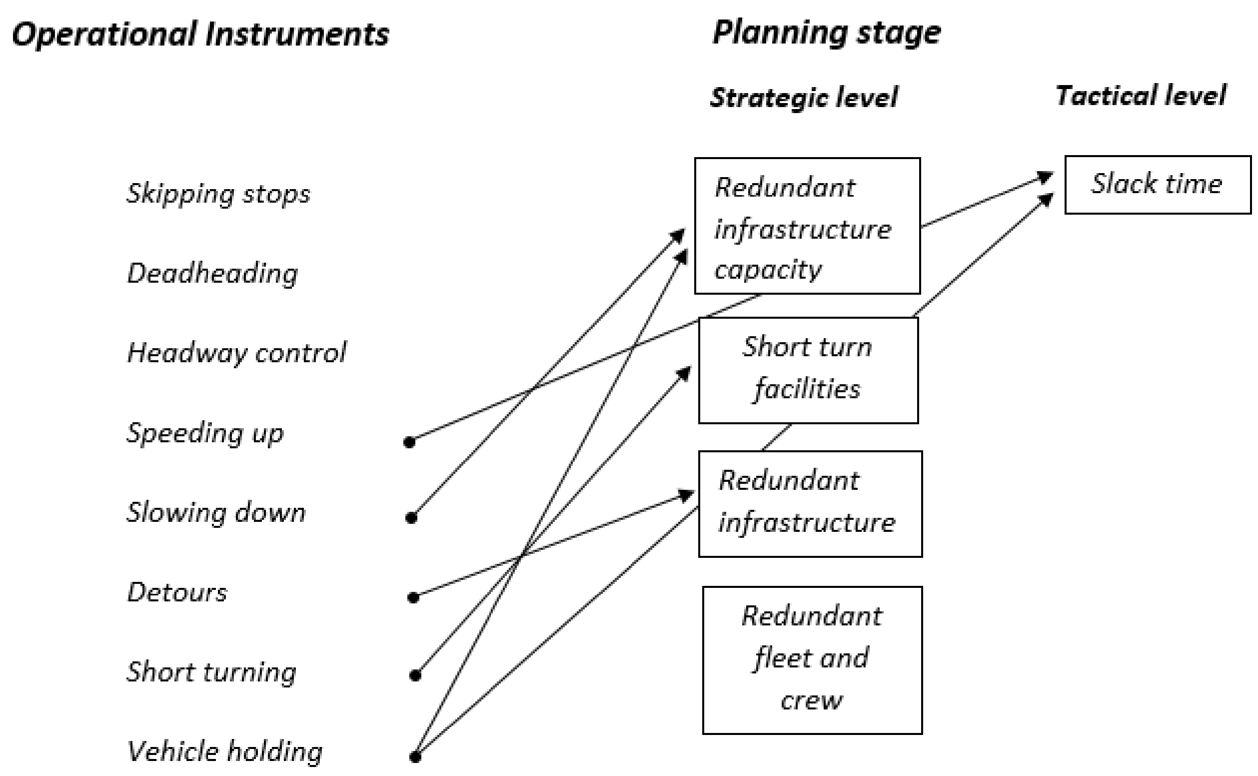



***Figure 39:*** Operational instruments and their relation with planning stages; (Van Oort 2011).

The OIs listed here are the ones used commonly by the dispatchers to tackle critical situation; they are used to restore service reliability when disruption events or disturbances generate a noticeable gap between actual and planned operations.

## *Operational instrument that does not require planning conditions*

- Skipping stops

When dispatchers decide to apply this operational instrument one or more (minor) stops are not served. If a vehicle is accumulating delay it is possible to make it skips one or two stops, in this way it is able to avoid the dwell time needed to board and alight passengers and can recover part or all the delay. *Koffman (1978) and Eberlein (1998)* studied this kind of operational instrument claiming that applying this strategy is only useful if the number of passengers travelling over the "skip- stop part" of the route is large and the number of boarding at this section is low. Because this is the case in which the passengers that have a bed perception of the service are way less that the passenger that are going to benefit from a restoration of the actual operation. (*See figure 40*).

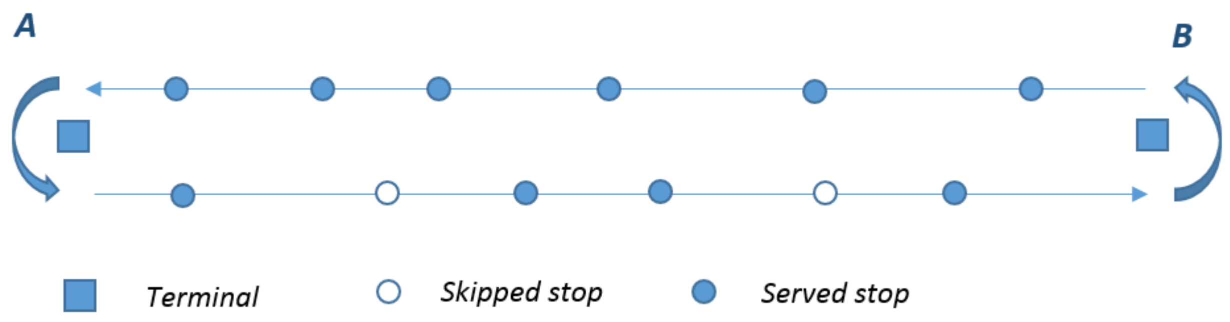



***Figure 40***: *Skip-stop in direction A-B.*

- Deadheading

Deadheading is an evolution of skipping stop in which are skipped all the stops that are in the last part of the route. The delayed vehicle is able to catch up with the planned operations because the dwell time is not needed anymore. Thanks to this it can recover all the delay, arrive at the terminal and begin the next trip on time. Also in the application of this operational instrument is present the trade-off between the passengers that are waiting in the last part of the route and the one that are waiting in the other direction. It can be applied to one up to all the vehicle that are serving the line. (*See figure 41*).

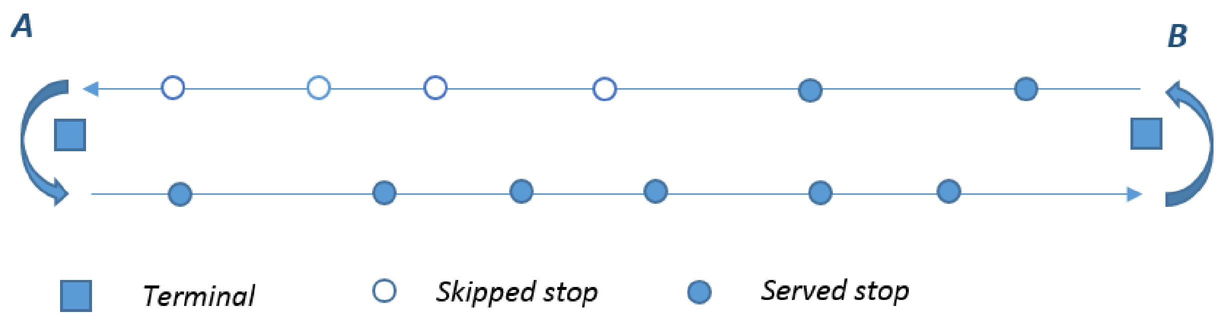


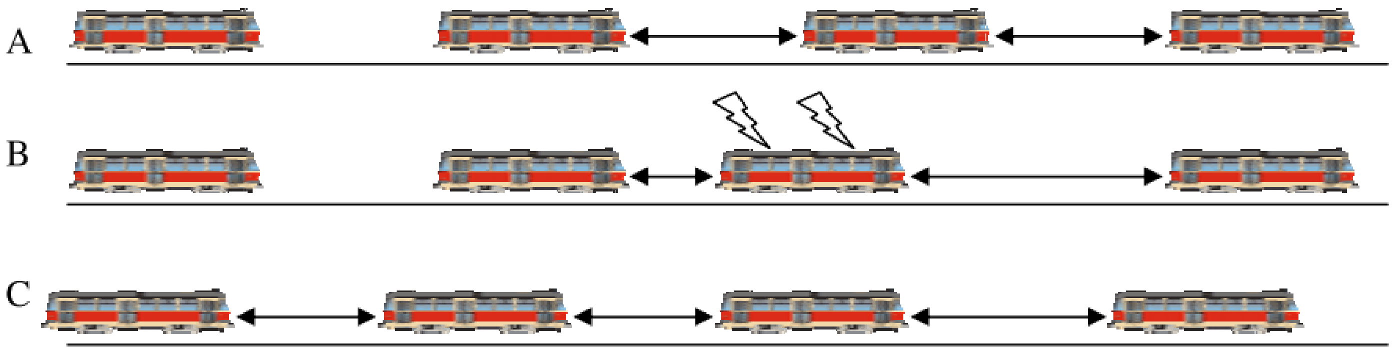

***Figure 41***: *Dead-heading in direction B-A.*

### Headway control

The aim of this operational instrument is the management of the regularity of the line (having regular intervals between consecutive means). Having a regular line is of extreme importance when the service is performed on frequency and not on punctuality (for example during pick hours) because during these parts of the day passengers tend to arrive at the stops randomly and as consequence their average waiting time can be way longer if the vehicles are not regular. In case of irregular headways is very easy to have overcrowded means, this lower the level of comfort perceived by passenger *(chapter 2.1.2*). In *figure 16, chapter 2.1.2* Van Oort illustrates the overcrowding due to irregularity.

If a vehicle is delayed in high frequency services, headway control may be applied. *Van Oort and Van Nes* (*2009*) studied in deep this operational instrument; *figure 42* shows how they represent the principle of headway control.

"*Due to a delay, the headway before the vehicle increases and the headway behind it decreases. By delaying these vehicles, regularity will partly restore. This kind of control may be applied to all vehicles on the line. Either the control room may be in charge or the driver himself. In both cases, actual information should be available of location and headway adherence. Speeding up the delayed vehicle may be helpful as well, but is often hard, due to security restrictions*." (*Van Oort and Van Nes 2009*).




*A: Vehicles drive with equal headways ;*

*B: One vehicle is delayed and the headway in front increases, behind it decreases;*

*C: By slowing down successive and preceding vehicles the regularity will be partially restored.*

***Figure 42****: Principle of headway control.*

### *Operational instruments requiring planning conditions*

This category of operational instruments differs from the previous one because are needed some requirements at tactical and strategic level to apply them. So, in order to make them really effective it is necessary to have done a good job during the design phase otherwise their implementation on the line could worsen the variability of the service rather than improving it. For the concern of this thesis we will focus our energies only at operational level, this means that for the application of this operational instrument we will inherit the advantages and the disadvantages that characterize the current situation. *Van Ort* with the relation chart presented in *figure 39* shows schematically the relations between these OIs and the strategic and tactical aspects that need to be taken into consideration to make them effective and capable to restore service reliability when needed.

- Speeding up vehicles

This operational instrument consists in both accelerating the vehicle and increasing the stopping time. The application of this OI has some limitation because the safety of passengers and drivers it is an aspect of crucial importance and this sometimes denies its usage. Another aspect that it is necessary to take into consideration is that the presence of traffic congestions make impossible its implementation.

Now it is worth to introduce and to explain its relation with the design timetable, in fact the amount of slack that is inserted during the design phase is fundamental for the application of this operational instrument. *Van Oort* in his PhD thesis clarify the relation between the operational instrument and the slack inserted during the design phase with a simple and clear example: *" If an operational speed of 25 km/h is possible and the trip times are based on 20 km/h, speeding up is quite easy. If in this case trips are designed on an average of 24.5 km/h speeding up gets harder and the effect will be smaller".*

- Slowing down vehicles

Slowing down vehicles to increase schedule adherence may consist of both *decreasing driving speed* and *increasing stopping time*. If vehicles drive faster than they are planned to do (due to both operational and timetable issues), slowing down helps them to get back on schedule. The requirement in the network design for this instrument is redundant capacity on the line or at the stop where speed is reduced. Especially if infrastructure is shared with other traffic or public transport, delays may be introduced for them. Mostly, the capacity constraint is important for rail bound service due to less flexibility, but also bus services may experience negative consequences of restricted capacity. *In Gifford (2001), Banks (2002) and Chang (2003)* slowing down vehicles is described further in detail.

- Detours

A detour is an alternative route between parts of the original route. Detours are a very effective measure in case of blocked infrastructure. But also when infrastructure is still available (i.e. recurrent delays are experienced), schedule adherence may be enhanced by applying detours. If detour routes are available enabling vehicles to catch up (e.g. by shortcuts) schedule adherence may increase again. Important condition for applying this instrument is that redundant shortcut infrastructure should be available (in time and space) and especially in rail bound systems they should be designed and constructed additionally. This will need attention at the strategic level and will increase the costs of the infrastructure.

- Short turning

This is another powerful operational instrument to recover delay and re-stabilize the regularity of the system. The vehicle on which is applied this OI turns in a point of the line as presented without passing for the terminal (*see figure 43*). This OI has to be adopt carefully because, also if it is able to recover quickly a big delay, it has a bad impact on the comfort level perceived by the clients. Short turning can be applied if part of the line is impracticable due to an accident or in case of other obstacles that deny the vehicle passage. For its application is necessary to design in advance the infrastructure that allow the means to turn (this is mainly for rail bounded means but also busses need to have enough space to make this kind of maneuvers).

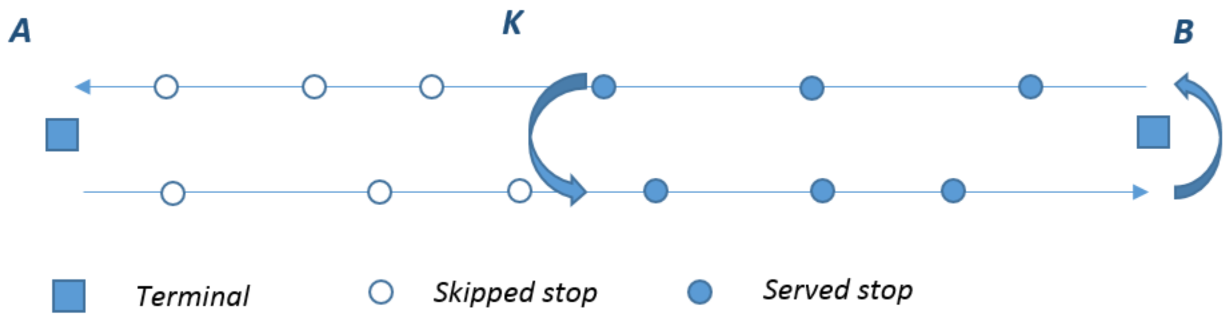



***Figure 43****: Short turning at point K.*

- ### Vehicle holding

*Dessouky et al. 2003, Fu and Yang 2002* analyze in depth this operational instrument. In their research they describe holding as the practice to stopping the vehicle in a certain point (called holding point) for an amount of time that allows to recover the delay and re-stabilize the service level of the line. To apply this operational instrument is important to take in consideration during the design phase the necessity to have some points on the line in which it is possible to stop the vehicle. Another aspect to take in consideration at tactical level is that the efficacy of this OI it is influenced also by the slack time of the line (tight or loose time table design). The strategies used to apply this operational instruments are fundamental to not decrease the perception of quality of passengers, so it is important to spread the holding time as much as possible in order to not make feel passenger the sense of inefficiency caused by staying still.

All the operational instruments presented in this section are useful to maintain the line regular and avoid propagation of delays. It is important to understand that some of them have also an impact on passengers that for instance have to alight because the vehicle needs short turning to recover a delay. These kind of instruments are for sure powerful in recovering a critical situation but at the same time has a bad impact on the travelers. Since the final objective is to increase the level of satisfaction of the clients hence attract more of them and increase ridership it is important to use them very carefully. It is important to encourage the use of ones that do not have side effects on passengers and if there is no other choice, it is important to provide dispatchers with info that helps them in understanding their impact on customers.

Now that we have a general idea about disruption management methods in urban public transport system and not only. It is interesting to understand the state of art of the tools that public transportation companies have at disposition to elaborate and analyze data.

### *Performance indicators for service reliability analysis*

In order to improve service reliability it is essential to monitor and predict its level. For this reason we need proper indicators. The commonly used indicators which are supposed to express reliability are related to the measurement of the punctuality, but accordingly with what found in *chapter 2.1.2* the measurement of the headway variations can be consider a more accurate indicator for its monitoring.

*Van Oort* during his research on service reliability lists and describes different indicators explaining that given the stochastic nature of public transport operations, statistical measures such as standard deviation or percentiles are logical indicators. A typical example is the coefficient of variation of headway, as shown by *equation 1 (Cham and Wilson 2006)*. This indicator may relate to an aggregate characteristic of a public transport line, or a branch served by a set of public transport lines. *Equation 1 shows the coefficient of variation of actual headways per stop*, but in practice expressing this indicator on line level is also common use, by calculating the average value over the stops.

$$CoV\left(H_{l,j}^{act}\right) = \frac{StD\left(H_{l,j}^{act}\right)}{E\left(H_{l,j}^{act}\right)} \qquad \textit{Equation 1}$$

Where:

$CoV\ (H_{l,j}^{act})$= *Coefficient of variation of actual headways of line l at stop j;*

$H_{l,j}^{act}$= *Actual headway of line l stop j;*

$StD(H_{l,j}^{act})$= *Standard deviation of line l and stop j;*

$E(H_{l,j}^{act})$= *Expected headway of line l at stop j.*

In practice, however, the use of purely statistical measures is limited. Commonly used indicators focus either on *punctuality*, the extent to which the scheduled departure times are met, or on *regularity*, the variation in the headways.

Taking the perspective of the production process (*chapter 2.1.2*), the percentage of trips performed within a predefined bandwidth, are useful reliability indicators. *Equation 2* expresses this type of indicator for average departure deviation for a complete line. This indicator represents to which extent the production process requirements are met.

$$P_l = \frac{\sum_{j=1}^{n_{l,j}} \sum_{i=1}^{n_{l,i}} P_{l,i,j}\,(\alpha^{min} < D_{l,i,j}^{act} - D_{l,i,j}^{sched} < \alpha^{max})}{n_{l,i} * n_{l,j}} \qquad \textit{Equation 2}$$

Where:

$P_l$ = *Relative frequency of vehicles on line l having a schedule deviation between* $\alpha^{min}$ *and* $\alpha^{max}$*;*

$P_{l,l,j}$ = *Relative frequency of vehicle i on line l having a schedule deviation between* $\alpha^{min}$ *and* $\alpha^{max}$ *at stop j;*

$D_{l,i,j}^{act}$= *Actual departure time of vehicle i on stop j on line l;*

$D_{l,i,j}^{act}$= *Scheduled departure time of vehicle i on stop j on line l;*

$\alpha^{min}$= *Lower bound bandwidth schedule deviation;*

$\alpha^{max}$= *Upper bound bandwidth schedule deviation;*

$n_{l,i}$ = *Number of trips of line l;*

$n_{l,j}$ = *Number of stops of line l.*

Punctuality may also be defined as the (average) deviation from the timetable at a specific stop, a set of stops, or for all stops of a line. The latter is shown by *equation 3 (Hansen 1999).*

$$P_l = \frac{\sum_{j=1}^{n_{l,j}} \sum_{i=1}^{n_{l,i}} |D_{l,i,j}^{act} - D_{l,i,j}^{sched}|}{n_{l,i} * n_{l,j}} \qquad \textit{Equation 3}$$

Where:

$P_l$=*Average punctuality on line l.*

Please note that this formulation has an important shortcoming. It does not indicate whether vehicles depart too early or too late, which has a large impact on passenger waiting time. If only a set of stops is considered, the location of the stops may be of influence.

Headway deviations is one of the valuable way to express the regularity of the line. As analyzed and reported in chapter 2.1.1 (*Customer source of value*) the service reliability is composed by level of comfort perceived by passengers plus level of travel time reliability and in chapter 2.3 (*Causes of service variability unreliability*) it is explained how a high level of service regularity impacts positively on these two aspects. *Hakkesteegt and Muller (1981)* introduced the ***PRDM*** *(Percentage regularity deviation mean)*, which shows the average deviation from the scheduled headway as a percentage of the scheduled headway. The calculation of the PRDM is presented in *equation 4.* This equation shows the calculation of the ***PRDM*** per stop. Taking into account all the stops, a calculation of the *PRDM* for the total line is also possible.

$$PRDM_{l,j} = \frac{\sum_i \left| \frac{H_{l,j}^{sched} - H_{l,i,j}^{act}}{H_{l,j}^{sched}} \right|}{n_{l,j}}$$ *Equation 4*

Where:

$PRDM_{l,j}$= *Relative regularity for line l at stop j;*

$H_{l,i}^{sched}$= *Scheduled headway for vehicle i on line l;*

$H_{l,i}^{act}$= *Actual headway for vehicle i on line l at stop j;*

$n_{l,j}$= *Number of vehicles of line l departing at stop j.*

All measures presented focus purely on characteristics for the supply side, but it should be noted that indicators for punctuality and regularity are linked with travelers side as well. These indicators do not quantify directly the impact that variability has on travelers, such as the extra travel time but in all these indicators presented also the passengers are taken into account because as seen previously (*chapter 2.1.2*) irregularity of the service create huge discomforts both for the demand and the supply side since they are strictly related one another. So Maybe it’s not considered directly the travel time or the level of comfort considered but having a high level of regularity of the line assures an average minor travel time for passengers than the one offered by an irregular line. Hence maximizing the regularity of the line means minimizing the travel time for the passenger using the resources available in a certain moment. Another aspect that it is important to consider is the strict relation that exists between passengers' comfort level and the line regularity (*figure 16*).

### *Critical conclusions analysis*

In this last chapter of the literary review analysis, we have described the tools that are used nowadays by urban public transport system to tackle disruption management issue. In the beginning we studied in detail all the operational instruments that are currently used by control room operators to solve criticalities and we have understood that some of them are really powerful but at the same time generate also negative effects on passengers. For this reason it will be fundamental to consider also this aspect during the creation of the DSS we are going to introduce along this thesis. In the end we have described different indicators that are utilized by urban public transportation companies to evaluate performances. We have found that the *percentage regularity deviation mean (PRDM)* could be a good KPI to evaluate service reliability of the line and it has been suggested as guideline for the part of the team in charge to create the *service reliability algorithm* and *objective function*.

# 3. Thesis’ framework

During the literary review we have analyzed all the aspects that characterize disruption management in urban public companies, we focused also on the different approaches taken by other industries to tackle this issue. The main objective of this section is to start shaping the DSS utilizing the knowledge gathered during chapter 2. This section will be constituted by two parts:

1. ***General systems and logics (chapter 3.1):*** In this first part we will focus generally on the main logics that will lead the support system we are going to introduce. Initially we will recall the concepts of general control methods, already studied in *chapter 2.2.1,* contextualizing them in the specific case of surface public transport system that operates in urban areas. After our attention will move on describing the overall logics that characterize the disruption management process adopted by other industries (airline, railway) that will be utilized by our support system.

2. **Disruption management support system (DMSS) skeleton (*chapter 3.2*):** During the second part of this chapter we will introduce the structure of the DMSS presenting the main components that form it. We will increase the level of detail in their description only on the aspects that have been presented during the literary review analysis. A comprehensive and detailed analysis of the system will be performed during *chapter 5* “***Thesis’ model***”.
   Three main part will compose the support system, we will be more specific along *chapter 3.2*:
   - *Data side;*
   - *Process side;*
   - *Additional information side.*

## 3.1 General systems and logics

Before describing the general structure of the disruption management support system (DMSS) it is worth to analyze the system starting form a broader point of view, this introductive analysis is divided in two sections:

1. ***General control methods:*** This part is constituted by a description of the general control method principles and by a short analysis to explain why they are suitable in improving the performances of the surface public transportation systems (SPTS) that operates in urban area. (*Chapter 2.2.1*)

2. ***Overall logic of the system:*** In this part are described the main logics of the DMSS that are used in other industries and that fit SPTS purposes.

### *1. General control methods*

To improve service reliability it is necessary to maximize the match between operations and planning. After analyzing the operational process of the surface pubic transport system (SPTS) it has been found that general control methods are suitable means to achieve a good control over output variability (*Heylighen and Joslyn 2001).*

In the literature analysis we have found that variability and unreliability may arise due to both internal and external factors and that those two aspects have a great impact on service reliability. Controlling is a method that may reduce or remove the variability and unreliability, increasing consequently the level of service reliability. In *Van den Top (2010)* is presented a description on how using cybernetics and how describing reliability of systems. Cybernetics is the general science of controlling systems. It focuses on functions and information flows rather than on what the system consists of and it may therefore be applied to SPTS. The cybernetic principles are compatible with those of process control theory that aim at *maximizing production while maintaining a desired level of product quality and safety and making the process more economical (Hahn and Edgar 2002).* Cybernetics makes use of basic notions; below we will show them form the SPTS perspective:

- *The desired output:* The service carried out on the lines;

- *Disturbances*: The disruption events and little disturbances that interacting with the operational process generates variability;

- *<u>The regulator</u>*: This is the DMSS that has the objective to adjust the process;

- *<u>The buffer</u>*: A buffer consists in an addition of resources (*time, crew*) that enable the system in carrying out the correct output even when disturbances occur.

In literature are analyzed different kind of control methods *(Ashby 1956).* The goal of the control is to achieve the desired values of the output under disturbance(s). *Three types* of control are presented and each of them has some particularities that have been evaluate suitable for our purposes:

- ***Using a buffer*** *(figure 44)*: A buffer is often determined during the design of a system. It absorbs a number of disturbances. This method is passive, since no adjustments can be made after the design and the buffer is available independently form the presence of actual disturbances.

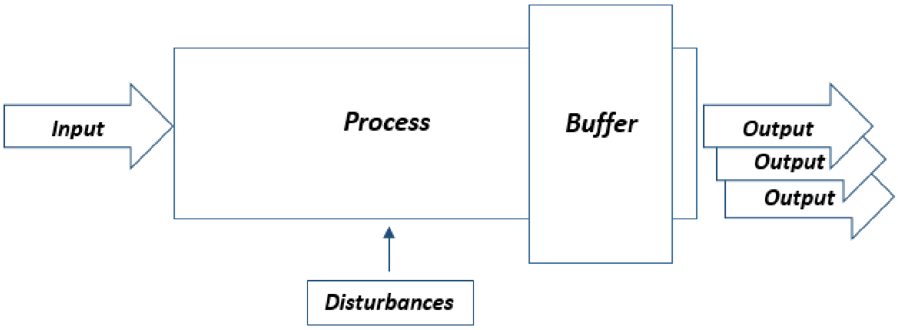



***Figure 44****: Control methods: Buffer.*

- ***Feedback*** *(figure 45)*: This is a reactive mode. The regulator measures how much the output deviates from its desired value and then acts afterwards. Instruments affecting the process and thereby reducing the impacts of disturbances are applied.

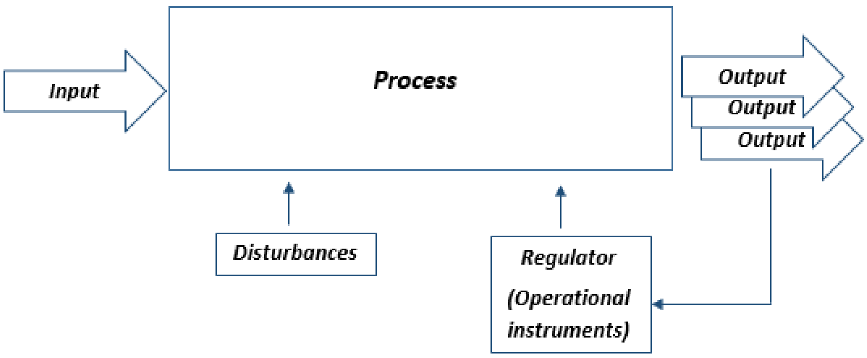



***Figure 45****: Control methods: Feedback.*

- ***Feed-forward*** *(figure 46):* This mode is anticipatory; the regulator predicts the disturbances and then assesses the impacts on the output. Measures are chosen that influence the process such that no or a minimized effect of the expected disturbances on the output will be noticeable.

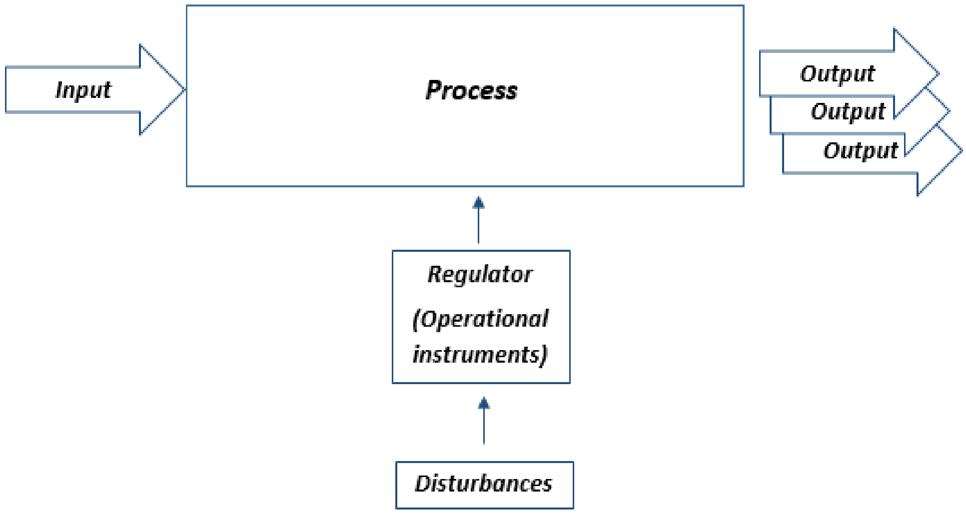



***Figure 46***: *Control methods: Feed-forward.*

The ambition of the DMSS will be to combine this three kind of control types:

- ***Using a buffer method*** will increase the level of flexibility (increase crew and time) of the entire surface public transport system, consequently it will improve the ability to react to critical situation. The idea is to make the crew scheduling entity more flexible in order to have an extra buffer of time and being able in this way to better manage disruption events.

- ***Feedback method*** will be fundamental since the DMSS has always to monitor the output level of variability in order to understand if the corrective actions taken are giving the expected results.

- ***Feed forward method*** will make the system proactive to inefficiencies, in this way there will be enough time to intervene before the situation gets irrecoverable (*foreseeable inefficiencies, figure 20*). The idea is that the system will continuously monitor some parameters (alerts) that describe the level of service offered; in case its performances will be judged insufficient, an algorithm will suggest a set of operational instruments to apply on the line to restore the service reliability at a satisfactory level.

## *2. Overall logic*

The overall logic of the DMSS is the same used in the airline and in the railway industry. For airline operations, Kohl et al. (2007) describe the disruption management process by *figure 47*. The process is similar in the railway system as well; in fact the two industries follow the same macro-approach.

The disruption management process can be called also operational process since its core, namely the monitoring of the resources, continuously takes place also when no disruption has occurred. The process involves monitoring the resources and evaluating possible conflicts whenever the process deviates from the planned operations.

If a conflict is indeed detected, an iterative process of identifying and evaluating possible corrective solutions is performed. when an appropriate decision is reached appropriate countermeasures are suggested to operators that will decide in the end if implement them or not.

When the operational plans are carried out in practice, they are monitored closely. The performances of the system are monitored carefully to ensure that it is providing the service as planned or re-planned. Taking into account that any deviation between the planned and the actual position of a resource may cause a conflict in the resource assignment.

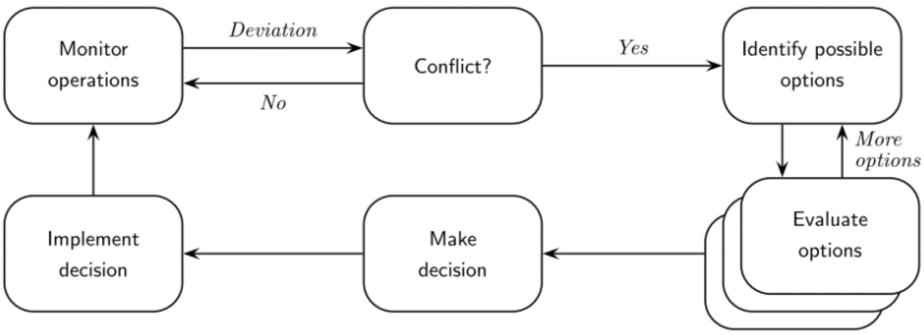



***Figure 47****: Disruption management approach, overall logic.*

The entire process can be divided in *three principal steps*:

***The first step*** is to determine if a detected deviation can result in a conflict. Predicting upcoming conflicts requires knowing the propagation of delays and resources' availability into the future.

The ***second step*** begins in case of a conflict in the timetable or in the assignment of resources, at this point the dispatchers, helped by the DMSS, must decide how to react to it. In case of small deviations it may be relatively simple to assess the possible options, but in case of a more involved disruption there are often numerous possible alternative countermeasures with different impacts on the system performances.

The system to suggest corrective actions for bringing back the line to an acceptable level of efficiency has to intervene on three dimensions:

1. *TTD (Time table design);*
2. *VS (vehicle scheduling);*
3. *CS (crew scheduling).*

A further complicated part of the decision process is the estimation of the conflict's duration, this problem will be overtaken applying to the algorithm a *wait and see logic*.

The ***third*** and last ***step*** is the ***implementation of the decision in practice***. The practical implementation consists of two major tasks:

- *Evaluation and implementation of the corrective actions suggested by the DMSS;*
- *Communication of the changes to the proper parties.*

The changes in expected arrival times of means at the various stops and terminals are automatically recorded in the information systems by the DMSS, the same goes for changes in the assignment of resources and for rerouted and canceled means. Having always an updated picture of the entire transport system allows the dispatchers to query the DMSS for details on how the resources are utilized in the adapted situation.

Once implemented the suggested corrective actions by the dispatcher the DMSS will monitor the development of the re-planned operations rather than the original one.

A crucial part of the implementation is to communicate the changes to the proper parties. Especially to the crew that needs to know in time any changes to their duties. Once the dispatcher will decide to implement the corrective actions it will communicate to the crew the changes in their duty.

If from the macro point of view the model used by other industries suits at perfection our purposes. We will see in the following sections that this is not true for the single components that constitute the DMSS (*figure 48*).

## 3.2 Disruption management support system skeleton

After this first chapter in which we have analyzed the situation from a broader point of view it is necessary to enter in the main topic. *Figure 48* shows the skeleton of the disruption management support system (DMSS) ideated for surface public transportation system (SPTS) that operates in urban area. In the figure are presented all the components of the DMSS and how they are linked one another.

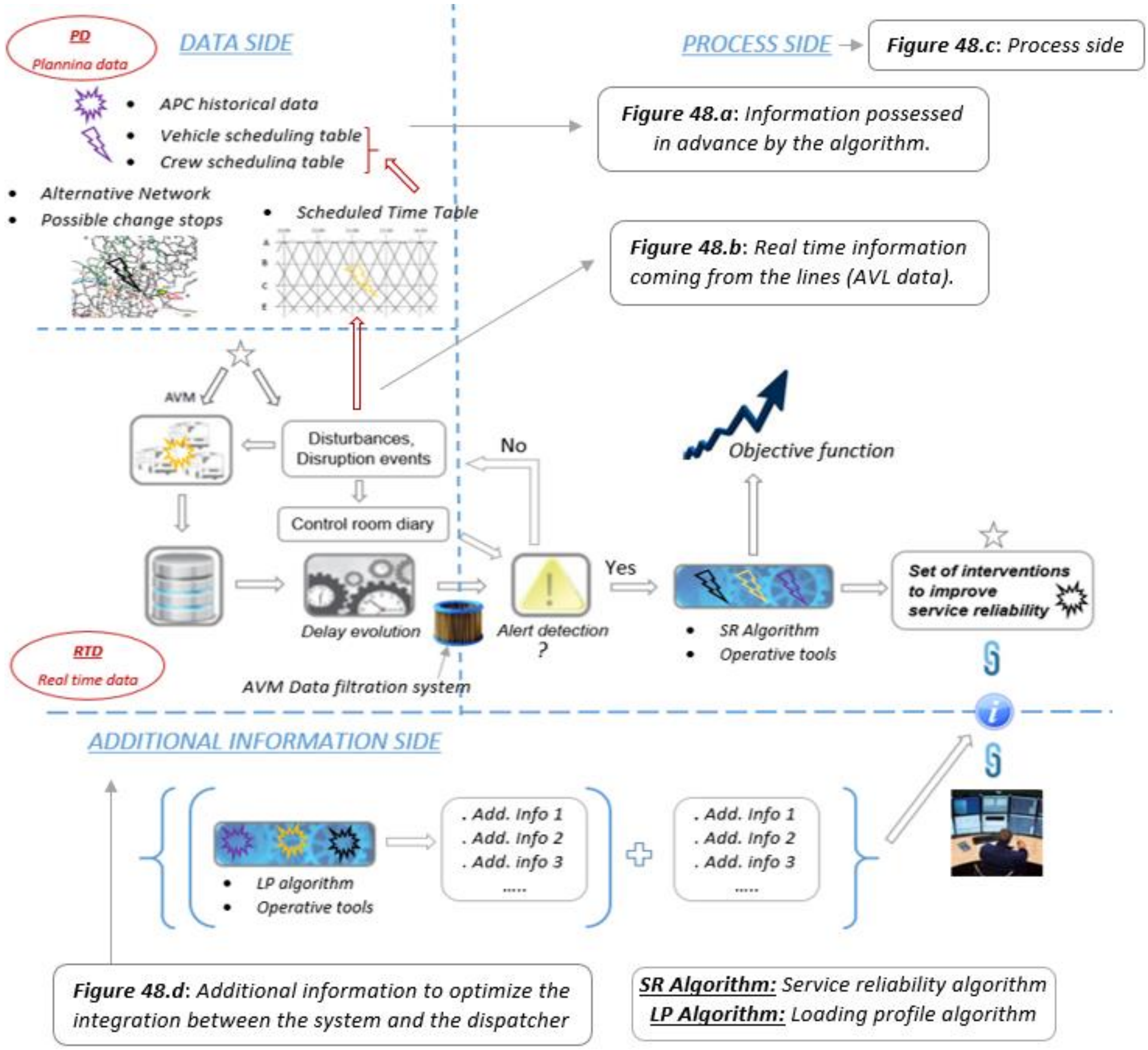



***Figure 48**: DMSS (Disruption management support system) overview.*

The entire system can be divided in ***three macro-sides***:

1. The ***1st macro-side (DATA SIDE)*** is about the acquisition, the management and the cleaning of the real time data coming from the different lines. It is on the left side of *figure 48* it starts from the acquisition of the data coming from the lines and it ends before the alert detection. In this side is presented also the data coming from the planning phase that is known in advance.

1. The ***2nd macro-side (PROCESS SIDE)*** is about processing the real time data coming from the $1^{st}$ part and giving suggestions *(when, where and which operative tools implement)* to the dispatchers to improve the service reliability of the system.
   It is on the right side of *figure 48*, it starts with the alert detection part and it ends with a set of suggested interventions to improve service reliability given by the SR (*service reliability*) algorithm.

2. The ***3rd macro-side (ADDITIONAL INFORMATION SIDE)*** is about generating an entire set of additional information that will have the objective to make the dispatcher aware of the impact on passengers' quality aspects generated by the implementation of the operational instruments suggested by the DMSS. The final goal of this side is to increase the usefulness of this support system and to make it a tool completely integrated with the operator. It is on the lower side of *figure 48* and it is linked with the set of suggestions generated by the DMSS.

The DMSS will work to optimize an ***objective function*** that has the aim to increase the service reliability of the SPTS (surface public transport system) .

As found in the literature analysis the ***service reliability*** (*travel time reliability + level of comfort*) of the surface PT system is the aspect that passengers care the most (*Jackson and Jucker 1981, Black and Towriss 1991, König and Axhausen (2002)).* But we will not limit our attention on this aspect, in fact we will provide the dispatcher with additional info that will help him in having an broad view on the impact that implementing certain kind of operational instruments will be generated on passengers.

In literature there are a lot of studying regarding indicators able to express the performances of surface PT system *(Cham and Wilson (2006), Hansen (1999)).* In the end, the indicator valuated more suitable in describing service reliability is the one able to express headway deviations (one of the major cause in the decreasing of service reliability).

*Hakkesteegt and Muller (1981)* introduced the ***PRDM*** *(Percentage regularity deviation mean*. The calculation of the PRDM is shown in *equation 5.* This equation shows the calculation of the ***PRDM*** per stop. Taking into account all the stops, a calculation of the *PRDM* for the total line is also possible.

$$PRDM_{l,j} = \frac{\sum_i \left| \frac{H_{l,j}^{sched} - H_{l,i,j}^{act}}{H_{l,j}^{sched}} \right|}{n_{l,j}}$$

*Equation 5*

*Where:*

$PRDM_{l,j}$*= Relative regularity for line l at stop j;*

$H_{l,i}^{sched}$*= Scheduled headway for vehicle i on line l;*

$H_{l,i}^{act}$*= Actual headway for vehicle i on line l at stop j;*

$n_{l,j}$*= Number of vehicles of line l departing at stop j.*

This indicator focuses purely on characteristics of the supply side, but it should be noted that indicators for punctuality and regularity are linked with traveler's side as well. This indicator do not quantify directly the impact the variability has on travelers, such as the extra travel time. But it is possible to claim that also the passengers are taken into account because irregularity of the service create huge discomforts both for the demand and the supply side since they are strictly related one another (*Noland and Small 1995, Noland and Polak 2002, Van Oort and Van Nes 2004 and Van Oort 2011)*. So Maybe it's not considered directly the travel time but having a high level of line's regularity assures an average minor travel time for passengers than the one offered by an irregular line. Hence maximizing the regularity of the line means minimizing the travel time for the passengers using the resources available in a certain moment. This equation it will be suggested as guideline to the operational research group of Politecnico di Milano that will be in charge of the algorithm and of its objective function creation.

Now that we have a general idea on how the system works and from which element it is composed and which is the objective function it has to maximize it is important to go further in detail analyzing each single component in order to understand which aspects have been already studied and which one have to be ideated from scratch. To carry out this studying we have decided to follow the division already presented in figure 48, we'll start tackling the ***data side*** for continuing later on with the ***process side*** and the ***additional information side.***

### 3.2.1 Data side

The ***Data side*** of the DMSS can be divided in two main categories:

1. ***Information possessed in advance by the algorithm (PD→Planning data)***(*Figure 48.a*)

In this part are presented three elements (see *figure 49*) that are not related with the real time DATA acquisition from the lines. This information is possessed in advance by the algorithm, it enables the *SR algorithm* and the *LP algorithm* to generate a set of suggested interventions that if implemented can improve the service reliability of the line.

2. ***Real time information coming from the lines (RTD →real time data)*** (*Figure 48.b*)

This is the part of the system (see *figure 50*) that manages all the information coming from the lines and clean it in real time in order to provide reliable data that will be elaborated in the second part (*process side*). The entire system can be seen as a circle because all the information coming from the lines, once elaborated by the DMSS, generates a set of suggested interventions that, if implemented, create a new situation on the line. The new situation on the line produces a new flow of information that is the new In-put of the system.

## *1. Information possessed in advance by the algorithm (figure 48.a)*

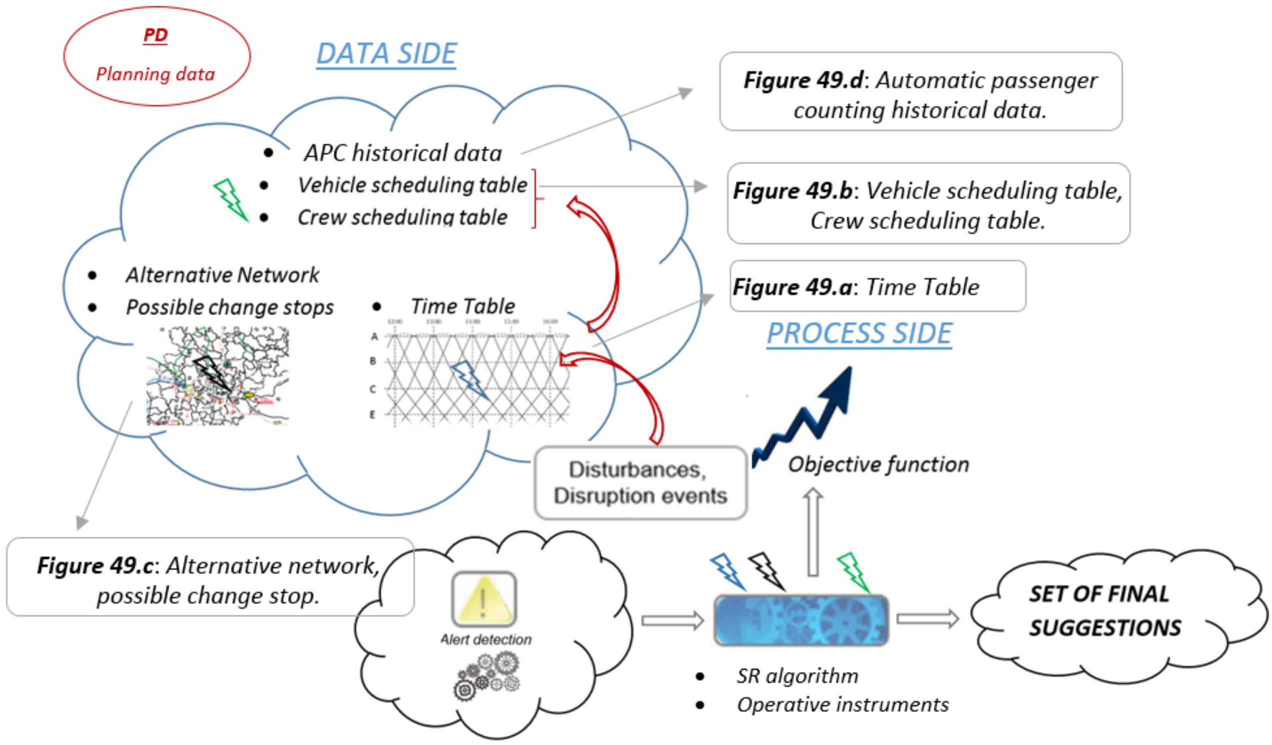



***Figure 49***: *DMSS (Disruption management support system's Data side (Info possessed in advance by the system).*

As it is possible to see from *figure 49* in the blue cloud there are the three components that interact with the algorithm sides of the support system. This information has updated daily to provide the DMSS with all the elements that it needs to work properly.

The *four components* are:

1. *Time table design of the day;*
2. *Alternative network and possible change stops;*
3. *Vehicle scheduling table and crew scheduling table;*
4. *Automatic passenger counting historical data.*

### 1. Time table design (TTD) of the day (*see figure 49.a*)

*The TTD is the document in which is reported the time of all the passages at the stops of all the means on each line during the day*. This information is fundamental since it is used by *objective function* (OF) of the service reliability algorithm. The OF changes with the time because it is related to the number of means that are serving the line. So, thanks to the TTD, the SR algorithm will know in advance which is the optimal scheduled headway hence the optimal regularity of the line, furthermore the objective function will try to keep the actual operation as aligned as possible with the scheduled one; in the end the regularity of the line will be the primary goal of the system. *The headway is the basic variable on which it is built the objective function and it represents the time that passes between two consecutive passages of two consecutive means at a to a certain stop see equation 5).*

2. Vehicle scheduling table and crew scheduling table (*see figure 49.b*)

*Crew scheduling table and vehicle scheduling table are the documents in which are inserted all drivers' shifts and all the means used by them to perform their duty*. The SR algorithm will use this info to know which drivers are on the line, which vehicle they are driving and when/where their duty it is supposed to finish. Thanks to this info the algorithm will be able to apply some of the new operational instrument ideated to make the public transportation system a less stiff entity. As already mentioned the new OIs (*explained in detail during chapter 5 "Thesis' model*) aim at increase crew schedule flexibility, for this reason it is necessary provide the algorithm with all of the info related to crew, vehicles (*point 3*) and change stops (*point 2b*). Another aspect that is important to considered is the repercussion that a great disruption event can generate on the timetable and consequently on the vehicle scheduling and on the crew scheduling table.

If a critical event that provokes a huge change in the environment in which the system operates happens , a new timetable will be generated manually and after the system will re-allocate automatically the other resources (*vehicle and crew*). As soon as a normal situation will be restored, the system will re-start working using the original time, vehicle and crew tables.

3. Alternative network and possible change stops (*see figure 49.c*)

The SR algorithm uses this information when it tries to apply different kind of *operative instruments* (OIs) to increase the service reliability of the line.

*a.* <u>*Alternative network*</u>: this info is used in the application of OIs that requires a variation from the common travel path (e.g. shirt turning). This kind of operational instruments will be suggested with all the indications on how apply them on the line. For this reason the SR algorithm needs all the set of alternative routes that a certain mean on a certain line, according to its position, can take.

- *Example*

*If we think about the application of a short turning to a tram it is easy to understand that due to its operational constraint (it needs both railways and overhead cables to* *operate) it can perform variation of its travel path only in predetermined places. The alternative network contains all the information about these issues.*

b. <u>*Possible change stops:*</u> This info are used by the new set of OIs that will be introduced to make the public transport system more flexible. The algorithm will know in advance which are the possible change stops on the line in which the driver can change/finish its shift. Nowadays the place where the driver finishes its duty or part of its shift is fixed *(place and time)*. Naturally the other change stops are selected in strategic position on the line (*e.g. close to a vehilces' deposit*).

### 4. Automatic passenger counting (APC) historical data (*see figure 49.d*)

This is the historical data that describes in average the loading profile of the vehicle along the line and the average number of passengers alighting and boarding at each stop. To be clearer in the explanation it is necessary to introduce the technology that allows to obtain this data automatically, we are talking about ***Automatic passenger counting systems (APC).***

Nowadays most of the public transportation companies are equipped with these devices. These systems are electronic machines that count the number of passengers that board and disembark at every bus stop. They, together with AVL systems, form the two most important technologies that every transit system should have. This technology replaces the *schedule checkers* that otherwise are in charge to collect ridership information manually. The historical data collected with this technology gives us the possibility to model the *loading profile of passengers during trips on a specific line and vehicle*.

*MacKechnie (2012*) analyze and explain in depth this kind of technology. We start listing the main advantages and disadvantages that characterize these devices.

*Advantages:*

- APCs can collect ridership for as many as every single trip operated if they are installed on 100% of the bus fleet;

- They also reduce cost, because even if initial startup costs are high in the long term it costs much less to collect ridership information via APC units than it does to hire employees to manually collect it.

*Disadvantages:*

- The main disadvantage is that APC units are sometimes not as accurate as manual collection. APC units collect accurate information from 80 - 95% of the time while manual collection is generally accurate between 90 and 95% of the time.

In the same article written by the American author it is explained how the system works. The core of the APC system is composed by two sets of two sensors each at the same height level that are installed at both the front and rear door. When passengers enter or exit the door they break an infrared beam, which causes a computer to record a boarding or alighting depending on the order in which the two beams are broken. The sensors are enough to provide a gross level of ridership; if stop-level ridership is required, geographic information must be provided by a GPS system such as an Automated Vehicle Locator (AVL) program. Data is then downloaded to a computer for future further analysis.

## *2. Real time information coming from the line (see figure 48.b)*

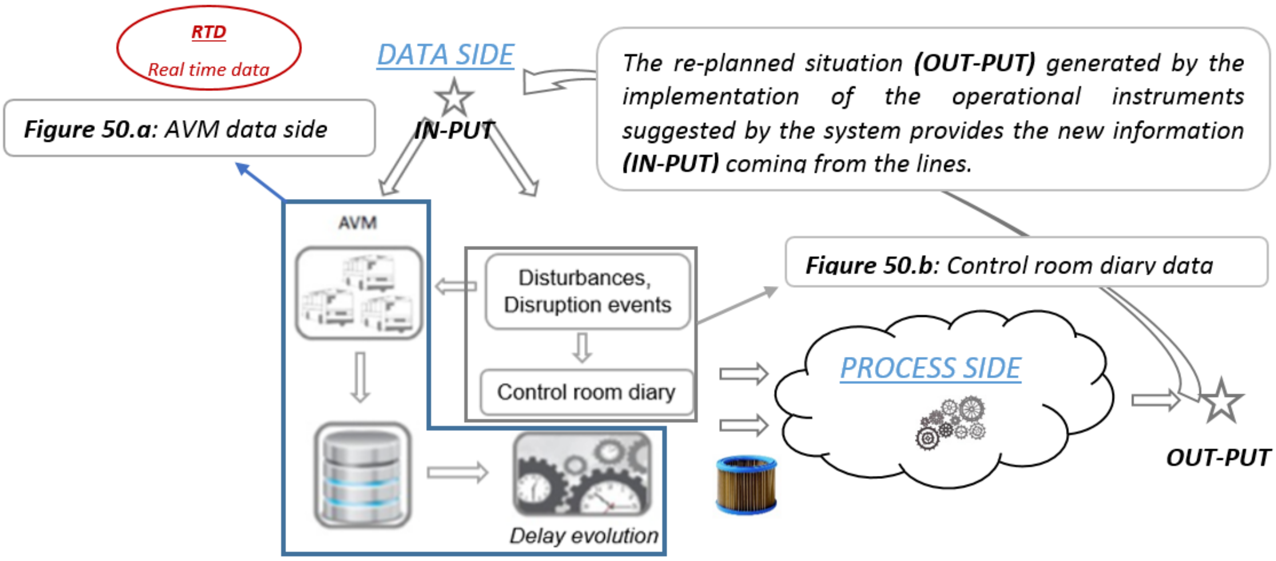



***Figure 50**: DMSS (Disruption management support system)'s Data side (Real time info coming from the line).*

There are two kind of data that will be elaborated by the system:

1. *Activity Vehicle Monitoring (AVM) data;*
2. *DATA coming from the control room diary.*

### 1. AVM (activity vehicle monitoring) (*see figure 50.a*)

AVM system represents a fundamental tool for the integrated management of the urban mobility. AVM allows the automatic acquisition of the principal operational data coming from the service and consequently the management of the information flows needed for the modulation of the service. The main services provided by the system are:

- The monitoring of the vehicle;
- Collection of real time data about the service;
- Distribution of information to the passengers;
- Support to the planning phases;
- Support to the maintenance of the service.

This instrument allows the continuous real time monitoring of all the fleet on the different lines.

In literature these kind of data has been already used to make a posteriori analysis (*Van Oort 2012, GOVI tool, there they are called AVL data*). The systems already proposed used consolidated data.

The ambition of the DMSS is to use ***real time data*** coming continuously from the lines to the central control room.

The fact to use real time data rises a fundamental question:

- ***Which is the level of reliability of using such data?***

In order to answer this question it is important to understand which are the technologies currently used to manage this kind of data. From the literature we know that all the information concerning the location of the different means on the line is sent to the control room through a radiofrequency transmission mechanism, generally the vehicles are divided in two categories accordingly with the transmission technology they use:

1. ***Analogic vehicle*** that are equipped with devices that transmit using simple radiofrequency;
2. ***Digital vehicle*** that are equipped with TETRA technology (TETRA *trans european trunked radio* is a digital system that allows the transmission of voice, data etc.) that has a level of reliability much higher respect to the traditional one.

Furthermore, it is important to take into account that there are two different technologies also to locate the different means on the line:

1. ***Odometer***: this device counts the turns of the drive shaft. It is reset every time it encounters a marker that is installed in a known position. Combining this two information it is possible to know the location of each means on the line. All the means are equipped with this kind of technology.

2. ***GPS***: some means are also equipped with GPS technology, this one is able to give more accurate data respect to the usage of the only odometer.

It is evident that these technologies are capable of error. What we conclude is that ***not all the data collected has a sufficient quality level*** that allows it to be used for the following analysis. In order to have a system that works properly it is crucial to understand which among it can be considered valid and which one havs to be discarded.

Due to the reasons explained above it is necessary to define a method able to filter real time data coming from the line. Because it is evident that the quality of out-put coming from the system are strictly related with the quality of the in-put.

### 2. Control room diary (See figure 50.b)

The control room diary is an application that it is used to register all the events that happens on the different lines. The objective of this app is to gather real time information of the events that happen on the different lines.

Literature does not tackle this kind of problem because public transportation companies do not have the need to analyze real time information on the events that happen on the line. The operators on the control room usually fill in spreadsheets that are at the end of the day saved and stored in DBs.

In order to have an effective system able to suggest effective intervention it is necessary the presence of a system able to give real time information of all the events that happen on the line.

## 3.2.2 Process side

The ***Process side*** is the part of the DMSS (see *figure 48.c*) that analyzes all the information coming from the data side suggesting in the end the interventions to take in order to increase the service reliability offered by the transport companies.

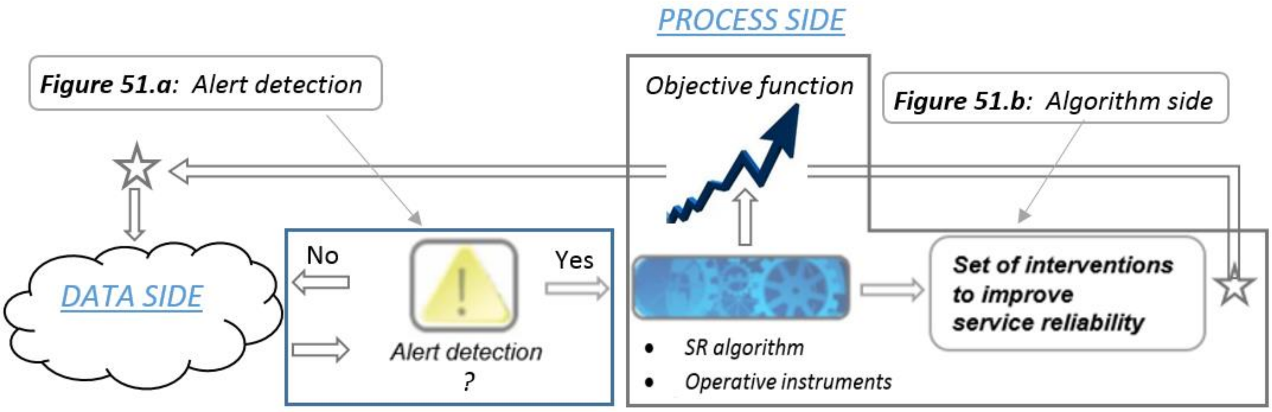



***Figure 51**: DMSS (Disruption management support system)'s process side.*

This side is composed by two main parts:

1. ***The alert detection one*** that continuously monitors the data coming from the data side (IN-PUT) and activate the algorithm when a critical situation is detected (OUT-PUT).

2. ***The algorithm one*** that has as objective function the improvement of the service reliability. It starts working on data coming from the "Data side" (IN-PUT) once an alert is detected and in the end suggests ***when, where and which*** operational instruments implement to improve lines' performances (OUT-PUT).

### *1. Alert detection (see figure: 51.a)*

The Alert detection system is the part of the DMSS that links the data side with the algorithm side. Literature does not have specific researches or studying regarding this because the DMSS is very innovative and first of a kind in surface PT systems.

The general rules applied came from the risk management theory, the approach that will be followed can be described principally in two major steps:

1. ***Definition of indicators*** that monitors the trend of specifics aspect of the system that are considered meaningful;

2. ***Definition of thresholds***, linked to each indicator, that once overtaken can advise the presence of a danger.

All the set of indicators and thresholds will have to be created from scratch. Finding patterns that relate different data one another and that predict a future dangerous situation will be the most difficult part, after will be necessary to create indicators able to identify them; the last step will be the definition of acceptability's levels for each one.

## 2. *Algorithm side (see figure: 51.b)*

The algorithm side is composed by four main parts that are linked one another as presented in *figure 52*:

1. *Algorithm basic logic;*
2. *Objective function of the algorithm;*
3. *Priority rules for applying OI;*
4. *Set of Operative tools to use in order to reach the optimal level of service reliability on the lines.*

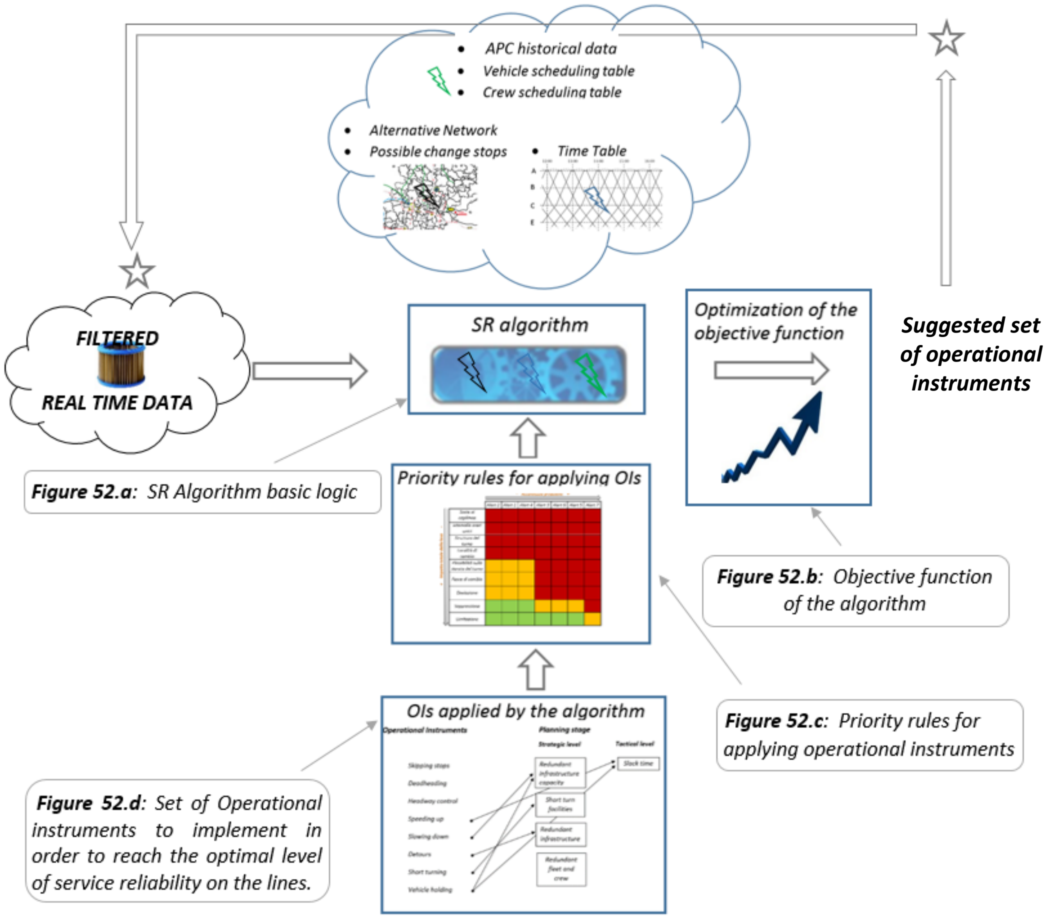



***Figure 52:*** *Algorithm side components.*

Before to start explaining each single element that compose the Algorithm side it is worth to spend few words in clearing up how the four parts are related one another:

The filtered real time data coming from the different lines is the *IN-PUT* of the algorithm side. Once a certain Alert is activated on a certain line the algorithm starts working simulating how the objective function, that represents the service reliability, changes if are applied different operative instruments. The OIs are divided in different categories. Accordingly to the alert activated a certain group of OIs is applied in different ways by the algorithm until it is found the combination that optimize the objective function. In the end the winning group of operational instrument (*OUT-PUT*) are suggested to the dispatchers.

### Algorithm basic logic (*see figure 52.a*)

The main issue concerning the algorithm is to define the way it will have to proceed in order to find the optimal set of operational instrument to implement on the line or to a set of lines to improve its/their performances.

According with the logic of the system the algorithm will start working on filtered real time data (*IN-PUT*) when the "Alert detection component" detects a possible future dangerous situation, in the end it suggests a set of OIs (*OUT-PUT*) to implement on the line with the aim to increase the service reliability and avoid inefficiencies.

Now we can define the approach that will lead the algorithm in suggesting the set of operational instruments that optimizes the performance of the line.

Due to the high level of environment's uncertainty in which the surface PT system has to operate and due to the enormous number of variables with which it has to interact the classical scenario based modelling approaches *(see Kouvelis and Yu (1997), Ben-Tal et al. (2009) and Ruszczynski and Shapiro (2003)*) has been discarded.

To overcome the scenario based modelling's shortcomings it has been introduced a new approach that solves the problems over listed, this technique is known as ***On-line combination problem.***

Rather than trying to describe the possible outcomes at the occurrence of a disruption by enumerating scenarios it tries to *describe the uncertainty of the situation as an online combinatorial optimization problem (see Borodin and El-Yaniv (1998)).*

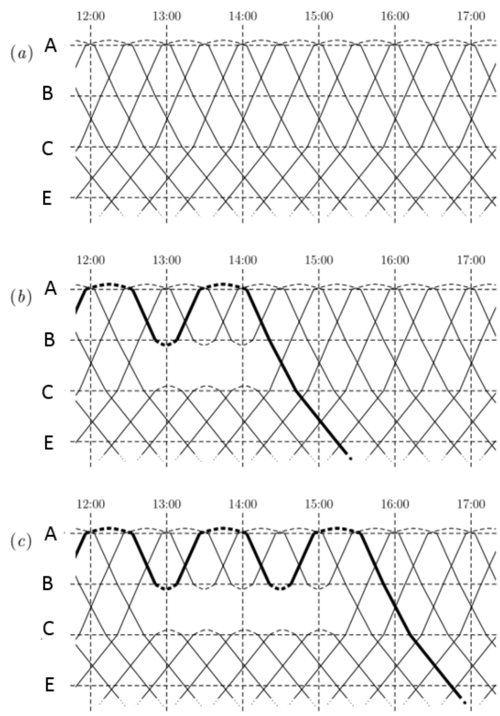
The occurrence of a disruption and the development of the situation can be describe by the following elements:

- The undisrupted scenario $\boldsymbol{S_0}$;
- A finite list of updates ($\boldsymbol{t_1,S_1}$) , . . . , ($\boldsymbol{t_n,S_n}$).

Here, the scenario $\boldsymbol{S_0}$ describes the state of all parameters in the system in the undisrupted situation. An element in the list is composed by two elements one is the instant $\boldsymbol{t_i}$ and a scenario $\boldsymbol{S_i}$ that describes the system at time $\boldsymbol{t_i}$. The element ($\boldsymbol{t_i,S_i}$) denotes that at time $\boldsymbol{t_i}$ the system changes to $\boldsymbol{S_i}$. The list thus represents the uncertainty of the development of the situation.

The task is then at time instant $\boldsymbol{t_i}$ to re-plan the resources (vehicles and crew) in the system so that the new plan is feasible under the constraints described by scenario $\boldsymbol{S_i}$. At this time there is no knowledge of future changes in the system, *i.e.* the rest of the list ($\boldsymbol{t_{i+1},S_{i+1}, . . . ,t_n,S_n}$) is not known. Also, the number of updates $\boldsymbol{n}$ is not known.

In the context of *disruption management*, the scenario $\boldsymbol{S_i}$ describes the updated timetable, the vehicle availability, and all parameters regarding the crew scheduling. The disruption in *figure 53* can be modeled by letting $\boldsymbol{S_0}$ describe the ordinary timetable of *figure 53 (a)* and letting the list consist of two updates (*t1,S1*), (*t2,S2*).




F***igure 53***: *(a) Time-space diagram for part of the some line. (b) Adapted timetable after the occurrence of a disruption between B and C. (c) Adapted timetable according to updated on the disruption.*

The first element is (***$t_1$,$S_1$***) where ***$t_1$*** = 12:45 and ***$S_1$*** describes the timetable update in *figure 53 (b)*. Similarly, the second element in the list is (***$t_2$,$S_2$***) where ***$t_2$*** = 13:45 and ***$S_2$*** describes the timetable update in *figure 53 (c)*. This way of modeling the progression of a disrupted situation is known in practice as a ***wait-and-see approach*** *see Wets (2002)*. In this approach, no assumptions are made on the probability distribution of the occurrence of the possible scenarios. This approach is valid because overtake the problems of scenario-based approaches. *The part of the tam coming from the operational research department of Politecnico di Milano will be in charge of the development of this side.*

### Objective function of the algorithm (*see figure 52.b*)

Check after Overall logic description, general objective function of the system (*see equation 5 – chapter 3.2). The part of the tam coming from the operational research department of Politecnico di Milano will be in charge of the development of this side.*

### Priority rules for applying operational instruments (*see figure 52.c*)

These priority rules have the aim to give to the algorithm a hierarchical structure in applying operative instruments in order to find the combination able to optimize the objective function that at the same time generates the less negative impact on passengers. This logic, which aims at linking the detection of an alert with a set of operative instrument, it is first in his kind.

Nowadays all the Operative instruments are used without distinction, an important breakthrough will be the classification of the different operative instruments accordingly to the power that they have in solve a critical situation and accordingly to the impact that they have on the passengers' service perception once applied.

### Set of Operative instruments used by the SR (service reliability) algorithm (see figure 52.d)

The last part is to define which will be the operative instruments that will be used by the algorithm in order to improve the objective function presented above. Literature analyzes the OIs very deeply (*Cham and Wilson (2006)*, *Van Oort 2011*) and according to what found from their analysis we selected the set of indicators presented by *figure 53*:

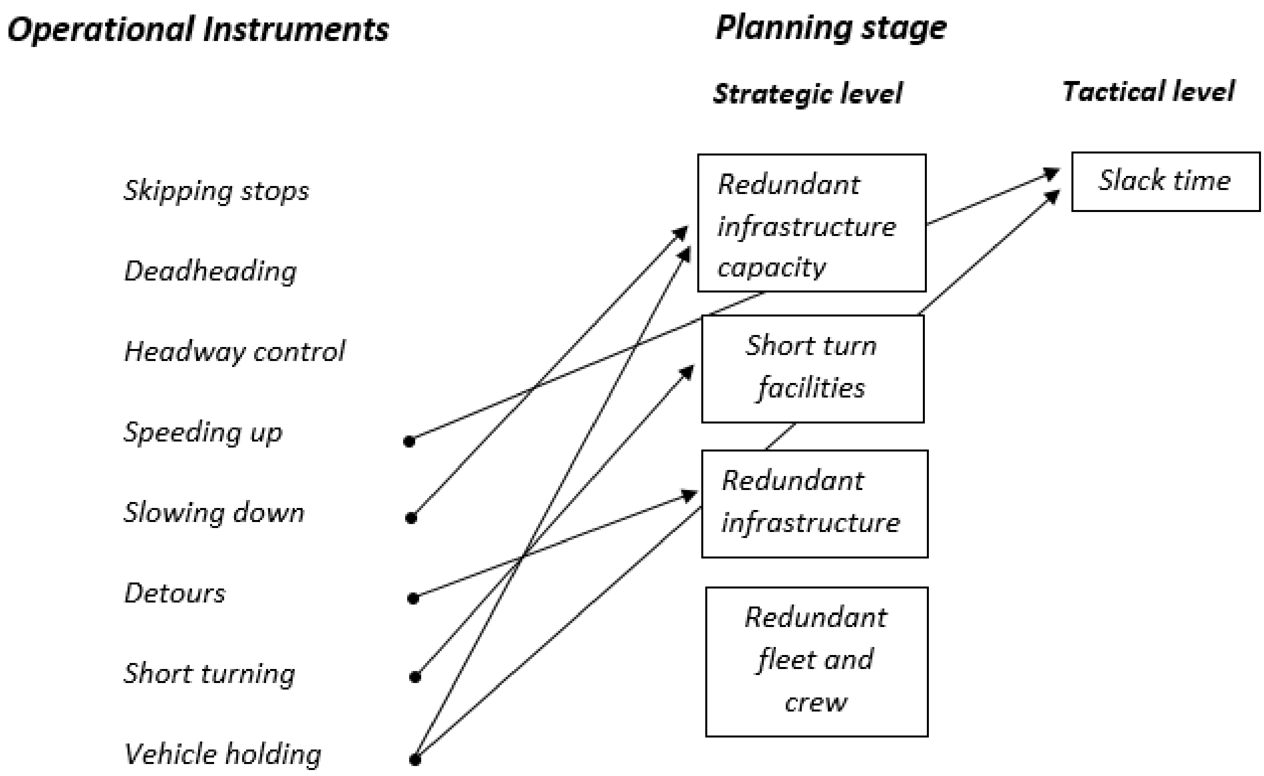



***Figure 54***: *Operational instruments currently used to improve service reliability.*

- <u>*Skipping stops*</u>

Skipping stops means that some (minor) stops of the line are not served. When a vehicle is late and has to catch up, skipping stops may speed up the vehicle thereby decreasing the delay (as illustrated by *figure 55*). (*see Koffman (1978), Li et al. (1993) and Eberlein et al. (1998)).*

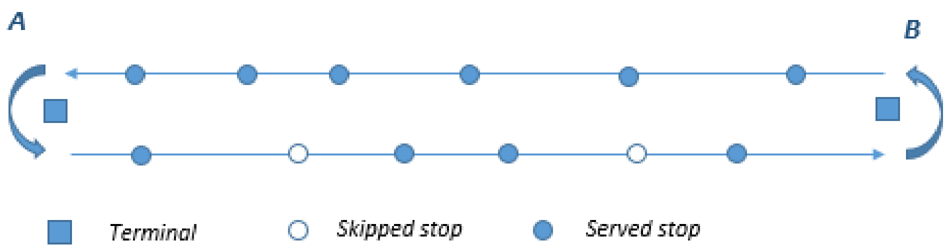



***Figure 55:*** *Skip-stop in direction A-B.*

- *Dead-heading*

Deadheading is a special mode of skipping stops (see f*igure 56*). In this case the last part of the route isn't served for passengers anymore. (*see Eberlein et al. (1998*)).

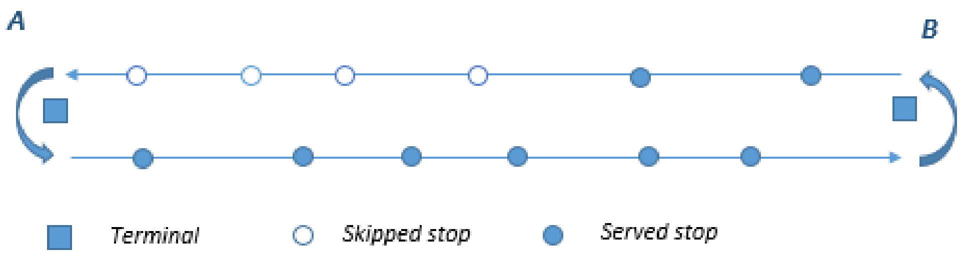
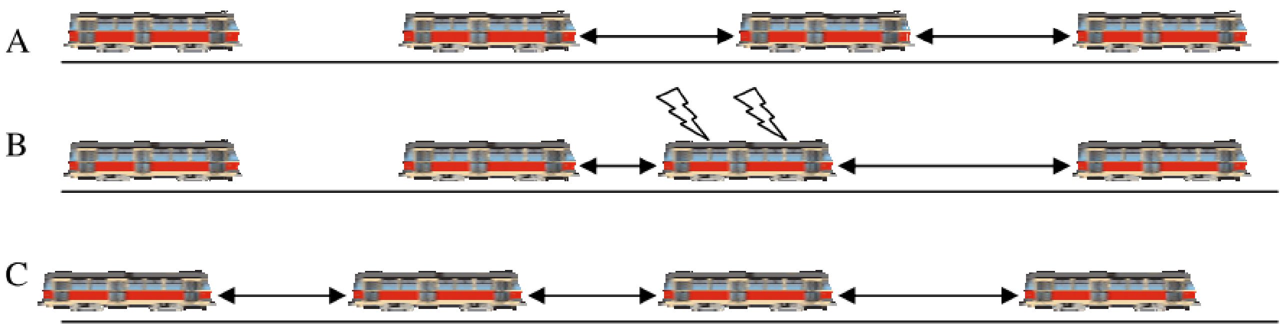



***Figure 56***: *Dead-heading in direction B-A.*

- *Headway control*

When a vehicle is delayed in short headway services, headway control may be applied. *figure 57* shows the principle of headway control (*Van Oort and Van Nes 2009a*). Due to a delay, the headway before the vehicle increases and the headway behind it decreases. By delaying these vehicles, regularity will be partly restored. This kind of control may be applied to all vehicles on the line.




*A: Vehicles drive with equal headways;*

*B: One vehicle is delayed and the headway in front increases, behind it decreases;*

*C: By slowing down successive and preceding vehicles the regularity will be partially restored;*

***Figure 57***: *Principle of headway control.*

- *Speeding up vehicles*

Speeding up vehicles may consist of increasing the driving speed as well as decreasing the stopping times. If a vehicle is delayed, the theoretically easiest solution is to speed it up. Guarding traffic safety is very important when this instrument is applied. But another important issue is the design of the schedule, because you need to have the margin to speed up the vehicle *(see Gifford (2001), Banks (2002) and Chang et al. (2003)).*

- *Slowing down vehicles*

Slowing down vehicles to increase schedule adherence may consist of both *decreasing driving speed* and *increasing stopping time*, this is an effective instrument as well. If vehicles drive faster than they are planned to do (due to both operational and timetable issues), slowing down helps them to get back on schedule. *In Gifford (2001), Banks (2002) and Chang (2003)* slowing down vehicles is described in further detail.

- *Detours*

A detour is an alternative route between parts of the original route. Detours are a very effective measure in case of blocked infrastructure. But also when infrastructure is still available (i.e. recurrent delays are experienced), schedule adherence may be enhanced by applying detours. *(see Tahmasseby (2009)).*

- *Short turning*

An often applied instrument to gain time is the short turning, which means that a vehicle turns into the opposite direction somewhere along the route (instead of at the terminal). This instrument may be both applied if infrastructure is blocked and in recurrent delay situations. When a vehicle is short turned, it only provides transport on a part of the route (*see figure 58*). See *Tahmasseby (2009).*

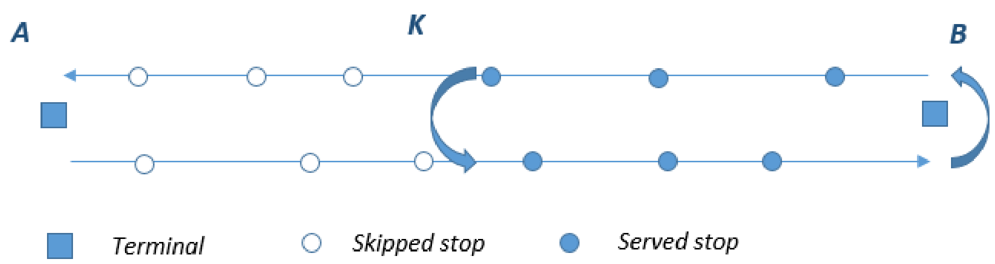



***Figure 58****: Short turning at point K.*

- *Vehicle holding*

A very common instrument of improving schedule adherence at the operational level is holding (*see e.g. Dessouky et al. 2003, Fu and Yang 2002, Liu and Wirasinghe 2001 and O'Dell and Wilson 1999)*. Holding implies stopping a vehicle at a certain point called holding point. At the holding point the decision of holding is taken, based on the actual schedule adherence and the holding strategy (e.g. applying maximum holding time).

All the operational instruments listed above are useful to maintain the line regular. It is important to understand that some of them have also a negative impact on passengers that for instance have to get off the means because the vehicle needs to short turn to recover the delay. These kind of instruments are for sure powerful in recovering a critical situation but at the same time have a bad effect on the travelers. Since the final objective is to increase the level of satisfaction of the clients hence attract more of them and increase ridership it is important to use them very carefully. It is important to encourage the use of ones that do not have side effects on passengers.

For this reason it will be important the creation of a set of rules that the algorithm will have to follow in applying the different operational instruments (*Priority rules for applying operational instrument*). Furthermore, the third part of the system (*additional information side*) will have the task to show to the dispatchers the impact that implementing certain decisions will have on passengers.

Another big shortcoming with which the surface PT systems (SPTSs) have to deal is the incompatibility between the stiff structure of the time, vehicle and crew tables and the high level of uncertainty that characterizes the environment in which the SPTS has to operate.
Another point that we will develop in the following sections is the creation of a new set of operative tools that will be able to make the entire system more flexible.

## 3.2.3 Additional information side

This is the third and last macro-side that composes the DMSS. This part is fundamental to make the support system well integrated with the control room operators. This additional info will help them in understanding how the OIs suggested by the DMSS, that aim at maximizing service reliability, will impact on other passengers' quality aspects. *Figure 59* has the aim to contextualize this side in relation to the entire support system.

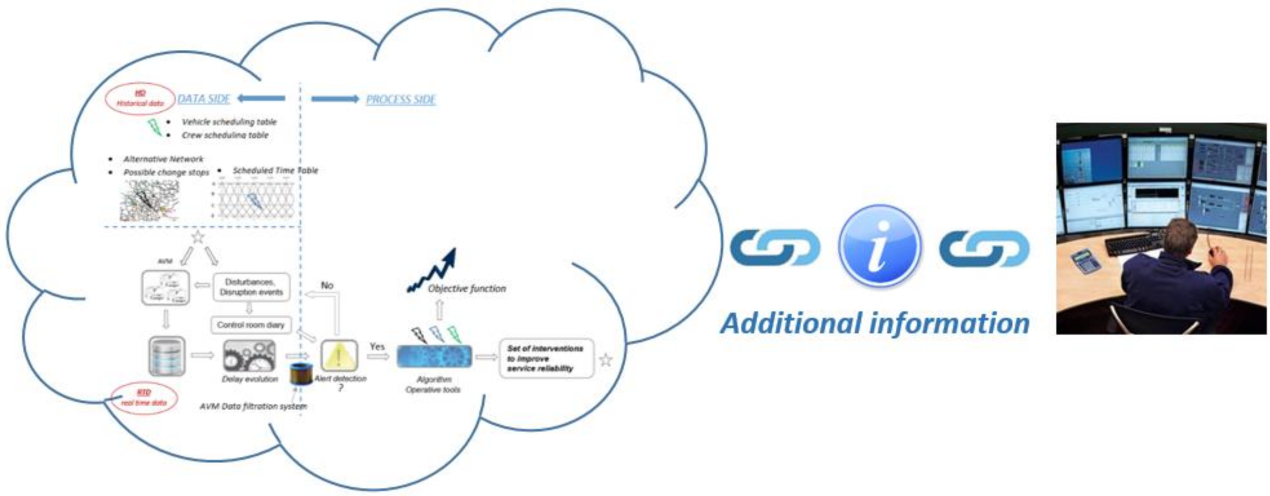



***Figure 59***: *Disruption management support system, additional information side.*

In order to develop this side we will follow two principal steps:

1. ***Influence diagram creation***: The objective of this first step is to analyze how the implementation of different operative instruments interact with the quality aspects considered valuable to passengers.

2. ***Definition of auxiliary information:*** The final achievement of this second step is the creation of logics, assumptions and reasoning that can be used to define the auxiliary information that are necessary to make the DMSS a helpful system well integrated with the dispatchers and link it with the specific OIs.

The main objective of the two macro sides introduced previously (***data side*** and ***process side)*** is to generate the operative suggestions able to maximize the service reliability (*travel time reliability + comfort*) of the line. While the aim of this third macro side is linking effectively the suggestions generated by the support system with the dispatcher, who is the actor that in the end has to decide if implementing or not the OI proposed.

## 1. *Influence diagram creation*

Influence diagrams are instruments used to describe the relationship between several elements that can affect the results of a decision. The diagram can be used as a basis for creating computer-based models that describe a system or as descriptions of mental models managers use to assess the impact of their actions.

***In this case we will use them to identify which are the relations between the different operational instruments and the different quality aspects that are evaluated important by passengers.***

The sources that provided the material and the knowledge necessary to create the influence diagrams are principally two:

1. ***Literary review analysis:***

    a. In *chapter 1.2 – Literary review* ***(Customers source of value in public transport)*** are analyzed the researches of different academics that deeply studied both:

    i. The *quality aspects considered valuable to passengers* (*Baker and Cameron 1996, Van Hagen et al. 2007, Van Oort 2011);*

    ii. *The level of importance that customers assign in average to each quality aspect (Jackson and Jucker 1981, Black and Towriss 1991 and König and Axhausen 2002).*

    b. In *chapter 2.3 – literary review* ***(Causes of service variability and unreliability)*** are *studied and listed the causes of service reliability and unreliability* (*Abkowitz and Engelstein 1983; Strathman et al. 2000; Van Oort 2011)*

    c. In *chapter 3.6 – literary review* ***(Operational management in public transportation system)*** are a*nalyzed all the operative instruments that are currently used by public transport companies to deal with inefficiencies*. (*Van Oort 2011, Koffman 1978 and Eberlein 1998, Van Oort and Van Nes 2009)*

The combination of the information gathered in these chapters gave the possibility to build a good knowledge about *quality aspects considered valuable for passengers*, *operational instruments used by public transport companies to deal with disruptions/disturbances* and *the relations that exist among this different variables/instruments.*

2. ***6 months internship at ATM S.p.A. :***

   At ATM S.p.A. I had the possibility to support in various occasions different dispatchers during their duties. This experience helped me in understanding which are the real effects generated by the implementation of certain operational instrument both on *line regularity* and on *passengers' level of service perception*. Furthermore having the possibility to work close to expert with more than 15/20 years of experience in the field gave me the possibility to understand clearly the dynamics and repercussions caused by the implementation of certain operational instruments on passengers' quality aspects.

The information and the knowledge gather in the different studying-experiences described above are at the base of the reasoning that will allow us to build the *influence diagrams (ID) that describes the relations between the implementation of a certain group of operative instrument and the consequent repercussions that they have on the different passenger's quality aspects.*

## 2. Definition of auxiliary information

This section can be divided in two different part:

1. *Definition of the variables, assumption and logics that will be used to generate the additional information;*

2. *The creation of the link between the information generated and the specific operational instrument.*

There are no previous studying that can lead us through the creation of this side. But the experience and the knowledge gained during the internship and during the literature analysis combined with the expertise of professors and researchers (TU Delft) that have been studying this issues for years will provide the basis to develop also this last section.

# 4. Thesis Methodology

After the construction of the DMSS (*disruption management support system*)' skeleton starting from the literature analysis, it is necessary to build the system from a micro-point of view defining all the elements that will permit it to work in the real life.

The objective of this part of the thesis is to describe the various steps I and the research groups with which I worked with went throw to define the details of the new system. I'll explain which kind of data we have used, with whom I have interacted, how I have interact with them and the kind of software we have used in order to define all the aspects that compose the DMSS.

The entire disruption management project can be divided in two different phases since it has been developed in two different times and places even if the final objective, ***increase customer attraction and retention***, it has always been the same:

3. ***In the first phase,*** I worked for 5 months as an intern at ATM S.p.A. covering the role of *junior risk manager-junior process analyst*. During this period me and the Italian research group created and validated the set of variables, logics and assumption used to generate the support system that aims at minimize service variability.

4. ***In the second phase*** I worked for six months at TU Delft university faculty of Technology policy and management covering the role of researcher. The first step was writing a document in which I wrapped and translated all the work performed during the internship. After having analyzed and validated the results obtained in the first step with my Dutch thesis adviser and other researchers of the TU we have identified a way to improve the effectiveness of the DMSS. In the end, we decided to create a set of logics and indicators that will provide additional information to control room operators to help them in assessing the impact generated on passenger's quality aspects after the implementation of certain kind of OIs.

The work performed in Milan ca be divided in four main steps that are listed in *table 10*.

| ***Step*** | ***Brief description*** |
|---|---|
| 1 I (Italy) | *Definition of variables, logics and assumptions used to build the model* |
| 2 I | *Predisposition of the databases*<br>*(definition of variables, logics and assumptions ; simulation and validation)* |
| 3 I | *Simulation on variables and logics* |
| 4 I | *Validation and revision of variables and logics* |

***Table 10***: *Methodology's steps list (work performed in Italy).*

Due to time constraints and the massive amount of work to perform my mentors wanted me in the beginning to create a set of logics in order to select the most significant lines and days on which perform the validation phase of the variables, logics and assumptions on which the DMSS will be built. But in the end the actual validation carried out by me was specific on one line, they preferred to have an initial feedback on all the parts of the system instead of having an in depth analysis on few components. The analysis on the other lines it would have been performed by other employees during my absence. The case analyzed by me ***will be highlighted in bold.***

While the approach used to develop the part of the project created in the Netherlands have followed a different scheme (*table 11*).

| ***Step*** | ***Title*** |
|---|---|
| 1 N (Netherlands) | *Redaction of a unique document with all the work performed during the internship* |
| 2 N | *Validation of the document created and identification of a way to optimize the effectiveness of the DMSS* |
| 3 N | *Creation of a set of logics and variables to generate the additional information that will optimize the integration between the DMSS and control room operators* |
| 4 N | *Validation of the set of logics and variables generated* |

***Table 11****: Methodology's steps list (work performed in the Netherlands).*

To better explain who did what during the project it is presented *figure 60 (figure 60.a; figure 60.b),* it is a scheme in which are listed all the actors that participated in the different phases that brought to the creation of the system.

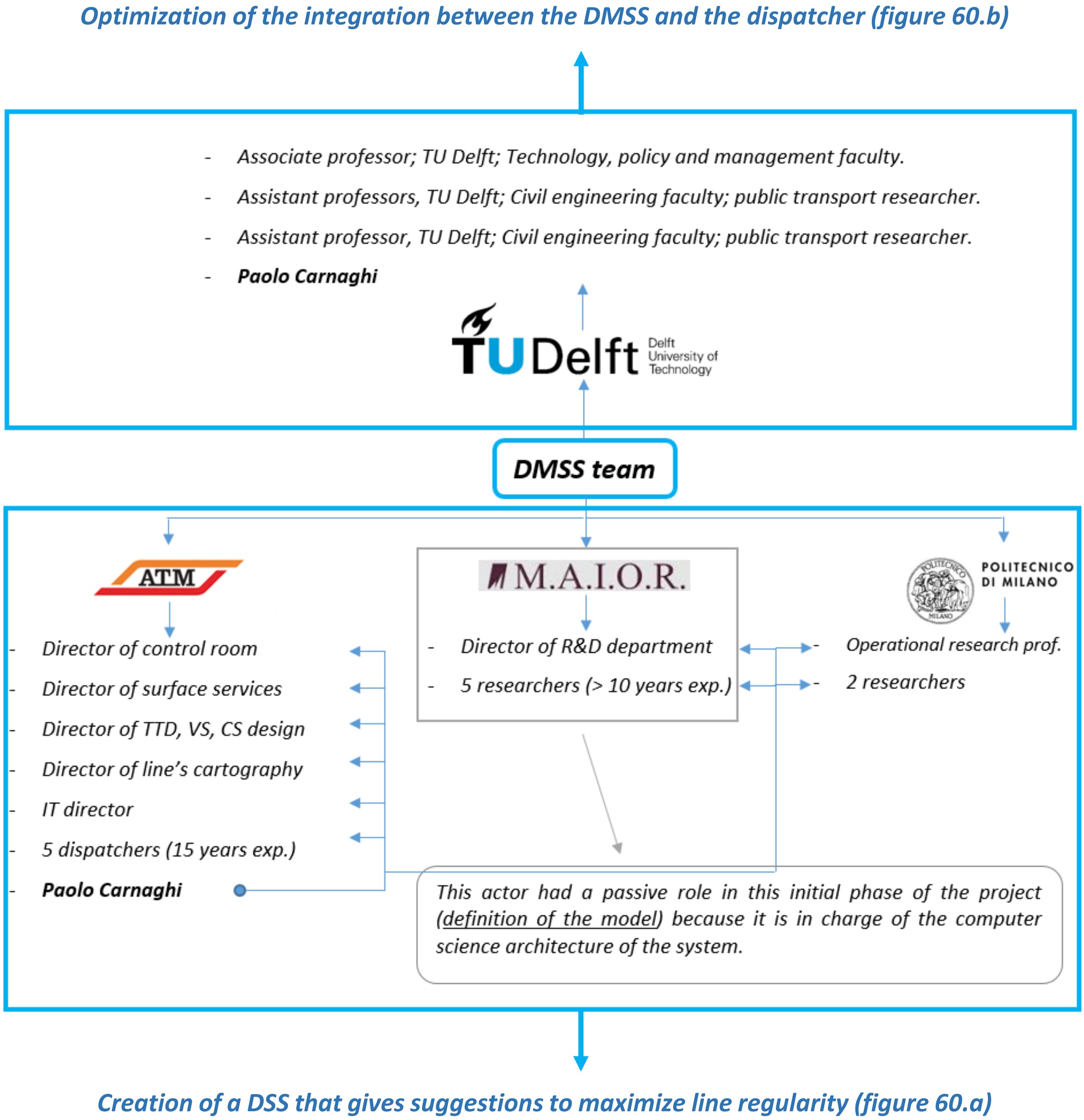



***Figure 60***: *Disruption management team members.*

## 4.1 Creation of a DSS that aims at maximizing line regularity

In this section we will describe in detail the methodology followed to achieve the project objectives during the internship performed in Milan at ATM S.p.A. (Public transport operator of Milan). To do this we will follow the structure presented in the beginning of the chapter (*see table 10*).

### *Step 1 I: Definition of variables, logics and assumptions used to build the model*

The first phase in the creation of the DMSS has been the identification of the different variables, assumptions and logics on which the system is built. *Figure 60.a* shows the principal actors that worked together in order to define them. In this first step we did not work on data but we have tried to define and describe the logics upon which each single part of the system is built, only during a second phase we tested them using data coming from ATM's databases.

In order to better explain all the steps done to create the variables, logics and assumptions that constitute the DMSS it is represented a synthetic version of the support system's skeleton created in Italy (*figure 61),* this will allow us to be clearer and to analyze its main components separately.

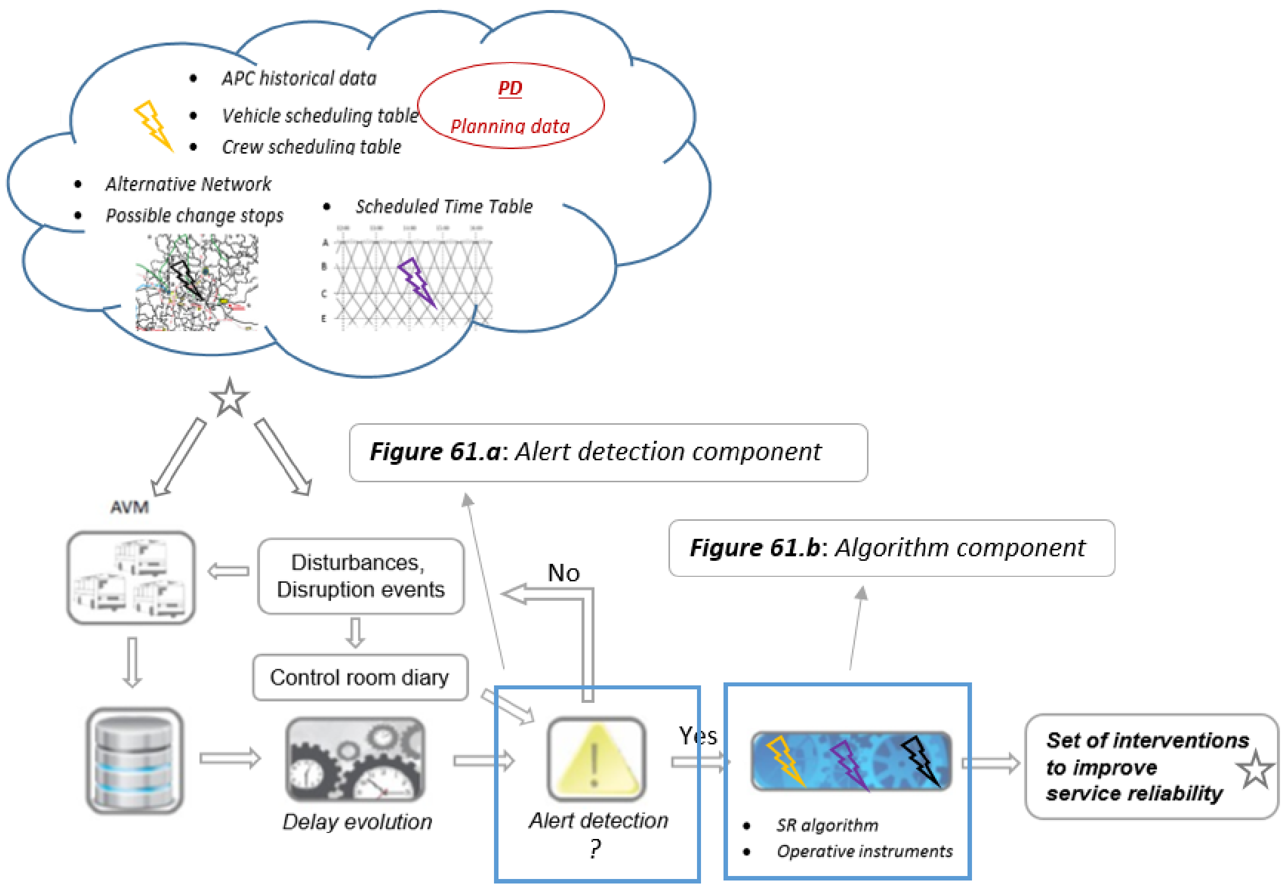



***Figure 61**: Overview of the part of work performed during the internship at ATM S.p.A.*

The two components of the DMSS that are involved in the ***"Definition of variables, logics and assumption used to build the model"*** are the *"Alert detection"* and the *"Algorithm".*

- Alert detection (*figure 61.a*)

All the actors listed in *figure 60.a* participated to define the structure of this component. I have been personally in charge to define the set of indicators and logics that would have been used to foresee critical situations.

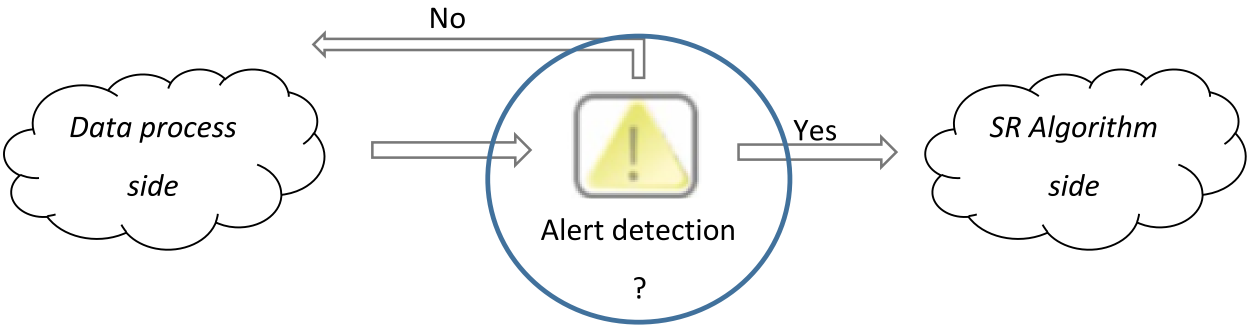



***Figure 62***: *Alert detection component.*

As a *fist step* I supported 5 different dispatchers during their duties in the control room for 3 weeks. During this time I took notes and I observed how they are used to work in order to understand how the entire process of controlling is carried out currently. In the mean time I have read also all the documents produced by the three actors (*ATM S.p.A., M.A.I.O.R., Politecnico di Milano*) about disruption management and also all the papers on which I built my literary review analysis.

After this first approach I have been able to understand the various dynamics that rules the control room, the disruption management and the public transport system agencies in general. With this new knowledge I tried to ideate all the logics and the indicators that in the end form the "alert detection component" *(second step).*

Once written a first document with a draft version of the indicators and the logics I send it to all the actors involved in the project *(third step).* After a week it was set a meeting in which everyone brought its own comments and suggestions to improve what created. In the end a fist set of indicators and logics was approved to pass to the test phase in which they have been subjected to data analysis validation *(firth step)*.

### o Algorithm rules and new operative instruments definition (*figure 61.b*)

These two elements can be considered part of the same component even if they are two different entities because they are strictly related one another (see *figure 63*).

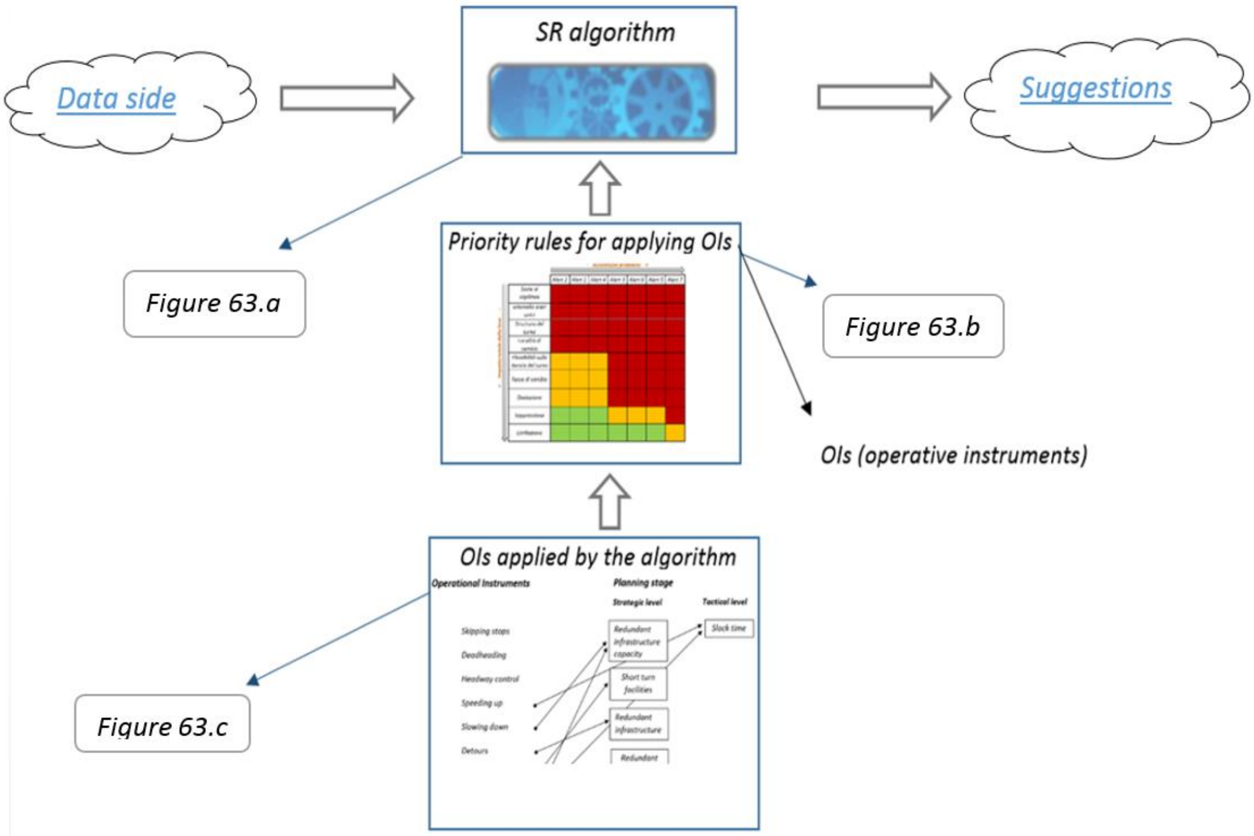



***Figure 63**: Algorithm and new operative tools.*

As it is possible to see from *figure 63* the algorithm it is composed by three different parts that are related as shown:

- *Algorithm;*
- *Priority rules logic for applying the OIs;*
- *OIs applied by the algorithm.*

Each of these parts have been generated following different steps, now we will explain how it has been built each of them.

- *Algorithm (figure 63.a)*

Politecnico di Milano was the main actor in charge to design the algorithm and the objective function through which it will be possible to define the set of OIs to take for increasing the service reliability of the line. I personally supported the group of professors in the definition of the objective function but the other actors did not participate in the definitions of these two aspects because it was a very technical task and the group coming from the Polimi was the only one with the capabilities to perform it.

- *Priority rules logic for applying the OIs (figure 63.b)*

The *first step* to build the matrix that gives priority rules for applying the OIs was to create the logics and the variables that would have been used to join a certain *alert/group of alert* with a particular set of *operative instruments*.

I was the main actor in charge of the creation of this component; during my work I have been supported/advised by the *director of TTD, VS and CS*, the *director of control room* and the *director of the surface services* with their teams. After several meetings the group presented the logics and the variables to all the actors involved and after a discussion on the document presented the stakeholders improved and consequently agreed upon all the work done. *(second step).*

Once obtained the main priority logics and variables it has been created a survey in order to build the relations between OIs and Alerts *(Third step).*

All the actors filled in the survey and after elaborating all the results it has been possible to build the final priority matrix.

- *OIs applied by the algorithm (figure 63.b)*

Part of the OIs proposed are already used by the dispatchers and they have been inserted also among the ones that will be used by the algorithm to generate the suggestions that aim at improving service reliability of the service.

But there are also some new operative instruments created ad hoc in order to make the entire surface public transport system more flexible hence more able in reacting to critical situation. In order to create these new indicators, related to the crew scheduling tables, the *fist step* was the creation of a draft document with the collaboration of the *Director of TTD, VS, CS design and its team,* this document contained a detail explanation on how the Operative instruments would have worked.

The document was sent to all the stakeholders of the project (*second step*). After one week everyone brought a revised version of it with comments and suggested improvements and during the meeting the final version of the document with a definitive version of the new OIs was redacted (*third step*).

### *Step 2 I: Predisposition of the database*

Once defined all the variables and the logics of the DMSS it has been fundamental clean the database, in order to prepare the historical data for the simulation analysis. I performed this task with the support/ supervision of the IT director and its team. This phase had three main objectives:

1. Clean historical data that were used for the simulation, in order to obtain meaningful results during the validation phase (*point 1);*
2. Understand which kind of data can be considered usable by the system once functioning (every record (AVM data) registered in the database is linked to a code that describes the modality of acquisition, the point is to understand which of these codes are valid and which not) *(point 2)*;
3. Understand the consistency of Time Table Design (Understand if the travel time forecasted during the planning phase is coherent with the actual one) *(point 3)*.

- Point 1-2 (Creation of data filtering system's rules)

The first two points can be merged as a unique task since they have the same objective (analysis for clustering the codes). After an initial phase *(first step)* in which *me with the IT director , the director of surface services and their teams*, during 4 meetings, tried to separate the codes that can be considered valid form the one that can not (using the knowledge coming from their experiences), our the attentions went on the ambiguous ones.

On these codes has been necessary to perform a further analysis *(second step).* To do this we have selected the entire month of ***February 2013*** (It is the month that has the worst performances), particularly we have analyzed those days in which the *weighted average daily frequency regularity* (the indicator used by the company to evaluate the performances of the system [0%$_{\text{(worst performance)}}$-100%$_{\text{(best performance)}}$]) have been the worst. We have utilized this approach because it is very probable that during those days there have been a lot of criticalities and consequently it is possible to observe many occasions in which there are ambiguous codes. In this way it is possible to understand if these codes can be considered valid or not. For what concern the lines, we have chosen the one that are defined as ***lines of power*** (*High frequency – High demand – Low performances)*, because are the ones on which the DMSS will work.

The day and the selected lines are the following:

1. ***L14: 21/02/2013 → 72% RiFmgp***;
2. L95: 21/02/2013 → 74% RiFmgp;
3. L61: 21/02/2013 → 71% RiFmgp;
4. L92: 05/02/2013 → 68% RiFmgp;

All the data for this analysis comes from the ATM data warehouse in which is stored all the data of the service performed, in order to extract the needed information we have used SQL language to inquire the DBs. The data in the end have been analyzed with Microsoft Excel and Access in order to validate what found in the first step.

*The third step* was the validation and revision of what found during the analysis with all the stakeholders of the DMSS project during a final meeting. The meeting was divided in two main parts:

1. *The first part* was about the presentation of the results of the entire analysis to all the actors;
2. *The second* was about working together on the results obtained to find possible rooms for improvement.

*The fourth and last step* was the creation of a final document, with the help of all the parties, in which it has been updated all the improvements highlighted during the revision of the first draft. This document will be the guideline for the employee that will carry out the analysis on the other lines and days.

- Point 3 (Time table design validation)

I have been the main actor that carried out this analysis under the supervision of the *director of TTD, VS and CS, the IT director and their teams*. After an initial qualitative analysis ***(first step)*** of the situation we have found a set of meaningful data to analyze.

The principles adopted in order to define which are the most suitable lines and days to pick have been the same used for point 1-2.

To carry out this analysis we have processed historical data coming from the AVM system after their cleaning using what found from the analysis done in the point 1-2. The selected lines were:

- ***L 14***;
- L 61;
- L 92;
- L95.

These are the lines of power (*High frequency – High demand – Low performances*) on which the disruption system will operate.

We have chosen three days of the month of February for all the four lines:

- 5-02-2013;
- 13-02-2013;
- ***21-02-2013.***

All the data for this analysis comes from the ATM data warehouse in which are stored all the data of the company, in order to extract the needed information we have used an SQL language to inquire the DBs. The data in the end have been analyzed simulating the logics and the reasoning identified in the step 1 using Microsoft Excel and Access.

*The third step* was the validation and revision of what found during the analysis with all the stakeholders of the DMSS project during a final meeting. The meeting was divided in two main parts:

- *First part* was about the presentation of the results of the entire analysis to all the actors;
- *The second* was about working together about the results obtained and finding possible room for improvement.

*The fourth and last step* was the creation of a final document, with the help of all the parties, in which were updated all the improvements achieved respect to the first edition. This document will be the guideline for the employee that will carry out the analysis on the other lines and days.

### *Step 3 I: Simulation on variables and logics*

Once defined all the variables and the logics that compose the DMSS and after having cleaned the DBs from the data considered non-usable for the analysis it is time to validate what done theoretically in *step 1 I*. At this phase the attention goes to the *process side*, because for what concern the data side all the numerical analysis was performed previously in order to have at disposition high quality information to make the validation phase of the process side more reliable

The best way to describe the methodology used at this phase is to follow the division utilized in *step 1 I*:

1. *Alert detection part*;
2. *Algorithm part.*

### 1. Alert detection part

I have been the main actor that worked in this validation phase under the supervision of the *control room's director and the surface services' director with their teams*, even if the support of the IT director with its team was fundamental to retrieve the primary data to analyze.

The logics followed to make this analysis and to select the data to perform it are very similar to the ones used to tackle the validation of the database's predisposition phase.

We chose to validate the logics and variables of this part of the system using data coming by two sources (further explained in the framework section):

1. *Operative room control diary;*
2. *AVM (activity vehicle monitoring) data.*

The stakeholders involved in the development of this phase made two meetings in order to define in which time span carry out the analysis. The final choice was to focus on ***February*** (everyone agreed on the fact that this was the most critical month of the year and consequently also the period from which will be possible to have the highest amount of critical situations to analyze). Furthermore we have decided to analyze only ***weekdays*** because it is logic perform the analysis on a group of homogeneous data.

During those initial meetings the other fundamental topic was on which line performing the analysis. After a lot of reasoning, the final decision was to adopt different approaches according to the different kind of analysis to perform. The Alert definition part can be divided in two main sections:

1. *Events evaluation and analysis (risk-map creation);*
2. *Alert definition.*

1. *Events evaluation and analysis (risk-map creation)*

Fort this initial analysis it is used only the data coming from the operative control room diary. The attention goes on ***group of lines***. To build them we have created some logics based on reasoning that will be explained below.

The ***first step*** is to identify the line of power (LOP → *High frequency, high demand, low performances*) that are the ones on which the DMSS will focus, as we said previously the once highlighted are the following:

- ***14***;
- 92;
- 95;
- 61;

The main assumption used to build a sub-network was to consider only the lines that have a portion in common with the LOP, the ones that have only intersection will not be considered. This assumption is based on the fact that the probability that a disruption event will happen on an intersection is very low (the lines shares few meters together). While if there are lines that share entire line sections the probability that a disruption event damages also the main line is higher.

To perform this first analysis we have utilized the data coming from the entire months of ***March and February*** (*only weekly days*). The two months selected are the ones that have the worst performances (probable higher number of critical situation to analyze), while we have decided to use only weekdays in order to have homogeneous data (the service during holidays changes).

2. *Alert definition*

For this analysis we will use both AVM data and data coming from the control room diary. For this studying we have analyzed only the LOPs:

1. ***L14: 21/02/2013 → 72% RiFmgp***;
2. L95: 21/02/2013 → 74% RiFmgp;
3. L61: 21/02/2013 → 71% RiFmgp;
4. L92: 05/02/2013 → 68% RiFmgp;

The team decided to pick the day in which the four lines performed the worse (possibility to see a lot of criticalities) since there were no possibility to automatize this analysis (because the software that will have to perform this task wasn't created yet) and since it was a time consuming process. If there had been a validation of the logics and the assumptions made coming from all the lines in their worst day what built could have been considered reasonable. The various actors involved in this analysis agreed upon the validity of this approach.

After having retrieved all the data listed above using SQL queries, it has been analyzed using Microsoft Excel and Microsoft Access in order to verify if there were real consistency between the theoretical assumptions and the reality.

### 2. Algorithm part

Politecnico di Milano was the actor in charge to validate this part of the system. They selected ***line 37 on the 11th of September 2013***. They built a simulator that processed all the AVM data related to that date compering the results of what happened without the use of the DMSS with the possible achievable outcomes if there would have been used the DMSS in helping the operator in taking corrective actions. It is important to say that in this phase has been used a rudimental simulator compared to the real DMSS but in any case, since the main logic at the base were the same, a positive feedback coming from this version it would have been considered encouraging for the success of the original system.

## *Step 4 I: Validation and revision of the variables and logics*

The first part of this last step was sharing the analysis performed by each actor with the others and after two weeks in which everyone had the time to study the results coming from the research done by other parties we met. During the meeting that concluded this first phase of the project we discussed all the results coming from the various researches highlighting the points that needed improvement and the ones that instead seemed to be right. After two weeks in which every group improved the part of the model they were in charge various final documents have been written. All these documents will be used as guidelines to perform also the data analysis also on the other selected cases.

With the fourth step it is concluded the explanation of the methodology description concerning the work performed in Italy. Now we move to the part of the project done during the period spent in the Netherlands at the TU Delft.

## 4.2 Integration between the DMSS and the dispatcher

In this section we will describe in detail the methodology followed to achieve the project objectives during the period spent at TU Delft. To do this we will follow the structure presented in the beginning of the chapter (*see table 11*). *Figure 64* represents schematically the components that compose the part of work developed in the Netherlands.

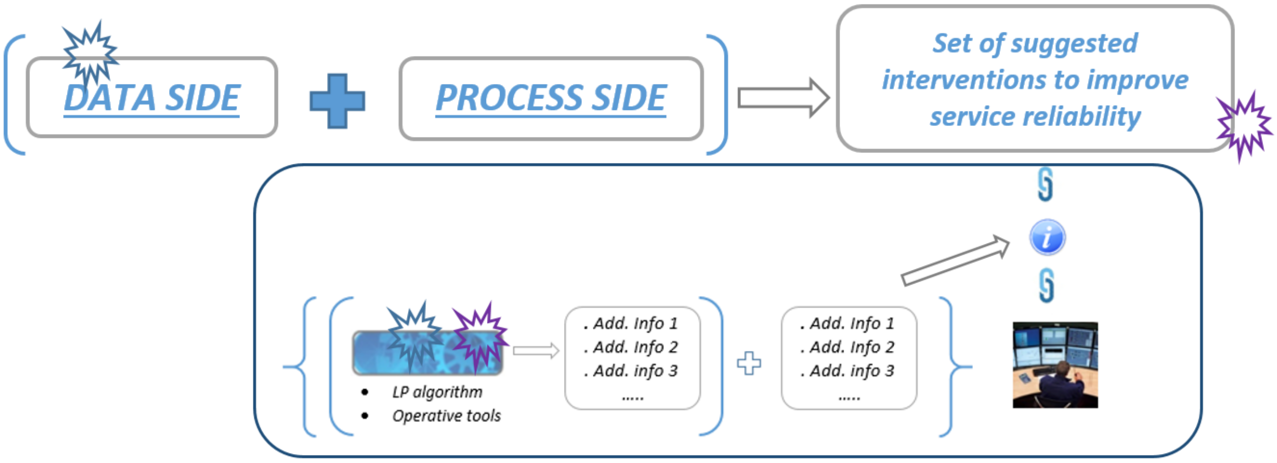



***Figure 64***: *Part of the work performed during my staying in the Netherlands as researcher at TU Delft.*

### *Step 1N: Redaction of a unique document*

After a first meeting with my Dutch thesis adviser we agreed that the best way to tackle and to organize the work that I would have performed under his supervision was to create a first document that would have merged all the work performed during the internship at ATM S.p.A . In this way he and other researchers would have been able to validate all the logics on which the DMSS is built and it would have been also clearer in which way intervene in order to make the entire support system a more effective tool. This first phase took a long time (two months and a half) because the work performed in Italy was very fragmented and in Italian. During the wrapping up and the writing process I worked alone.

### *Step 2N: Validation of the document created and identification of a way to optimize the effectiveness of the DMSS.*

Once finished a first version of the document I shared it with my thesis adviser that, once read it, decided to involve other two professors coming from the civil engineering department specialized in public transportation traffic modelling and scheduling. I had several meetings with them in which we discussed the work performed in Italy and after having analyzed all the indicators, logics and assumptions that constitute the disruption management support system all the team members showed satisfaction and enthusiasm regarding the level of innovation brought with this new research. The final output of this part of the job was a completely validation of the work developed during the internship in Italy.

After having achieved this first milestone, we had two meetings in which every member of the team came up with ideas to improve and integrate the part of the project developed in Italy. In the end under the lead of Wijnand Veeneman (my thesis adviser), we decided that the best way to add value of the work already performed was to identify a set of support information to provide to dispatcher in order to make them aware about the impact generated by the implementation of certain kind of operational instrument on the line.

This idea was born by the fact that the final objective of the thesis is to create a system able to increase customer acquisition and retention, while having a system that is set to maximize only the reliability of the service offered does not consider other quality aspects that are decision drivers for passengers. The validation of the work performed and identification of the new set of objectives to achieve involved all the Dutch team of the TU and it took almost one month.

### *Step 3N: Additional info to maximize the effectiveness of the DMSS*

In this third step the team put a lot of commitments in order to define the set of logics, indicators and assumptions that will be used to better support the control room operators in their decisions.

In the beginning the biggest part of the work was oriented in defining the relations that there are between the passengers' quality aspects and the implementation of all the different operative instruments that could be suggested by the DMSS. This work was fundamental to understand which kind of information would be useful to provide to control room operators in order to make them aware about the impact on passenger generated by the implementation of a certain OI. This part of the work lasted for three weeks and the support of Veeneman was fundamental in the definition and creation of these influence diagrams.

After this phase the help and the supervision of the researchers coming from the civil engineering department became fundamental. I worked close contact with them for an entire month; our objective was to create a set of robust mathematical equations that would have allowed us to describe and foresee the number of passengers alighting and boarding the vehicle at each stop along the line and to describe the loading profile of the vehicle of the line. This set of equations is fundamental because it provides the fundamental input for the indicators created to generate the additional information needed.

### *Step 4N: Validation of the set of logic and variables generated*

The last three weeks of my permanence in the Netherlands have been centered in the validation of the all assumptions, logics and indicators created and the writing of a unique document that wraps up all of them. During this last phase I had three different meetings with all the team and every time the possessors gave me comments and suggestions to improve the document. In the end, I received the complete approval and validation of the all thesis work from the three professors that followed me during my staying as a researcher at the TU Delft.

# 5. Thesis model

In this part of the thesis we will describe in detail all the part of the disruption management support system (DMSS) already presented from a wide point of view along the *framework.* We will present the logics the assumptions and the variables that compose each component of the DMSS. Before to start it is important to explain two indicators that will be used to get our results:

1) *Regularity in frequency;*

2) *Weighted daily average regularity in frequency;*

## *1) Regularity in frequency (RiF)*

Regularity in frequency is the indicator that it is used nowadays to evaluate the *level of the service effectiveness offered by the company (ATM S.p.A.).* This is also used by oversight authorities to assign prizes or fines according with the quality of the operations performed. Even if the DMSS' algorithm will maximize another objective function *(framework analysis, percentage regularity deviation mean PRDM)* the research group has evaluated reasonable use this indicator during the simulation phase on historical data to evaluate the service reliability offered by the line.

This because of two reasons:

1. *Because it is a good indicator to evaluate the performance level of the service offered;*
2. *Because all the historical data used during validation phase are related to this indicator.*

To compute this indicator it is necessary introduce the concept of ***headway:***

Considering a single *stop n* it is possible to compute the headway as the time that passes between the passage of a *mean Ω,* passed at *stop n*; *time **t: t** $_i$* and the successive one *mean Ω+1* passed at *stop n*; *time **t: t** $_{i+1}$*.

| *HEADWAY* | |
|---|---|
| ***Formula*** | $t_{i+1} - t_i$ |
| ***Unit of measure*** | *[sec]* |
| ***Optimal value*** | / |
| ***Historic value*** | / |

We can have two different kind of headways:

- $\boldsymbol{Scheduled\ Headway}: t_{i+1\ prog} - t_{i\ prog}$
  It uses *scheduled values*
- $\boldsymbol{Headway\ effettivo}: t_{i+1\ eff} - t_{i\ eff}$
  It uses *actual values*

Two consecutive passages at a stop is considered valid if and only if the difference between ***scheduled headway*** and ***actual headway*** is < than 180 sec. In the end the regularity in frequency it is considered as ratio between the *total number of two valid consecutive passages* and the *total number of scheduled consecutive passages*. This data has been computed per time slot ( time slot is composed by 60 minutes e.g. 5$^{th}$ time slot of the days goes from 4:00 a.m. to 4:59 p.m.) and then mediate along the entire day.

- ***Example***

*In order to make the theoretical explanation clearer we introduce a practical example:*

*We consider 8 consecutive different passages at the same stop performed by 8 different means:*

| Passage | $t_p$ | $t_e$ | $\Delta_p$ | $\Delta_e$ | $\Delta$ | σ 180 |
|---|---|---|---|---|---|---|
| $P_1$ | 06:25:00 | 06:25:32 | - | - | - | no |
| $P_2$ | 06:29:00 | - | 240 | - | - | no |
| $P_3$ | 06:33:00 | 06:33:12 | 240 | 460 | 220 | no |
| $P_4$ | 06:37:00 | 06:39:21 | 240 | 369 | 129 | yes |
| $P_5$ | 06:41:00 | 06:42:50 | 240 | 209 | -31 | yes |
| $P_6$ | 06:45:00 | 06:44:40 | 240 | 110 | -130 | yes |
| $P_7$ | 06:49:00 | 06:49:20 | 240 | 280 | 40 | yes |
| $P_8$ | 06:49:00 | 06:49:25 | 240 | 285 | 45 | yes |

- $t_p$: Scheduled passage time;
- $t_e$: Actual passage time
- $\Delta_p$: $t_{p,i+1} - t_{p,i}$ ;
- $\Delta_e$: $t_{e,i+1} - t_{e,i}$ ;
- $\Delta$: $\Delta_e$ - $\Delta_p$;
- P2 it is an eliminated ride that means that it was never performed;

- P7 e P8 are two double rides, the delta of both the rides are computed in comparison with P6.

In the end the ***RiF*** of this example is → 5/7 → ***71,4%.***

## *2) Weighted daily average regularity in frequency (wdaRiF)*

This indicator uses the *hour regularity in frequency* to compute the *daily regularity in frequency*. We will use a weighted average to consider differently the RiF of each time slot (*in this way the RiF of the time slot with few rides will weight way less respect to the RiF of a time slot with a lot of rides*).

To compute the weighted daily average regularity in frequency it is necessary to associate a *weight $F_i$* to each time *slot i:*

1. To find the weight of each single time *slot i / day y* it is used the linear function introduced below:

***Weight ($F_i$) =***

$$\frac{Number\ of\ scheduled\ passages\ at\ the\ stops\ performed\ by\ the\ menas\ in\ circulation\ at\ time\ slot\ k}{Highest\ number\ of\ sched.passages\ at\ the\ stops\ performed\ by\ the\ means\ in\ circulation\ at\ a\ certain\ time\ slot\ i}$$

***Notes:***

- ✓ This formula have to be applied to all the time slots;
- ✓ Time *slot i* is the time slot in which are registered the highest number of passages done at all the stops by the different means along the day.

2. ***wdaRiF***: $\frac{\sum_{i=1}^{n} X_i F_i}{\sum_{i}^{n} F_i}$

***Notes:***

- ✓ ***$X_i$*** *: The regularity in frequency associated to the single time slot i of the single day y;*
- ✓ ***$F_i$***: Represent the weight associated with the single time slot i, single day y;

The result obtained can be considered an accurate value in representing the daily ***regularity in frequency***.

- ***Example***

*In order to make the theoretical explanation more clear we introduce a practical example, the chosen case is L14; 21/02/2013:*

*0,008951 (weight) = 7/782*

| Line | Day | Time slot | OK | Total | RiF | Weight | Weighted Rif | wdaRiF |
|---|---|---|---|---|---|---|---|---|
| 14 | 21/02/2013 | 4 | 6 | 7 | 86% | 0,008951 | 0,006734 | ***72%*** |
| 14 | 21/02/2013 | 5 | 133 | 154 | 86% | 0,17284 | 0,1492705 | |
| 14 | 21/02/2013 | 6 | 460 | 601 | 77% | 0,674523 | 0,5162738 | |
| 14 | 21/02/2013 | 7 | 739 | 891 | 83% | 1 | 0,8294052 | |
| 14 | 21/02/2013 | 11 | 534 | 638 | 84% | 0,716049 | 0,5993266 | |
| 14 | 21/02/2013 | 12 | 449 | 645 | 70% | 0,723906 | 0,5039281 | |
| 14 | 21/02/2013 | 13 | 520 | 655 | 79% | 0,735129 | 0,583614 | |
| 14 | 21/02/2013 | 14 | 541 | 654 | 83% | 0,734007 | 0,6071829 | |
| 14 | 21/02/2013 | 15 | 489 | 645 | 76% | 0,723906 | 0,5488216 | |
| 14 | 21/02/2013 | 16 | 494 | 740 | 67% | 0,830527 | 0,5544332 | |
| 14 | 21/02/2013 | 17 | 474 | 781 | 61% | 0,876543 | 0,5319865 | |
| 14 | 21/02/2013 | 18 | 542 | ***782*** | 69% | 0,877666 | 0,6083052 | |
| 14 | 21/02/2013 | 19 | 383 | 780 | 49% | 0,875421 | 0,4298541 | |
| 14 | 21/02/2013 | 20 | 436 | 756 | 58% | 0,848485 | 0,4893378 | |
| 14 | 21/02/2013 | 21 | 371 | 535 | 69% | 0,600449 | 0,4163861 | |
| 14 | 21/02/2013 | 22 | 306 | 405 | 76% | 0,454545 | 0,3434344 | |
| 14 | 21/02/2013 | 23 | 332 | 368 | 90% | 0,413019 | 0,372615 | |
| 14 | 21/02/2013 | 24 | 260 | 340 | 76% | 0,381594 | 0,291807 | |
| 14 | 21/02/2013 | 25 | 164 | 214 | 77% | 0,24018 | 0,1840629 | |
| 14 | 21/02/2013 | 26 | 34 | 34 | 100% | 0,038159 | 0,0381594 | |

After this first part in which we have introduced this two indicator, that will be fundamental to understand some passages of the following work, it is possible to get back to the DMSS' model description .The chosen approach to develop this part will be similar to the one used in the previous sections. We will start showing the entire support system continuing with the description of each single component following the hierarchy shown in *figure 65*. The idea is to follow the stream of data from the acquisition of it (*in-put of the system*) until the final suggestions provided to the dispatchers (*out-put of the system*).

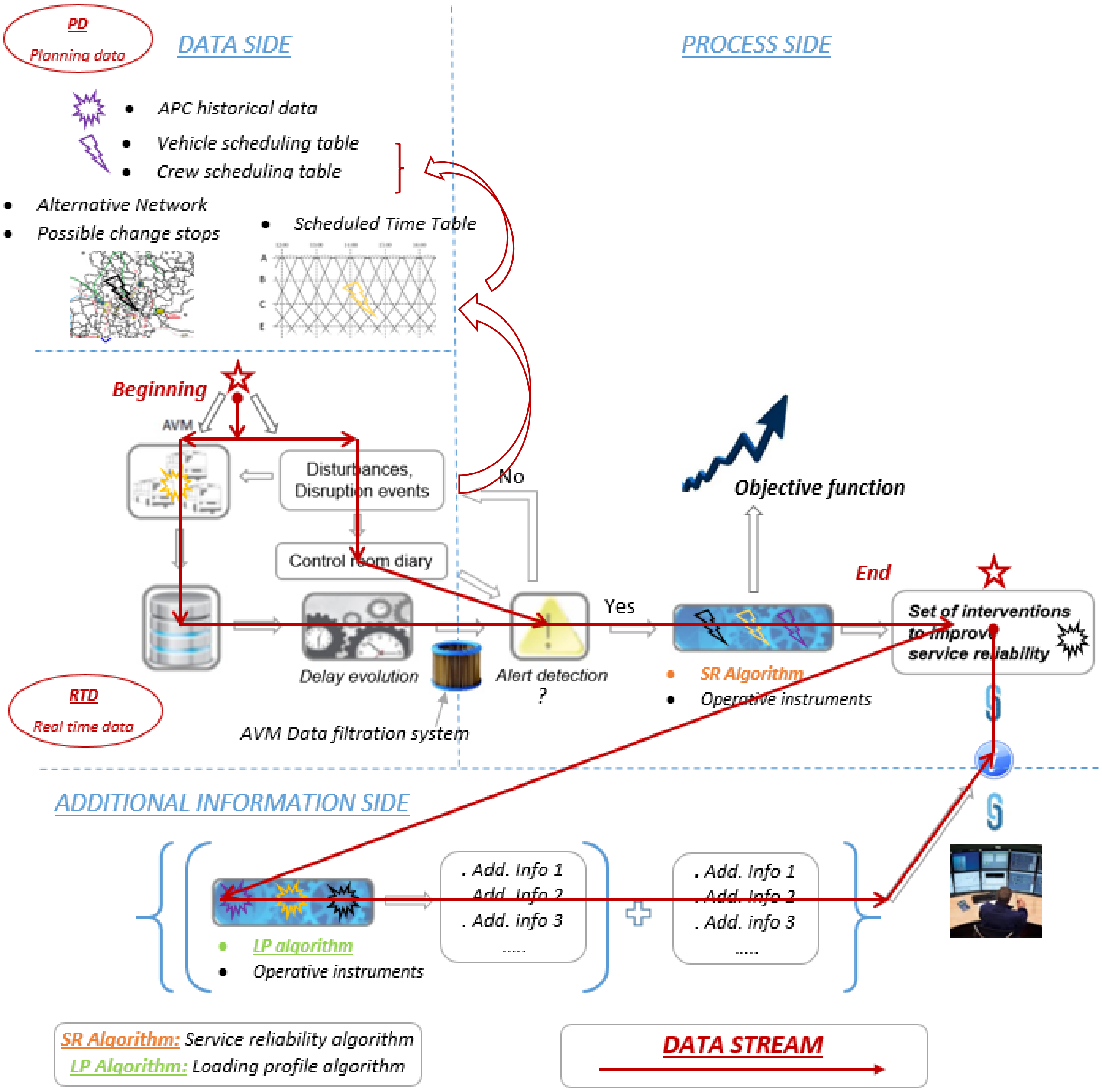



***Figure 65****: Disruption management support system (DMSS) overview, with data stream.*

Following the structure already presented during the thesis' framework we have divided the DMSS in three parts DATA SIDE, PROCESS SIDE and ADDITIONAL INFORMATION SIDE. In the previous section we have explained from a macro point of view the support system and the relation among the different components increasing the level of detail only on the aspects already studied in the literature. In this part of the thesis we will describe with a high level of detail all the tailored elements created from scratch to guarantee the DMSS' proper working.

## 5.1 Data side

Form the Data side the greatest part of the job was about the validation, filtration and elaboration of the different kind of data that will be the *in-put* of the DMSS. The objective is to provide the process side of the system with the highest quality data in order to give valuable suggestions to the dispatchers.

### 5.1.1 AVM data filtration system

According to the data flow stream presented in *figure 65* the first component that needs to be explained in detail because it is a new element created from scratch to satisfy the DMSS' needs is the ***AVM Data filtration system*** *(figure 66)*.  The set of rules, logics and assumptions presented in this chapter have the objective to filter the real time information coming from the lines to provide the *process side* of the system with high quality data that will be used to produce high quality suggestions to maintain a high level of service reliability.

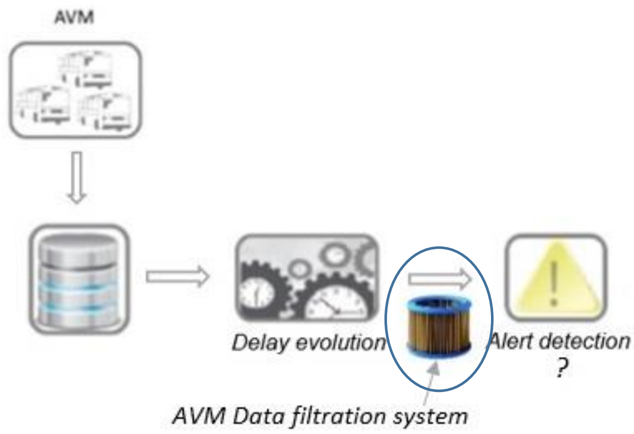



***Figure 66***: *AVM data filtration particular.*

As it has been already said in the *framework analysis* it is dangerous to use the real time data coming from the line because unfortunately not all of it has a sufficient level of quality that allows it to be used in the process side of the system. In order to have a system that works properly it is crucial to understand which among it can be considered valid and which one has to be discarded. Now we will introduce all the logics, the assumptions and the variables used to build the ***data-filtration system***.

The ***objective*** of this element is to target the records' code (*at each record registered is associated a code that describes the modality of acquisition of the single data*) evaluated not valid because generated by journey's anomalies that do not describe how the means really serve the line.

It will be introduced an *example* to better explain the concept.

- ***Example***

*There is an accident at a crossing and the means are obliged to drive part of the travel out of the line (see figure 67), consequently for an hour they are not able to serve two stops of the line. The system automatically re-compute the position of the means registering the passage at the stop even if the passage never happened in reality. This is because the system read the missing passage at the stop as a transmission malfunction and following old statistics rebuild an actual timetable.*

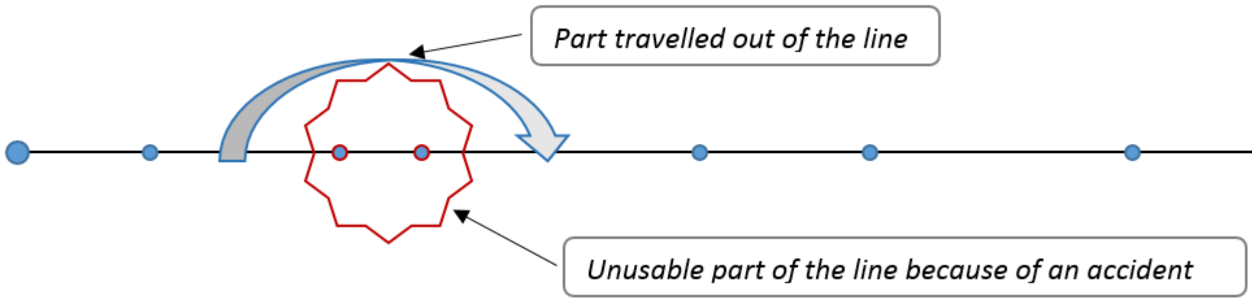



***Figure 67****: Scheme e showing what happens if part of the line is unusable.*

After a first analysis in which it was possible to validate and discard some of the code without any particular studying, the attention goes on the ones that have been considered critical because they need a further analysis in order to verify their validity.

A first selection brought to the identification of 8 codes (the ones listed under plus the code 0 that represents a regular registration) that composed the 95% of the records, the remaining 5% have been removed because considered meaningless. Below, in two different tables, are listed "**Initial discarded code**" (*see table 12)* and "**Critique code**" see (*table 13).*

| *Initial discarded codes* | |
|---|---|
| ***Error _ code*** | ***Description*** |
| ***Code1*** | *Planned deviation* |
| ***Code 2*** | *No functioning transmission system* |
| ***Code 1024*** | *No transmission in the center of the line* |

***Table 12***: *Initial discarded codes.*

| *Critique codes* | |
|---|---|
| ***Error- code*** | ***Description*** |
| ***Code 16*** | *The mean stops at least 3 minutes at the terminal* |
| ***Code 64*** | *The mean stops at least 3 minutes on the line* |
| ***Code 128*** | *The mean doesn't transmit during the final 5 stops* |
| ***Code 256*** | *The mean doesn't transmit during the initial 5 stops* |

***Table 13***: *Critique codes.*

In order to understand which of the four codes listed above can be consider valid it is necessary to go further in detail with the analysis.

The code are built using a binary system, this means that if one code will be considered not valid will be evaluated the same also all the ones that contain it.

- ***Example***

*If after the analysis will turn out that the code 16 is valid while the code 128 not, it will not have to be considered neither the code 144 because it contains the 128.*

Now we will present in detail all the reasoning done to build the filtering system's logics. To make it clearer we will divide the process to obtain them in different steps:

1) The *first step* is to divide the day in time slots of 4 hours each:
   - 5-8;
   - 9-12;
   - 13-16;
   - 17-20;
   - 21-24.

2) After this it is necessary to compute the ***number of registrations of each code for each time slot*** *(see table 14)* and the ***number of total registration made by the system for each time slot*** *(see table 15)****.*** Once obtained these values it is possible to compute the percentage value for each time slots, in this way they will be more readable and comparable once inserted in a graph. The analysis can be performed consider also the code in couples (16-64 ; 128-256), this is possible because we have codes that have similar meaning.

| *Time slot* | *Registration made by the system (single code i) β* | *%* |
|---|---|---|
| *5 _8* | *I* | *a (I/D)* |
| *9_12* | *O* | *b (O/D)* |
| *13_16* | *P* | *c (P/D)* |
| *17_20* | *A* | *d (A/D)* |
| *21_24* | *S* | *e (S/D)* |
| total | *D (I+O+P+A+S)* | 100% |

***Table 14****: Number of registration of the single code/couple of codes i divided for time slots (β).*

| *Time slot* | *Registration made by the system (all the codes) α* | *%* |
|---|---|---|
| *5 _8* | *Q* | *f (Q/U)* |
| *9_12* | *W* | *g (W/U)* |
| *13_16* | *E* | *h (E/U)* |
| *17_20* | *R* | *i (R/U)* |
| *21_24* | *T* | *l (T/U)* |
| Total | *U (Q+W+E+R+T)* | 100% |

***Table 15****: Number of total registration divided for time slots (α).*

3) To proceed with the analysis it is necessary to put in a graph what found at *point 2* and compare the trend of ***α*** the "*Number of total registrations made by the system for each time slot*" with the trend of ***β*** "*Number of registration made by the system for the single code i in each time slot*".

After this it will be possible to verify if:

- The presence of *code i* is due to a real temporary malfunction of the system and consequently can be considered valid because the service has been carried out regularly or;
- The presence of *code i* is due to changing of planned operations (*es. Part of the travel is performed off the line*) because of problems on the line. All the registrations with this particular code can not be considered valid because the means are not serving the line but are travelling outside it to face a critical situation.

4) In the end it is necessary to understand the causes that have generated the single code i. It is possible obtain this comparing the trends between ***α*** and ***β*** :

   - If ***α*** and ***β*** have the same trend this means that probably the code/couple of codes is generated by a malfunction of the transmission system, because the number of *code i* grows proportionally with the number of total registrations. Therefore if the total number of registrations increase consequently will increase also the probability to have a malfunction of the transmission system.
   - If ***α*** and ***β*** have different evolutions and the great part of *code i* are concentrated in the time slot where the line performed the worse (hence in the moment in which there are the higher number of dead heading, skipping stops ecc..) this shows with high probability that that particular *code i* has been generated by variations from planned operations.

## 5.1.2 Time table design quality

Another important aspect to evaluate is the ***quality of the scheduled travel time*** because the SR algorithm generates suggestions to maintain high reliability based on the headways generated dividing the total scheduled travel time of the line per the number of means that are serving the line (*see figure 68*).

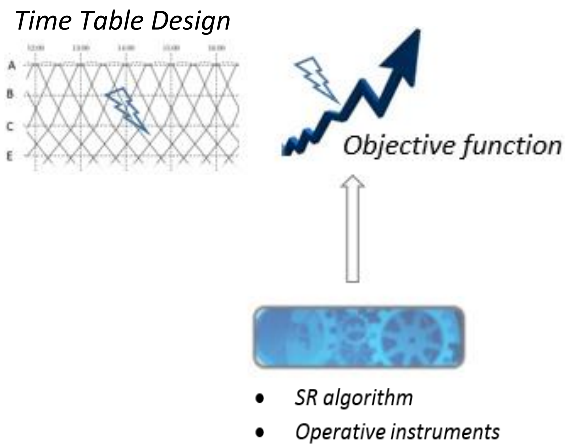



***Figure 68****: Interaction of the Time Table Design (it gives the scheduled travel time) with the other components of the DMSS.*

The problem tackle in this section is to understand how the support system will have to manage the means on the line in presence of a massive traffic jam or in case of terrible weather condition (snow, storm ecc..) and consequently the ***actual travel time of a means*** on the line is sensibly higher than its ***scheduled travel time***. In this case the support system would be able to maintain constant headways only for few means and it would not be able to control the others that will continuously accumulate delay. So the final objective of this anaysis is to *verify the level of alignment between the scheduled travel time and the actual travel time* in order to understand if during the planning phase the company inserts enough slack to absorb critical situations caused by traffic jams or similar events.

The reason for which it is necessary perform this kind of analysis is that if the system worked with wrong scheduled travel times it would give suggestions not able to optimize the regularity of the line, hence the optimization of the service reliability.

- ***Example***

- *Line α;*
- *Scheduled travel time: 20';*
- *Actual travel time: 30';*
- *Number of means on the line 20.*

*The optimal situation on the line is to have all the means with constant headway during pick hours.*

*Following this consideration it is possible to claim that:*

- *The optimal headway in the first case will be 1';*
- *The optimal headway in the second case will be 1,5'.*

*If this was the case and the system was set to work with a planned headway of 1' minutes there would be a problematic situation. The consequence is that the system would struggle to maintain the headway of 1 minute only for some means while the others would accumulate delay producing a lot of short turnings and dead headings, which are the OIs we want to limit.*

The variables used for the analysis is the ***travel time of the line*** that is composed by:

- *Time needed to travel the line in one direction;*
- *Time needed to travel the line in the other direction;*
- *Stopping time at the terminals.*

To perform this studying we have used ***two different analysis***:

## 1st analysis (Overall quality of the scheduled trip time)

1. The first step is to find the ***travel time deviation*** for all the trips performed during the day by all the means on the line. To do this we will use the following formula:

$$Travel\ time\ deviation\ (TTD)\ \% = \frac{Actual\ trip\ travel\ time\ (means\ i; time\ l) - scheduled\ trip\ travel\ time\ (means\ i; time\ l)}{actual\ trip\ travel\ time\ (means\ i; time\ l)}$$

2. Once obtained these values and computed the travel time deviation entity for all the trips during the all day, it is possible to move to the second level of studying:

a. First of all we need to separate all the trips done during the day (*see table 16)* :

| ***Total trip*** | ***TTD% > 10%*** | ***-10% < TTD% < 10%*** | ***TTD% < -10%*** |
|---|---|---|---|
| A | b | c | d |
| ***% on the total*** | b/A | c/A | d/A |

***Table 16****: Explanatory table travel time deviation (TTD) % repartition.*

3. The last step is to insert the results in a column graph to make them more readable. The scheduled travel time will be considered usable if the number of trips that exceed it of the 10% is less or equal to the 10% of the total.

***Notes:***

✓ The threshold of 10% it was given by the part of the team in charge to build the algorithm logic. According to their researches the DMSS will work properly with less than the 10% of the total trip with a TTD% higher than 10%;

Another fundamental aspect is to determine how they are distributed along the day, we will tackle this topic in the second analysis.

## *2nd analysis ( Daily trend travel time deviation %)*

1. In this second analysis we put all the various vehicles' travel time deviation computed in a line chart considering the all-day, ordering the records per ascendant time slot.
After are inserted in the same graph :

   a. ***Simple moving average on 5 periods:*** We have performed this analysis in order to mitigate the extreme values (generate probably by some events on the line that increase significantly the travel time of that particular trip).

   b. ***Exponential trend-line (grede 6):*** This analysis has the aim to track the trend of the travel time quality along the day. This studying is important to understand the daily ***distribution of the travel time deviation***. Since the DMSS will work in certain part of the day (when the service is performed in frequency) it is useful to understand when are concentrated the main deviations.

## 5.2 Process side

Now our attention goes to the ***process side***, in this second part of the system all the data is elaborated and processed into valuable information. In the end the support system gives suggestions to controllers for maintaining a high level of line's service reliability. Also for this side we will follow the data flows inside the system as rule to prioritize the element to analyze.

### 5.2.1 Alert detection component

The alert detection component (*figure 69*) is the part of the system that links the *Data side* with the core of the DMSS, the *SR algorithm*. It is composed by a set of rules, variables, and indicators that have the task to detect in advance possible critical situations of the line that without a prompt intervention can irremediably degenerate.

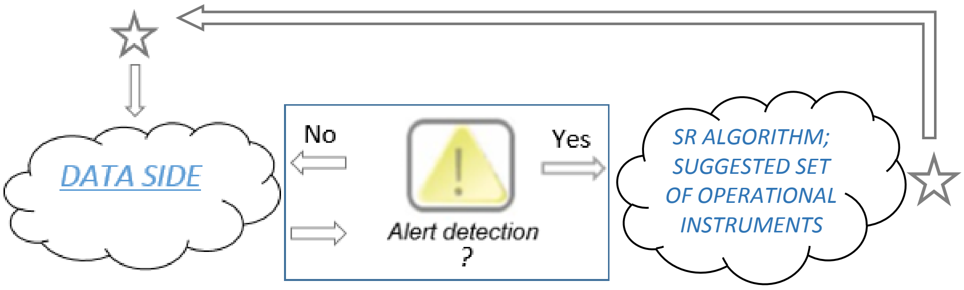



***Figure 69****: Alert detection component with context.*

Since this part of the system is very long and complex we decide to firstly introduce the 3 different alerts (*table 17*) that will be described in detail separately.

| ***Alert*** | ***Description*** |
|---|---|
| ***Alert 1*** | *"Occurrence of one or more events detected as critical on the risk map"* |
| ***Alert 2*** | *"Generation of a group of «steps» that overtakes the set of identified thresholds"* |
| ***Alert 3*** | *Increasing trend of "General deterioration of the line"* |

***Table 17****: Alerts presentation with short description.*

## <u>Alert 1</u>: "Occurrence of one or more events detected as critical on the risk-map"

The approach used to define this first alert is based on two main steps. We start introducing the two levels we have developed to build the logic of this first alert:

> ***1. First level (RISK-MAP CREATION):*** The objective of this first analysis is to create a quantitative method to sort different events and to highlight the most important that will be fundamental in the second part of the analysis.
>
> ***2. Second level (Alert Definition):*** With this second study we will define in detail which are the criteria (variables, logics, indicators) used to specifically create ***alert 1***.

### 1. First level (RISK MAP CREATION)

The most indicated technique to tackle this first phase is the ***risk mapping***. The final output will be the generation of a risk map (*figure 70*), that will follow *<u>quantitative principles</u>*, thanks to it will be highlighted the critical event for the *single line/group of lines* of interest. The usage of a *<u>quantitative approach</u>* is the most interesting part of this model, because, compared to a quantitative one, it has a higher level of accuracy and it is stronger from the logic point of view because based on mathematical principles.

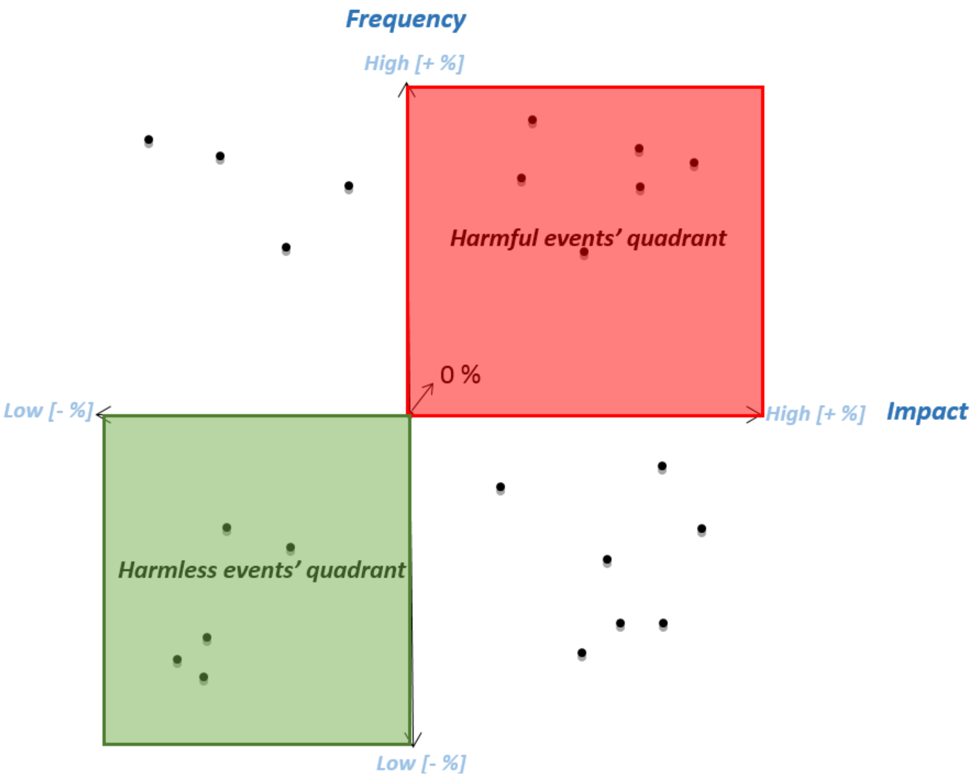


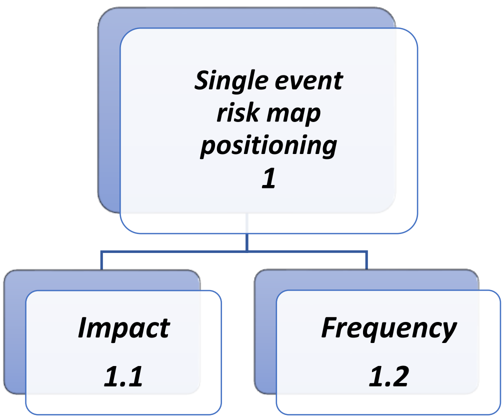

***Figure 70***: *Risk Map example.*

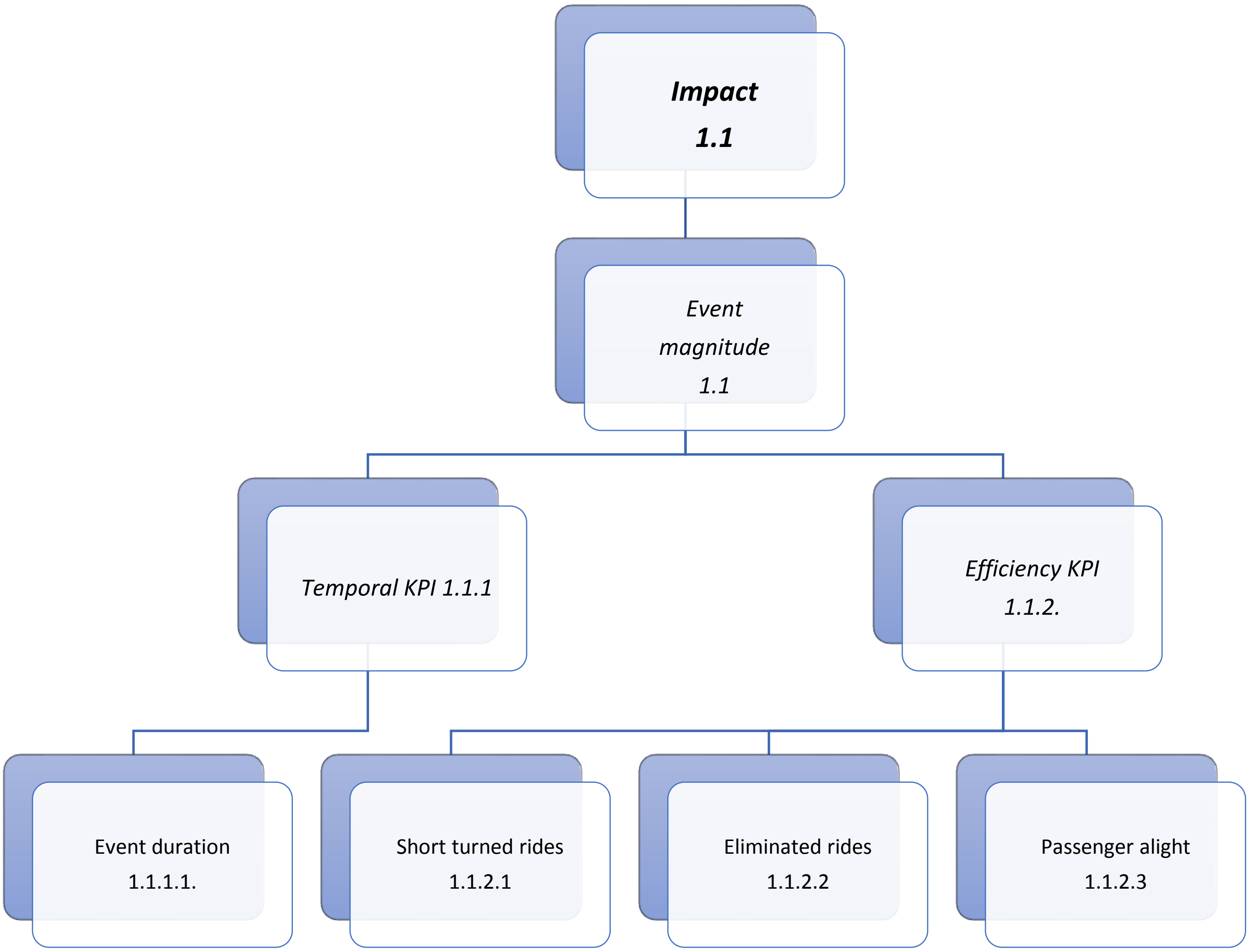
As shown in *figure 70,* once completed the events analysis and once built the risk map it will be possible to cluster the events in different categories. Principally it will be target two group of events:

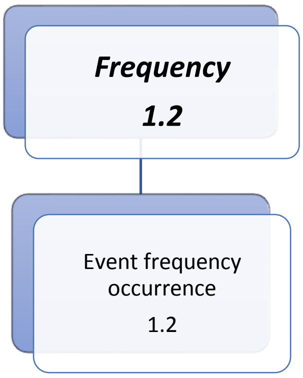
- ***Harmful events:*** These are the events with the higher impact and the higher frequency. For this reason it is necessary to focus on them because, if not treated properly, they can easily produce huge inefficiencies on the line.
- *Harmless events:* These are the events with the lowest impact and lowest frequency. For this reason it is not necessary to spend a lot of resources and energies to tackle them. Their position in that quadrant can be given or by the fact that they are harmless by nature or by the fact that they are already treated in the most efficient and effective way.

The position of a single event on the map is given by the *frequency deviation* and *impact deviation* of each single event respect to the *average event* (the concept and the procedures to find them will be examined in depth in the following sections).

In order to being able to apply the quantitative model mentioned above it is necessary to describe the indicators used to define numerically the position of the different events on the risk-map. Now will be presented the indicators following a hierarchical structure in order to show how they are interconnected one another, after they will be described in detail singularly. The two main categories are ***Impact*** (T*hose KPIs that are needed to define the positioning on the impact axe [X]*) and ***frequency*** (*Those KPIs that are needed to define the positioning on the frequency axe [Y]*).




Impact
1.1
Event
magnitude
1.1
Temporal KPI 1.1.1
Efficiency KPI
1.1.2.
Event duration
1.1.1.1.
Short turned rides
1.1.2.1
Eliminated rides
1.1.2.2
Passenger alight
1.1.2.3


Frequency
1.2
Event frequency
occurrence
1.2

At this point it is necessary to explain the base on which will be built all the successive work. In order to do this it is necessary to introduce an ***assumption*** that has the task to idealize the complex system that we are studying in order to simplify it and to allow an easier numerical analysis. The assumption made is the subsequent:

1. *We assume that the point of the line in which the event happens does not influence the results that it generates on the indicators listed above. This statement is wrong if we consider the single event. However, it is possible to assume that considering all the data related to a time span of some months there is a normalization process that brings to find the event average impact on the line (the situations extremely favorable and adverse mitigate one another giving in the end a realistic value of the event's impact on the line).*

Before to enter in the full description of the indicators it is worth to explain the method used to describe them. We will use the support of a table in which we will place all the information. (See *table 18).*

| ***INDICATOR NAME*** | |
|---|---|
| ***Formula*** | ………………………………………………………………………….... |
| ***Unit of measure*** | ………………………………………………………………………….... |
| ***Optimal value*** | *Which is the objective to follow* |
| ***Historical series*** | *Which is the historical series to consider*<br>*ex: last 12 mesi* |

***Table 18****: Table that shows the structure used to describe indicators.*

***Notes:***

- ✓ In the end a special section will be dedicated to notes, where, if necessary, it will be explained additional/supplementary features.

Now we explain a term that will be used through this section:

- ✓ ***Event x***: With this term we refer to the different kind of events that will be detected on the *line/group of lines* during the time span considered for the analysis. *(e.g. crushes, mean's breakdown,…).*

## 1.1 Impact

### 1.1.1 Temporal KPI

#### 1.1.1.1 Event duration

| EVENT DURATION | |
|---|---|
| **Formula** | $\sum_{i=1}^{n\,(\,event\ x\ numerosity\ in\ the\ time\ span\ considered)} \frac{\boldsymbol{Event\ i}\ identification\ time - \boldsymbol{Event\ i}\ resolution\ time}{n\ (event\ x\ numerosity\ in\ the\ time\ span\ considered)}$ |
| **Unit of measure** | *[min]* |
| **Optimal value** | *Minimization* |
| **Historical series** | *March and February 2013; only week days.* |

***Table 19****: Indicator "Event duration ".*

***Notes:***

- ✓ With this KPI it is possible to perform cross-temporal _ cross-location analysis. In this way it will be possible to understand which are the location and the periods of the year in which certain kind of events happen more *(this kind of analysis will not be performed in this thesis because the research group valued it is not fundamental for the DMSS' purposes)*;

- ✓ This indicator has to be computed for all the *kind of event x* that will be detected on the line/group of lines during the entire time span considered.

### 1.1.2. Efficiency KPI

#### 1.1.2.1 Short turning

| SHORT TURNING NUMEROSITY | |
|---|---|
| **Formula** | $\sum_{i=1}^{n\,(Short\ turned\ rides\ numerosity)} short\ turned\ ride\ i$ |
| **Unit of measure** | *[/]* |
| **Optimal value** | *0* |
| **Historical series** | *March and February 2013; only week days.* |

***Table 20****: Indicator "Short turning numerosity".*

**Notes:**

- ✓ The summation $\sum_{i=1}^{n(short\ turned\ rides\ numerosity)} short\ turned\ ride\ i$ it is a function that counts the various short turned rides generated by a certain event x along the time span considered;
- ✓ This indicator has to be computed for all the *kind of event x* that will be detected on the line/group of lines during the entire time span considered.

### 1.1.2.2 Eliminated rides

| ***ELIMINATED RIDES NUMEROSITY*** | |
|---|---|
| ***Formula*** | $\sum_{i=1}^{n\ (eliminated\ rides\ numerosity)} eliminated\ ride\ i$ |
| ***Unit of measure*** | *[/]* |
| ***Optimal value*** | *0* |
| ***Historical series*** | *March and February 2013; only week days.* |

***Table 21****:* Indicator ”Eliminated rides numerosity”.

**Notes:**

- ✓ The summation $\sum_{i=1}^{n(eliminated\ rides\ numerosity)} eliminated\ ride\ i$ it is a function that counts the various eliminated rides generated by a certain event x along the time span considered;
- ✓ This indicator has to be computed for all the *kind of event x* that will be detected on the line during the entire time span considered.

### *1.1.2.3 Passenger alight*

| ***PASSENGER ALIGHT*** | |
|---|---|
| ***Formula*** | $\sum_{i=0}^{n(passenger\ alights\ numerosity)} passenger\ alight\ i$ |
| ***Unit of measure*** | [/] |
| ***Optimal value*** | 0 |
| ***Historical series*** | *March and February 2013; only week days.* |

***Table 22****: Indicator "Passenger alight".*

**Notes:**

- ✓ The summation $\sum_{i=1}^{n(passenger\ alights\ numerosity)} passenger\ alight\ i$ it is a function that counts the various passengers alights generated by a certain event x along the time span considered;
- ✓ This indicator has to be computed for all the *kind of event x* that will be detected on the line during the entire time span considered.

## *1.1 Magnitude of the event*

Now it is necessary to outline a methodology to merge all the indicators just presented in an unique value that can be used to position a certain event x on the ***impact axe of the risk-map [X]***.

The idea is to identify the *average value of each indicators* taking as values to find it all the results coming from the different events. This value will allow us to compute the ***% deviation of each kind of event respect to the average event.***

Considering to have a ***number n of detected kind of events*** on ***line Y/ group of lines Z*** along a ***time span α*** (that can vary according to the needs) it is possible to compute the average values of each indicator using as population the results coming from the different kind of events**.** The result are the ***average event***'s values of each indicator (see *table 23*).

*Table average indicators*

| ***Indicator's name*** | ***Formula*** |
|---|---|
| ***Average event's duration*** | $\frac{\sum_{x=1}^{n\,(registerd\ event\ number)} Average\ duration\ event\ x}{n\,(registered\ event\ number)}$ |
| ***Average eliminated rides*** | $\frac{\sum_{x=1}^{n\,(registerd\ event\ number)} Eliminated\ rides\ caused\ by\ event\ x}{n\,(registerd\ event\ number)}$ |
| ***Average short turned rides*** | $\frac{\sum_{x=1}^{n\,(registerd\ event\ number)} Short\ turned\ rides\ coused\ by\ event\ x}{n\,(registerd\ event\ number)}$ |
| ***Average Passenger alight*** | $\frac{\sum_{x=1}^{n\,(registerd\ event\ number)} Passenger\ alights\ caused\ by\ event\ x}{n\,(registerd\ event\ number)}$ |

***Table 23****: Table average event's values of each indicator.*

At this point it is necessary a ***% deviation analysis*** for each kind event x, this is fundamental to verify the level of impact of each kind of event in each area (***an area is defined by an indicator***). Taking in consideration the assumptions, logics and indicators presented up to now it is possible to compute the ***% deviation values*** using the formulas presented in *table 24.*

| ***Indicator's name*** | ***Formula*** |
|---|---|
| **Duration of the event**<br>***deviation % event x / average event*** | $\frac{Duration\ of\ the\ event\ \ x - \ Duration\ of\ the\ average\ event}{Duration\ of\ the\ average\ event}$ |
| **Eliminated rides**<br>***deviation % event x / average event*** | $\frac{Eliminated\ rides\ numerosity\ event\ x - \ Eliminated\ rides\ numerosity\ \ average\ event}{Eliminated\ rides\ numerosity\ average\ event}$ |
| **Short turned rides**<br>***deviation % event x / average event*** | $\frac{Short\ turned\ rides\ umerosity\ event\ x - Short\ turned\ rides\ numerosity\ average\ event}{Short\ turned\ rides\ numerosity\ average\ event}$ |
| **Passenger alight**<br>***deviation % event x / average event*** | $\frac{Passenger\ alights\ numerosity\ event\ x - \ passenger\ alights\ numerosity\ average\ event}{passenger\ alight\ numerosity\ average\ event}$ |

***Table 24****: Table % deviation event x.*

***Notes:***

- ✓ All the different kind of event x detected will have to pass through this step;

- ✓ This step is necessary to ***make homogenous the different kind of indicators*** *(they are transformed %)*, in this way we'll have the possibility to merge them in a unique value.

At this point it is necessary to merge all the different results coming from the different indicators to obtain a ***unique value*** that will identify the ***position of a single kind of event x on the horizontal axe [impct]*** on the ***Risk Map***. To do this it will be necessary introduce a relation that weights and merges all the different values ***[X]*** related to a kind of event x. This value is the ***Event magnitude*** (see *table 25*).

| *EVENT MAGNITUDE* | |
|---|---|
| ***Formula*** | $\alpha * A + \beta * B + \pi * C + \Omega * D$ |
| ***Unit of measure*** | [%] |
| ***Optimal value*** | *Minimization* |
| ***Historical series*** | *Quarterly analysis* |

***Table 25****: Indicator "Magnitude of the event".*

***Notes:***

***A***: Duration of the event % deviation event x / average event;

***B***: Eliminated rides % deviation event x / average event;

***C***: Short turned rides % deviation event x / average event;

***D***: Passenger alight % deviation event x / average event.

- ✓ α, β, π, Ω, ἐ, ὀ: These variables represent the weights that each indicator has in defining the "event magnitude". After a careful analysis we have decided that the weights will be identified using ***Exccel's correl()*** function between the ***daily cumulated value of each indicators*** considering all the specific kind of events and the correspondent value of ***Average daily frequency regularity***(This is the value actually used by the company to assess the level of service reliability of the line). This will be done considering a timespan of a month.

## 1.2 Frequency

### 1.2.1 Event frequency occurrence

With this indicator the attention shifts on the ***vertical axe [Frequency]*** of the risk-map. The procedure is the same of the one utilized for the horizontal axe [*Impact*]:

- ✓ At the beginning we identify the ***number of occurrences*** for each single kind of event x *(table 26)*;

- ✓ After we will find the ***average event frequency occurrence*** using as population all the results coming from each single kind of event x;

- ✓ In the end through ***% deviation event x / average event*** it is possible to identify the event x's position on the vertical axe of the risk-map.

| SINGLE KIND OF EVENT X FREQUENCY OCCURENCE | |
|---|---|
| ***Formula*** | $\sum_{i=1}^{n\,(event\ x\ occurrance\ numerosity)} Event\ i$ |
| ***Unit of measure*** | *[/]* |
| ***Optimal value*** | *0* |
| ***Historical series*** | *February 2013; only week days.* |

***Table 26****: Indicator "Single kind of event frequency occurrence".*

***Notes:***

- ✓ The summation $\sum_{i=0}^{n\,(event\ x\ occurrence\ numerosity)} Event\ i$ is considered as a function that counts the number of time a certain event is detected, in this way we obtain how many times a certain kind of event x has happened in the time span considered. Once obtained the frequency occurrence of all the events it is possible to compute the **Average event frequency occurrence** *(table 27)* that will allow the computation of the % deviation of each kind of event x respect to the average one.

- ✓ This indicator has to be computed for all the *kind of event x* that will be detected on the line during the entire time span considered.

| Indicator name | Formula |
|---|---|
| ***Average event frequency occurrence*** | $\frac{\sum_{x=1}^{n\,(different\ kind\ of\ event\ numerosity)} Frequency\ of\ occurrence\ event\ x}{n\ (different\ kind\ of\ event\ numerosity)}$ |

***Table 27****: Indicator "Frequency of occurrence event i".*

Now it is possible to make the ***% deviation analysis*** of each single event x and consequently identify their position on the Risk-Map *(table 28).*

| Indicator name | Formula |
|---|---|
| Single kind of event frequency occurrence ***deviation % event x / average event*** | $\frac{Event\ i's\ occurrence\ numerosity - Average\ event's\ occurrence\ numerosity}{Average\ event's\ occurrence\ numerosity}$ |

***Table 28****: Indicator "% deviation single kind of event respect to the average one".*

## 2. Second level (ALERT DEFINITION)

Now that we have explained how to build a Risk-Map to classify the different events that occur on a line or a group of lines we have to explain how we have identified *Alert 1 "Occurrence of one or more events detected as critical on the risk-map".*

To define this alert it is necessary to follow ***three steps***:

1. ***Frequency regularity (FR) trend along the day.***

The first step is to put in a line graph the hourly Frequency regularity of the entire day of analysis**,** in this way we make the data more readable. Now it is possible to observe the parts of the day in which the line of interest performed the worst.

2. ***Control room diary's event list***

The second step is to list all the events detected on the line during the day of interest, highlighting the ones that are close in time to the great inefficiencies detected in the first step (*frequency regularity trend along the day*).

3. ***Comparison with risk-map results.***

The last step to validate this alert is to verify if the events temporally close to the great inefficiencies of the day, hence the one that probably contributed to their creation, are also valuated harmful in the risk map analysis.

A positive result coming from this comparison it is considered a confirmation that the events close to the great inefficiencies identified in the second step have contributed to their creation.

Usually this event are really harmful and last for long time, me and the research group decided to set a threshold of only 10 minutes because it is necessary to react promptly to this kind of situation. We evaluated 10 minutes a fair amount of time before to start activating the DMSS.

## *Alert 2: "Generation of a group of «steps» that overtakes the set of identified thresholds."*

### 1. *Computation of the "step"*

The first step to create this Alert is to order the data that we have at disposition first for ***table*** (The table is a code that represents a combination of vehicle/service; ascending order) and after for ***actual time slot*** (it represents the actual passage of the mean at the stop that can differ from the scheduled; ascending order). In this way we analyze the progress of the single mean along the service. The variable that is used to perform this analysis is *called* ***step [sec]***.

$$\boldsymbol{Step}: \; Advance/Delay \;\; stop_{n+1} \; means \; i - Advance/Delay \; stop_{n} \; means \; i$$

- ✓ Where stop $_n$ and stop $_{n+1}$ are consecutive.

The alert is activated if:

- In an hour *more than the 50%* of the steps recorded are higher than *+/- 300 sec. (5');*
- In an hour *at least the 10%* of the steps are recorded are higher than *+/- 600 sec. (10');*
- In an hour at least the 5% of the steps recorded are higher than *+/- 900 sec. (15').*

### 2. *Order the "steps" for ascendant time slot*

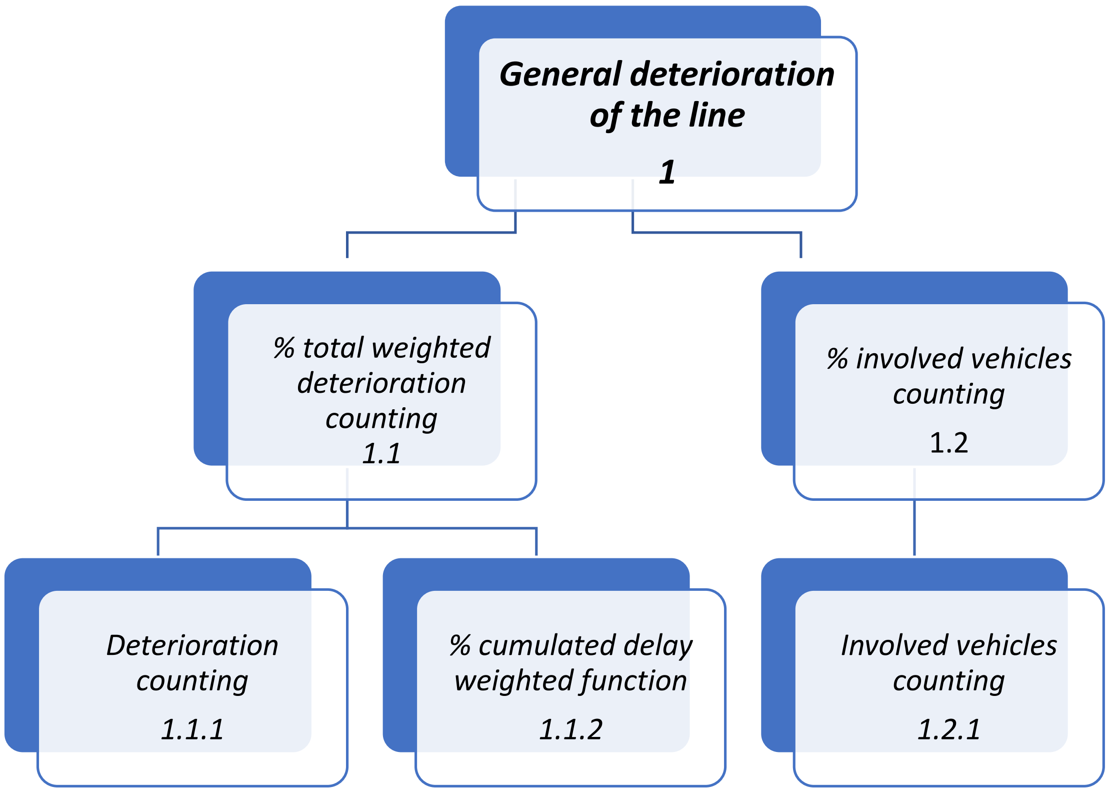
Once obtained all the steps along the day the next step is to order them for ascending time slot removing the order per table. Once done that it is necessary to put the values on a line graph to verify where there are the biggest anomalies highlighting the points in which the thresholds are overtaken.

### 3. *Comparison with frequency regularity trend along the day*

Once defined the part of the day in which there are the biggest anomalies the last step is to confirm the validity of this indicator is to verify if there is a correlation between the periods in which are identified these anomalies and the periods in which the line has performed the worst (Lower frequency regularity along the day).

### *<u>Alert 3</u>: "Increasing trend of "General deterioration of the line"*

Now we want to explain the variables, logics and assumptions that will constitute ***"Increasing general deterioration of the line".*** To describe this indicator it is necessary to introduce the two sub- indicators that compose it:




The concept of <u>***deterioration** is identified as the delay accumulation of a single mean for at least 5 consecutive stops*</u>. From this concept derives the two sub-indicators *"% total weight deterioration counting"* and *"% involved vehicles counting"* that are in a second time merged in *"General deterioration of the line".*

# 1 General deterioration of the line

## 1.1 % total weighted deterioration counting

### 1.1.1 Deterioration counting

The first step needed to compute this sub-indicator is to count how many *deterioration events (table 29)* occurred during the day.

| DETERIORATION COUNTING | |
|---|---|
| ***Formula*** | $\sum_{i:1}^{n\,(\,tot\ number\ of\ deterioration\ detected)} Deterioration\ i$ |
| ***Unit of measure*** | *[/]* |
| ***Optimal value*** | *0* |
| ***Historical series*** | *Computed real time* |

***Table 29****: Indicator "Deterioration counting".*

**Notes:**

- ✓ This is a ***function that counts*** the number of deterioration's occurrences in a certain time slot (a time slot is formed by 60 min, e.g. time slot 5 goes from 4:00 a.m. to 4:59 a.m.);
- ✓ There is ***not a unique relation between table and deterioration counting***; a table in a time slot can be associated to more deterioration events.

### 1.1.2 % cumulated delay weighted function

To compute *"% total weighted deterioration counting*" we have to introduce a group of weights that have the task to weight the delay generated by the deterioration *(the counting of a deterioration event that produces a delay of 6 minutes will have a double weight respect to a deterioration event that produces a delay of 3 minutes).*

The weight function is linked to the distribution of delays along the day (in this indicator we do not consider advances). To understand which weight assign to every single deterioration event it is necessary to compute the *numerosity of delay records in each delay slot.* In order to be clearer it is introduced an example (see *table 30).*

| Delay slot [sec.] | Delay record numerosity | % delay | % cumulated delay |
|---|---|---|---|
| 0-100 | x | r → (x/a) | v → (r) |
| 100-200 | y | q → (y/a) | l → (r+q) |
| 200-300 | z | b → (z/a) | j → (r+q+b) |
| 300-400 | f | c → (f/a) | w → (r+q+b+c) |
| ….. | g | z → (g/a) | y → (r+q+b+c+z) |
| **Sum** | a → (x+y+z+f+g) | | |

***Table 30**: explicative table to describe how to compute "Numerosity of delay records in each delay slot".*

Starting from the cumulated distribution it is possible to build the weighted function, which will have the quality to be robust. A certain delay can have different weights according to the performances of the line up to a particular instant.

Now we assign to different *% cumulated delay* a weight as shown in *table 31.*

| % cumulated delay | Weighted associated |
|---|---|
| 0-74% | 1 |
| 75%-84% | 2 |
| 85%-94% | 3 |
| 95%-98% | 4 |
| 99%-100% | 6 |

***Table 31**: Relation between "% cumulated delay" and "weighted associated".*

*Figure 72* shows graphically the trend of the weighted function respect to the *% cumulated delay*.

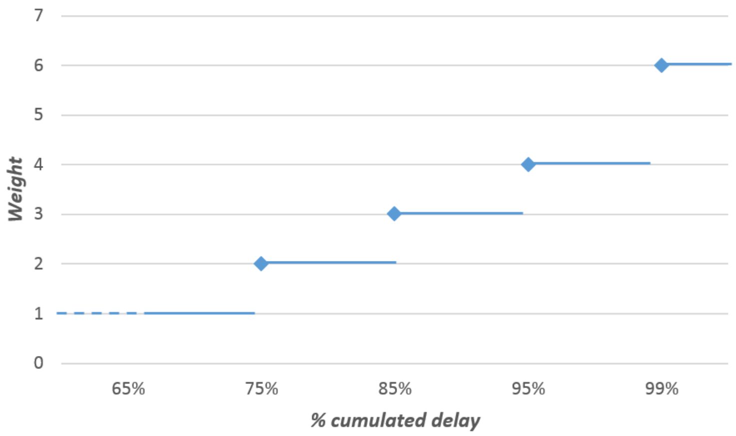



***Figure 71**: Graphical representation weighted function - % cumulated delay.*

Now that we have explained the relation between *"% cumulated delay"* and *"weighted associated"* it is possible to show how to find ***"% total weighted deterioration counting***"" (see *table 5.2.16*).

| Weight | 1 | | 2 | | 3 | | 4 | | 6 | | ***% total weighted deterioration*** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **% cumulated delay (x)** | 0%<x<74% | | 74%<x>84% | | 85%<x<94% | | 95%<x<98% | | 99%<x<100% | | | |
| **Time slot** | **Det. Cou.** | **Wei. Det. Cou.** | **Det. Cou.** | **Wei. Det. Cou.** | **Det. Cou.** | **Wei. Det. Cou.** | **Det. Cou.** | **Wei. Det. Cou.** | **Det. Cou.** | **Wei. Det. Cou.** | **Tot. wei. Det. Cou.** | **%** |
| *5 (4:00 a.m. – 4:59 a.m.)* | *q* | *w* | *e* | *r* | *t* | *y* | *u* | *i* | *o* | *p* | *g →(w+r+y+i+p)* | *f →(g/x)* |
| … | … | … | … | … | … | … | … | … | … | … | … | … |
| | | | | | | | | | | **Total** | *x* | |

***Table 32****: Explicative table "Deterioration counting".*

- **Det. Cou.** : <u>*Deterioration counting*</u> → here are reported how many episodes of deterioration occur in the particular time slot. Each deterioration event detected is inserted inside the table accordingly to its % cumulated delay slot (if the deterioration doesn't generate any kind of delay it will have a weight of 1).

  *Example (look at table 32):*
  *If a deterioration event will produce a delay of 10 minutes, in the time slot 5, and the delay generated is positioned in the % cumulated delay that goes from 95% to 98%, the counting of this particular event will be inserted in the red cell.*

- ***Wei. Deg. Cou.*** *:* <u>*Weighted deterioration counting*</u> → this is the value of the deterioration counting multiplied for its correspondent weight;

  *Example cont'd (look at table 32):*
  *This is one event, but since the delay generated is part of the % cumulated delay that goes from 95% to 98% it is multiplied per 4, this value it is inserted in the purple cell. The same treatment goes for all the deterioration events detected.*

- ***Tot. Wei. Det. Cou. :*** *<u>Total weighted deterioration counting</u>* → this value is the sum of all the values "*weighted deterioration counting"* keeping the separation per time slot;

  *Ex cont'd (look at table 32):*

  *Once a time slot (it represents an hour af the day) is finished the weighted deterioration counting values are summed and the results finishes in the orange cell. The same procedure it is followed for all the time slots that compose the entire day.*

- ***%*** : *<u>% total weighted deterioration counting</u>* → this is the percentage value of the *total weighted deterioration counting*. Since data is analyzed in real time this values changes every time a *time slots* finishes, this because the total *value X* changes over time. We introduced this to make the two sub-indicators homogeneous (%) hence agreeable.

  *Ex cont'd (look at table 32):*

  *Once two time slots are completed it is possible to start computing the % total weighted deterioration counting of each time slot. The results, that are updated each time a time slot finishes, are inserted in the green cell.*

### *1.2 % involved vehicles counting*

#### *1.2.1 Involved vehicles counting*

| ***INVOLVED VEHICLES COUNTING*** | |
|---|---|
| ***Formula*** | $\sum_{i:1}^{n(total\ number\ of\ vehicles\ involved\ in\ the\ deteriotation)} involved\ vehicle\ i$ |
| ***Unit of measure*** | *[/]* |
| ***Optimal value*** | *0* |
| ***Historical series*** | *Computed real time* |

***Table 33****: Indicator "involved table counting".*

- ✓ $\sum_{i:1}^{n(total\ number\ of\ vehicles\ involved\ in\ the\ deteriotation)} involved\ vehicle\ i$ is a function that counts the numbers of tables involved in the deterioration that are registered in a particular time slot.

*Table 34* shows how it is obtained *"% involved vehicles counting*" starting from involved vehicles counting.

| ***Time slot*** | ***Involved vehicles counting*** | ***% involved vehicles counting*** |
|---|---|---|
| *5* | *W* | *d→(W/L)* |
| … | … | … |
| ***Total*** | *L* | |

***Table 34****: Explanatory table to find "% involved tables counting".*

- ✓ The value of this indicator changes every time a time slot finishes, because the total value of involved tables counted changes.

## 1 General deterioration of the line

| GENERAL DETERIORATION OF THE LINE | |
|---|---|
| **Formula** | $\%\ total\ weighted\ deterioration\ counting + \%\ involved\ vehicles\ counting$ |
| **Unit of measure** | *[/]* |
| **Optimal value** | *0* |
| **Historical series** | *Computed real time* |

***Table 34***: *General deterioration of the line.*

- ✓ This indicator is the sum of "*% total weighted deterioration counting*" and *"% involved tables counting"*, the two sub-indicators have been computed in % in order to make them homogenous;

- ✓ This indicator have to be computed for each time slot.

*Table 35* shows how can be found general deterioration of the line divided per time slot.

| *Time slot* | *% total weighted deterioration counting* | *% involved vehicles counting* | *General deterioration of the line* |
|---|---|---|---|
| *5* | *d* | *f* | *m →(d+f)* |
| … | … | … | … |

***Table 35***: *Deterioration of the line divided per time slot.*

Once found the ***General deterioration of the line (GDL)*** per time slot the alert will be activated if it is detected an increasing trend of the indicator for at least 2/3 consecutive time slot. The following indicator has the task to detect the increasing trend:

***Increasing trend GDL:*** $GDL\ t\ \ <> GDL\ t-1 <> GDL\ t-2 <> GDL\ t-3$

- This symbol <> means that the relation between two element can be both of majority or minority;

- The indicator activates the alert only and only if there are ***2/3 relation of majority.***

## 5.2.2 Service reliability (SR) algorithm

Now the focus is moved to the algorithm, in this section we will describe all the logics variables and assumptions created to make this component, which is the core of the support system created, work properly. *Figure 72* shows the main components of the algorithm that will be the subchapters of this section.

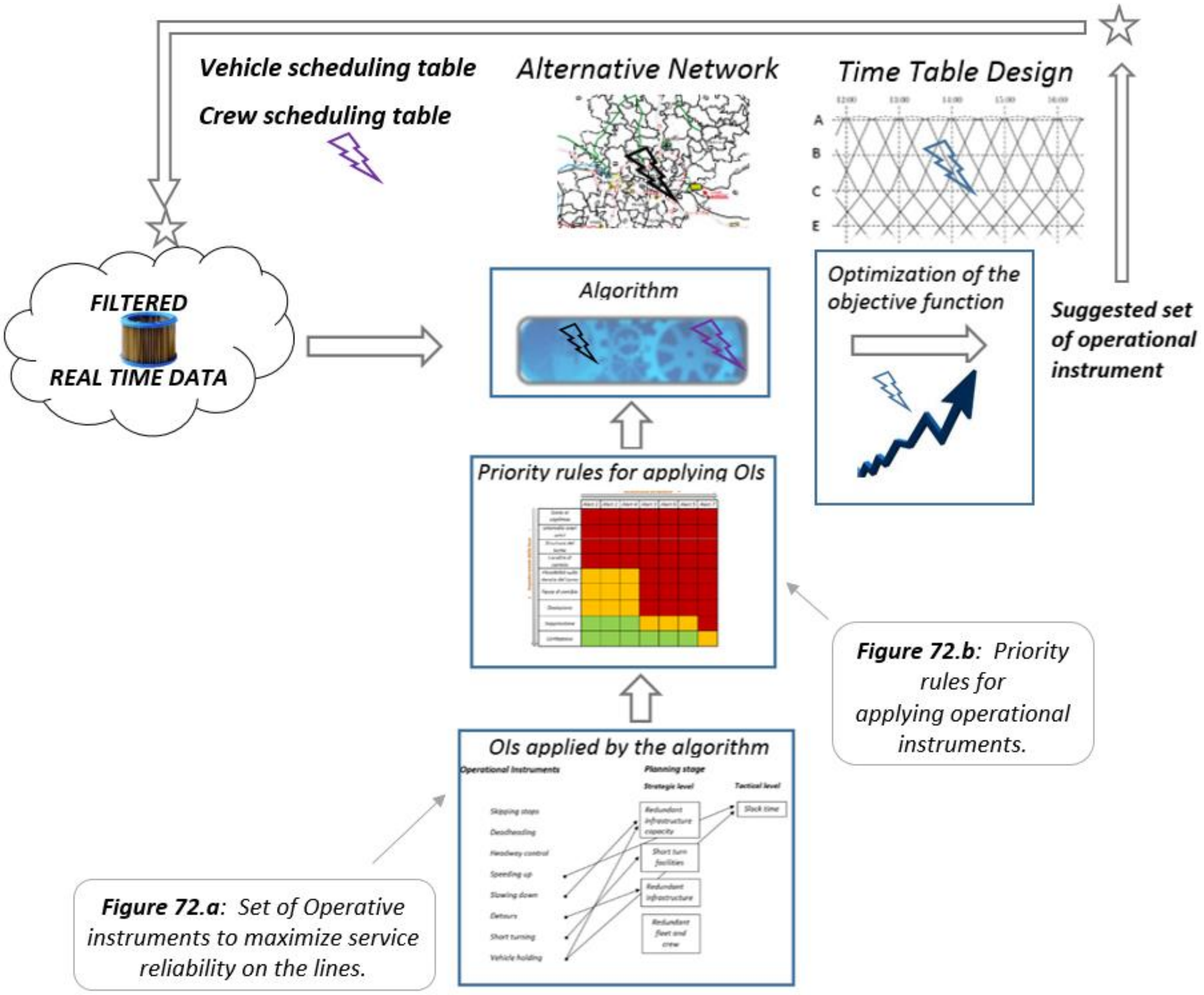



***Figure 72**: Algorithm side components.*

Looking at the entire *algorithm side* the parts on which we worked the most have been:

- The ***creation of new set OIs*** with the aim to make the entire public transport system structure more flexible (*See figure 72.a*).

- The ***creation of a set of priority rules*** that the algorithm will have to follow with the aim to build a hierarchical relation between the alert activated and the different operational instrument applicable (*See figure 72.b*).

## *New set of OIs*

The creation of this new set of operational instruments it is necessary to make the structure of the public transport system more flexible in order to make the system more reactive to disruption events and disturbances that interacting with the operational process increase the variability of the service offered hence decrease the service reliability.

The new set of operative instruments will be focus to increase the crew scheduling flexibility. An increasing in the flexibility is fundamental for two main reasons:

3. *To decrease the invasive interventions done by operators to guarantee drivers to arrive on time at the change station even if they lower the service reliability and create discomforts to passengers;*

4. *To reduce the delay propagation.*

While the first aspect is clear thanks to the analysis performed during this thesis, for the second one we will introduce an example to clarify it.

- *Example*

*Let us consider 2 shifts that has a break in the middle at the same time and at the same place, as shown in figure 73 (this is a pretty common situation).*

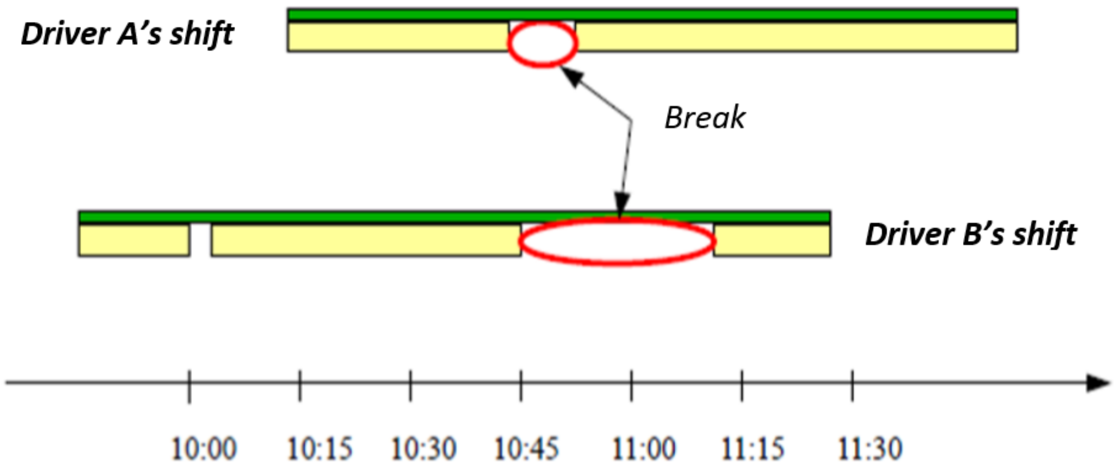



***Figure 73**: Case in which the two shifts have a break between 10:45 a.m. and 11:00 a.m.*

*If we hypothesize a delay on the driver A's shift that "eats" the break and impact on the second part of the shift (see figure 74).*

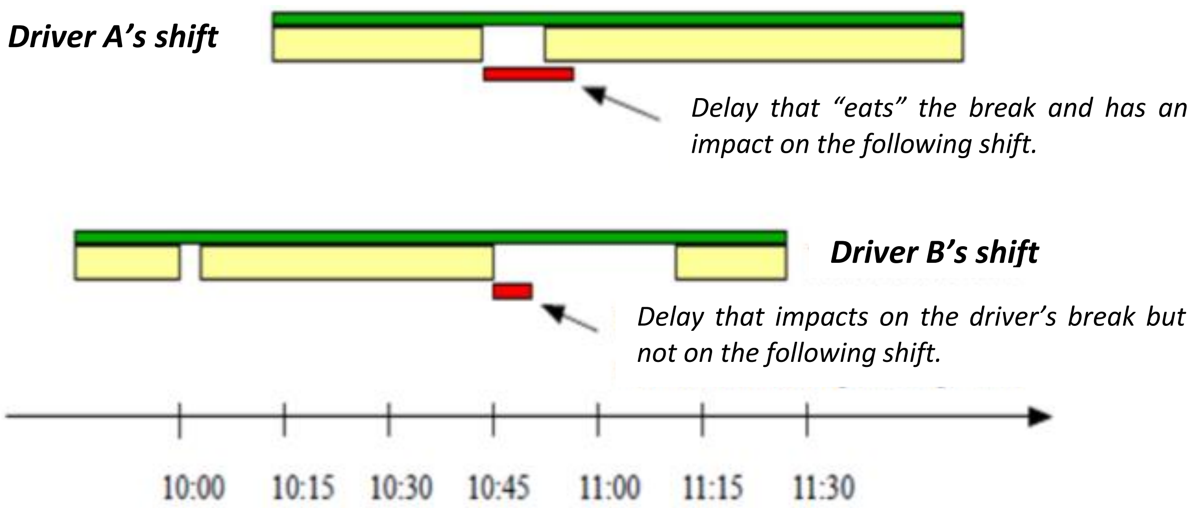



***Figure 74**: Driver A's shift with a delay (in red) of almost 15 minutes.*

*Without operating any kind of intervention, if the driver will do the entire scheduled break (as expected by contract), the result is a propagation of the delay on all the second part of the diver A's shift (See figure 75).*

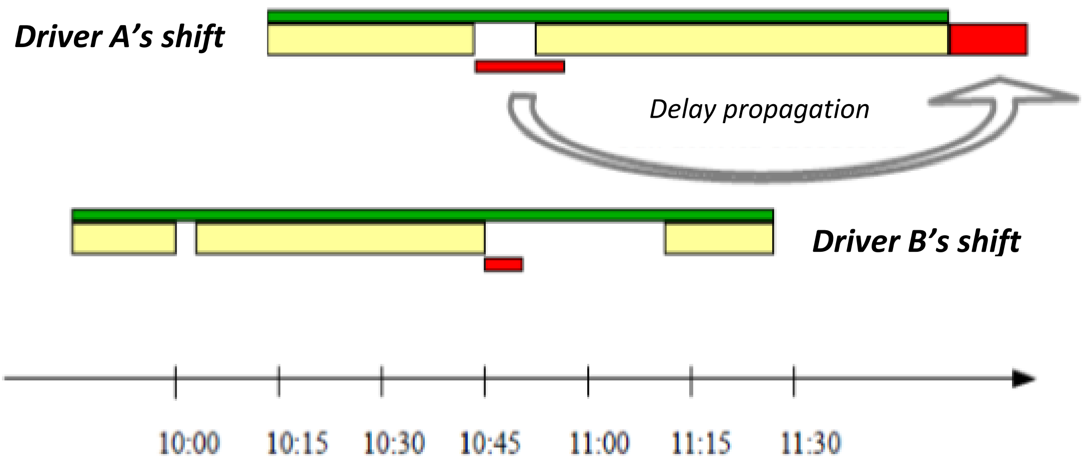



***Figure 75**: Propagation of the delay for the entire duration of Driver's A shift.*

*A possible way to solve this problem is to operate a short turn before the Driver A's break to recover the delay and allow it to arrive on time to the change station, as shown in figure 76.*

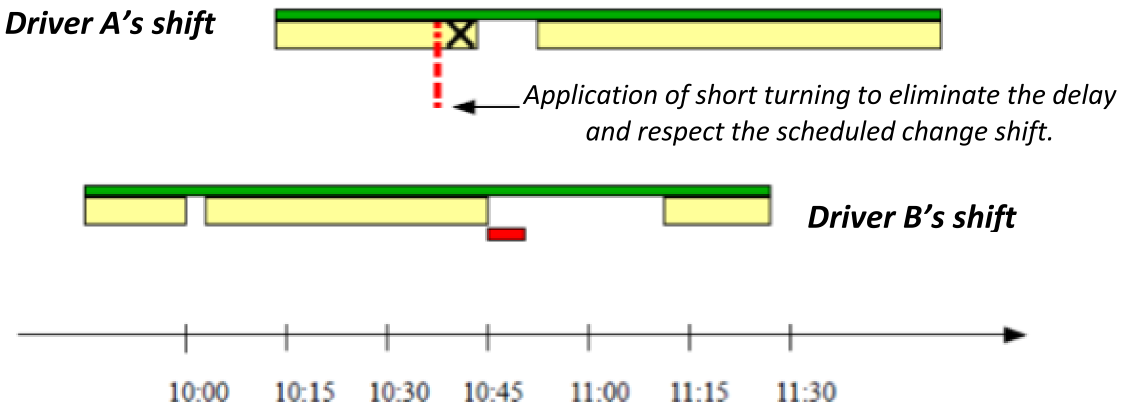



***Figure 76**: Short turning implementation to recover the delay.*

*It is clear that the change shift hours are critical and how in their proximity it is necessary to intervene with invasive operational instruments that on one hand can solve some problems but on the other they generate inefficiencies. However, they create also discomforts to the passengers that have to leave the mean and wait for the passage of the following one.*

*The new set of operational instruments that will be introduced next to the classical ones (already presented in the literature analysis and during the framework) will give the possibility to the operators to solve this kind of problems without generating any consequence on the passengers and on the general performances of the line. As said previously this set of operational instruments will be focused on crew scheduling and on making the entire public transport structure less stiff.*

*Thank to them the problem presented previously could have been solved without the application of any invasive operational instrument. The hypothesis in this case is to change the activities between the two drivers in order to eliminate the "**delay propagation**" effect as shown in figure 77:*

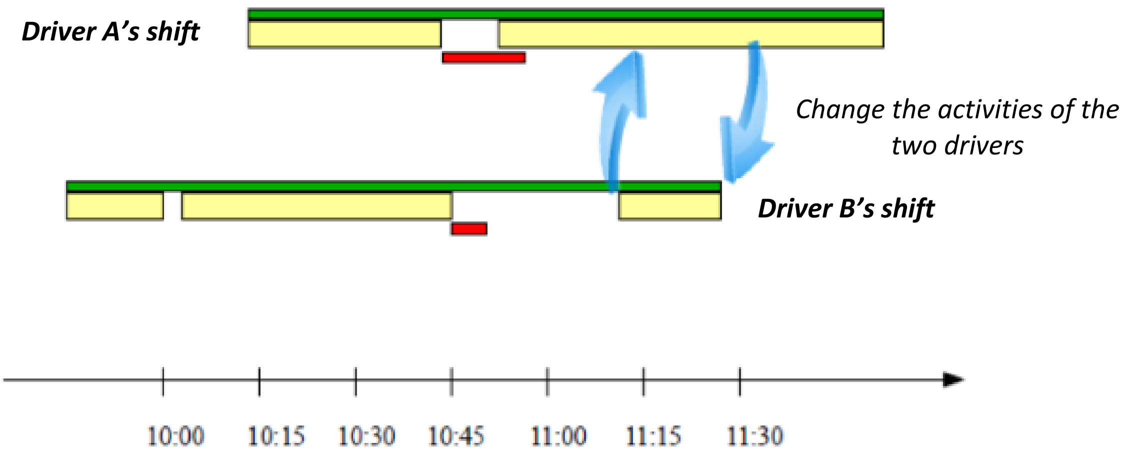



***Figure 77**: Change of activities between the two drivers.*

*Since the first driver (A) is in strong delay and it has a short break in the middle of the shift it will propagate for sure the delay also in the second part of the shift (see figure 77). According to what just said it would be a wise move changing the activities of the two drivers, in this way the result obtained will be the following (see figure 78):*

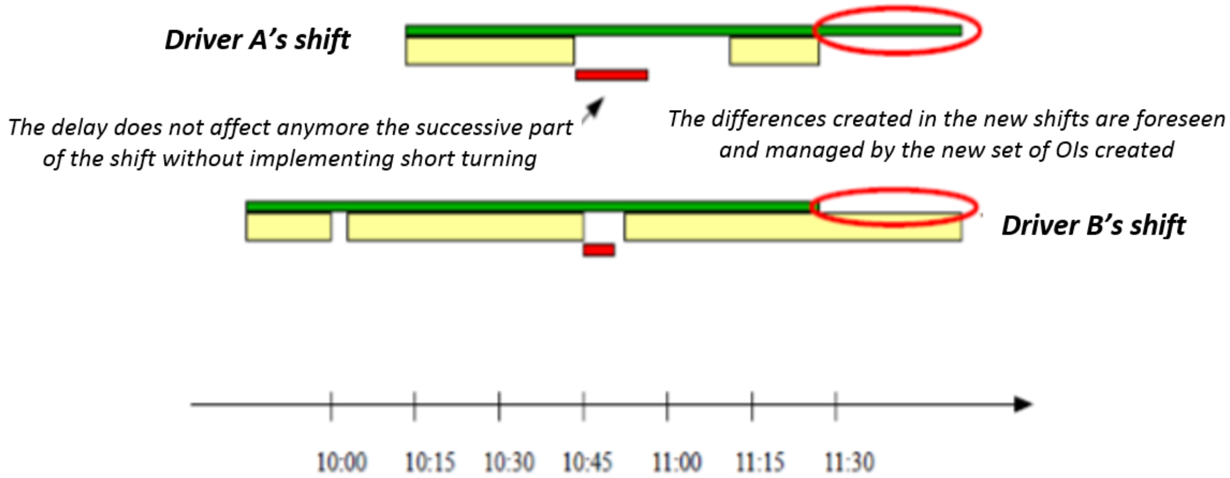



***Figure 78**: Result of changing activity of the two drivers.*

Now that are evident the benefits that an increase in the crew scheduling flexibility can bring to the operational performances of the surface public transport system it is important list and explain the new operational instruments that make this possible (see *table 36).*

| Crew scheduling flexibility’s operational instruments |
|---|
| ***Shift’s duration flexibility*** |
| ***Break flexibility*** |
| ***Shift’s structure flexibility*** |
| ***Change station flexibility*** |
| ***Stop at the terminals flexibility*** |

***Table 36****: Crew scheduling flexibility’s operational instruments table.*

1. ***Shifts duration flexibility***

Flexibility of 20’ on the scheduled duration of the drivers’ duty.

2. ***Break flexibility***

Flexibility to move the break in times and places (*these are selected point on the line known in advance by the algorithm*) different respect to the scheduled one.

3. ***Shifts structure flexibility***

Flexibility to change the scheduled structure of the shift. This operative instrument gives the possibility to change part of shifts between different drivers, as in the example presented above.

4. ***Change station flexibility***

Possibility to finish the duty in another change stations (*these are selected point on the line known by the system*) respect to the one scheduled.

5. ***Stop at the terminal flexibility***

Flexibility to absorb part of the delay accumulated by skipping part of the break at the terminal.

### *Set of priority rules for applying OIs*

Now it is necessary to explain and describe the variables, logics and assumptions that compose the ***priority rules*** followed by the algorithm to select the proper set of OIs that once applied can maximize service reliability of the line. In the end we will obtain a set of rules that regulate and describe the ***relations*** between the ***alert/group of alert activated*** and the ***best group of operative instruments*** to apply.

Now it is worth to recap both the ***Alerts*** (*table 37*) and the ***operational instruments*** (*table 38*) that will be used by the support system since they are fundamental to develop this last section.

| ***Alert*** | ***Description*** |
|---|---|
| ***Alert 1*** | *"Occurrence of one or more events detected as critical on the risk map"* |
| ***Alert 2*** | *Generation of a group of «steps» that overtakes the set of identified thresholds* |
| ***Alert 3*** | *Increasing trend of "General deterioration of the line"* |

***Table 37***: *Alerts' list with brief description.*

| ***Operational instruments*** |
|---|
| ***Skipping stops*** |
| ***Deadheading*** |
| ***Headway control*** |
| ***Speeding up*** |
| ***Slowing down*** |
| ***Detours*** |
| ***Short turning*** |
| ***Ride elimination*** |
| ***Vehicle holding*** |
| ***Shift's duration flexibility*** |
| ***Break flexibility*** |
| ***Shift's structure flexibility*** |
| ***Change station flexibility*** |
| ***Stop at the terminals flexibility*** |

***Table 38***: *Operational instruments list.*

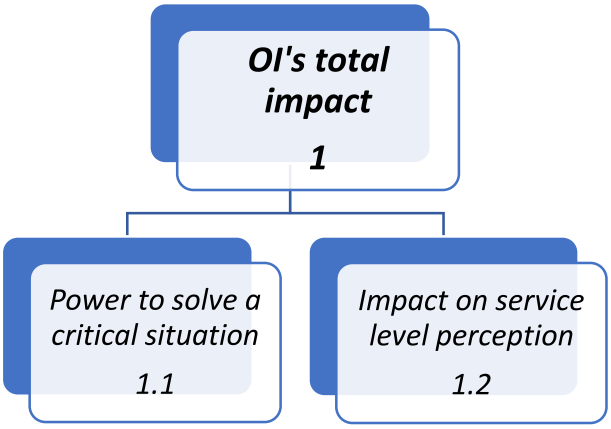
The final objective of this section is a construction of a ***<u>Priority Matrix Alert-OIs</u>*** that will describe, accordingly with the kind of alert activated, *which operational instruments to apply and the intensity with which a certain operational instrument has to be applied.*

In order to build the matrix we follow *two principal steps*:

### 1st step (priority definition):

The first step is to find the ***level of impact*** that each operational instrument generates on the system once applied and the ***alert/combination of alerts' accuracy*** in foreseeing a possible future critique situation.

We have found the impact generated by a single operational instrument computing a qualitative indicator called *"OI's total impact"* that has shown by the following chart is composed by two sub-indicators:




## *<u>1 OI's total impact</u>*

### *1.1 Power to solve a critical situation*

| POWER TO SOLVE A CRITICAL SITUATION | |
|---|---|
| **Formula** | $\frac{\sum_{i=1}^{n\ (nummber\ \ of\ expert\ interviewed)} Grade\ "Power\ to\ solve\ a\ critical\ sytuation"\ i}{n\ (nummber\ of\ expert\ interviewed)}$ |
| **Range** | 1/10 |

***Table 39:*** *Indicator "Power to solve a critical situation".*

***Notes:***

- ✓ To find the value of this indicator we have asked to different experts, which have been working for years in the public transport sector, to grade each operational instrument. In the end the average of all the evaluations gave us a value that represents the solving power owned by a certain OI.

- ✓ All the OIs possessed by the DMSS will be evaluated.

### *1.2 Impact on service level perception*

| *IMPACT ON SERVICE LEVEL PERCEPTION* | |
|---|---|
| ***Formula*** | $\frac{\sum_{i=1}^{n\,(nummber\ \ of\ expert\ interviewed)} Grade\ "impact\ on\ service\ level\ perception"\ i}{n\ (nummber\ \ of\ expert\ interviewed)}$ |
| ***Range*** | *1/10* |

***Table 40***: *Indicator "Impact on service level perception".*

***Notes:***

- ✓ To find the value of this indicator we have asked to different experts, which have been working for years in the public transport sector, to grade each operational instrument. In the end the average of all the evaluations gave us a value that reliably shows the impact that the application of a certain OI can have on service perception.

- ✓ All the OIs possessed by the DMSS will be evaluated.

We have chosen this two aspect because we have some operational instruments that has a huge power because are able to solve quickly a critique situation but that at the same time creates discomforts to the passengers.

### *1 OI's total impact*

| *OI'S TOTAL IMPACT* | |
|---|---|
| ***Formula*** | $Power\ to\ solve\ a\ critical\ situation +$ *Impact on service level perception* |
| ***Range*** | *1/20* |

***Table 41***: *Indicator "OI's total impact".*

The general impact of the single OI will be computed adding the results of the two sub indicators even if they have opposite meanings (*the first generate a positive impact while the second generate a negative impact*). The final objective is to find the general impact without judging if this is positive or negative.

### ***Gravity of the situation foreseen by the alert***

The same approach used to evaluate the operational instrument has been applied also for alert and combination of them.

Now we want to evaluate the capability and the accuracy that a certain kind of alert has in foreseeing a critique situation.

| PREDICTIVE ACCURACY OF THE ALERT | |
|---|---|
| **Formula** | $\frac{\sum_{i=1}^{n\ (number\ of\ expert\ interviewed)} Grade"predictive\ accurracy\ of\ the\ alert"\ i}{n\ (number\ of\ expert\ interviewed)}$ |
| **Range** | *1/10* |

***Table 42****: Indicator "Predictive accuracy of the Alert".*

***Notes:***

- ✓ This indicator is computed for each alert and combination of them;
- ✓ To find the value of this indicator we have asked to different experts, which have been working for years in the public transport sector, to grade each alert/combination of alerts. In the end the average of all the evaluations gives us a value that reliably shows the predictive accuracy of the alert/combination of alert.

### 2nd step (OIs-alert detected relation):

Now it is necessary to outline a hierarchy with the objective to differentiate different OIs. It is based in identifying the required application intensity of a specific OI to solve a certain critical situation detected by the activation of an Alert. Furthermore, with this hierarchy we want to give different priority levels in the usage of the OIs at disposition of the algorithm to improve line's service reliability.

There can be ***three diverse modality of usage:***

- ***Light usage:*** This modality of usage shows that a certain operational instrument linked to the detection of a certain alert have to be used as less as possible, giving the priority to the higher level OIs.

- ***Medium usage:*** This modality of usage is in the middle, this means that an OIs with medium priority will be used only if the Intensive usage OIs have not been able to solve the critical situation.

- ***Intensive usage:*** the OIs with this level of priority are the ones that have been judged more suitable in tackling the critical situation detected by the activation of a certain alert, these are the first one that are applied to solve the critical situation identified on the line.

***Notes***

- ✓ It is important to stress that the modality of usage of a certain OI changes accordingly to the kind of alert detected.

The process that explains how the algorithm will tackle the critical situation on the line that activates a certain alert will be presented by *figure 79 - 80.*

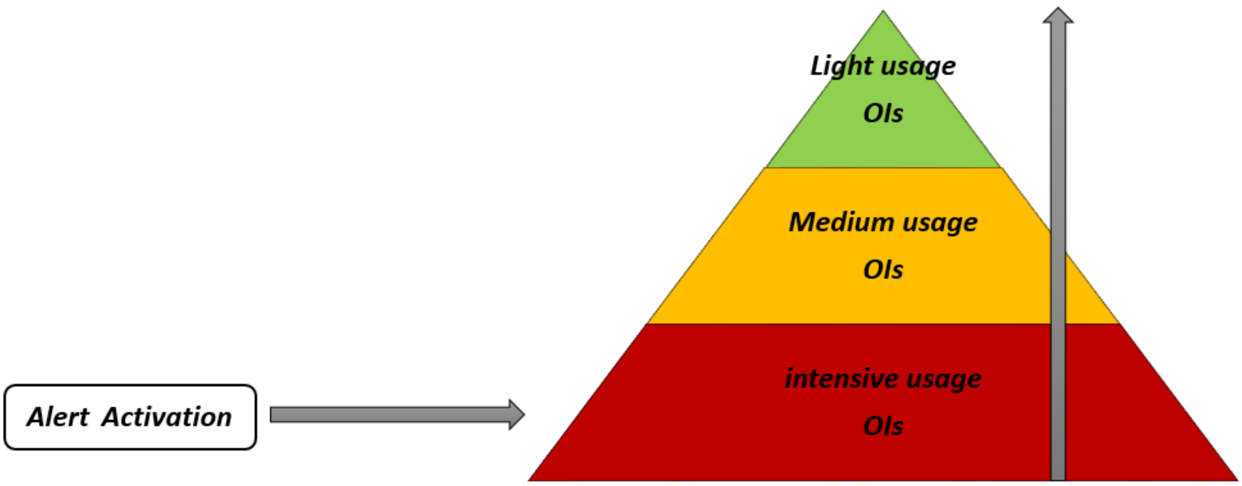
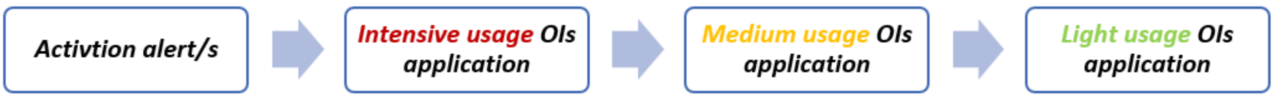



***Figure 79****: OIs' intensive usage pyramid.*

As it is shown in *figure 79* the process followed by the algorithm to pick the set of OIs to restore the service reliability of the line follow the logic presented below:

5. *Alert/s activation;*
6. *Application of intensive usage OIs (related to the alert/s activated), if with them the algorithm is not able to bring back the regularity it passes to step 3;*
7. *Application of medium usage OIs (related to the alert/s activated), if with them the algorithm is not able to bring back the regularity it passes to step 4;*
8. *Application of light usage OIs (related to the alert/s activated).*




Now we have all the elements that allow us to build the *matrix alert/leva*.

Now it is possible to create the ***Priority Matrix Alert-OIs*** following two single steps:

1. *First of all we have to order both the Alerts and the OIs in ascendant order following the results obtained in the fist phase.*
2. *After we will build the relations among them asking to the experts inquired in the first phase to fill-in the matrix presented under following some rules.*

| | *OI 1* | *OI 2* | *OI 3* | *.....* |
|---|---|---|---|---|
| *Alert 1* | | | | |
| *Alert 2* | | | | |
| *Alert 3* | | | | |
| *Alert 4* | | | | |
| *Alert 5* | | | | |
| *......* | | | | |

***Figure 80***: *Priority matrix alert-OI example.*

As explained previously it will be identified for each alert/group of alert the group of OIs evaluated more suitable in solving the critical situation detected by its activation. The finial objective is to apply the OI that generates the less possible discomforts to the passengers.

We will build the matrix asking to the same group of experts questioned in the first phase to fulfill an empty matrix (following some indications), the final result will be obtained following the approach successively explained:

1. ***The first step is to assign to each kind of intensity (light, medium, intense) a value range:***

| | |
|---|---|
| ***Intensive usage*** | [7-9] |
| ***Medium usage*** | [4-6] |
| ***Ligth usage*** | [1-3] |

2. ***Mediating the values coming from all the fulfilled matrixes it is possible to obtain the final Alert/OI matrix.***

### 3rd step (data gathering and final matrix construction)

In this section we process the values obtained from the various interviews in order to build the final matrix that contains the priority rules that the algorithm will follow to find the best set of OIs to apply on the line to recover its service reliability.

As previously said we are going to consider not only the single alert but also the combination of them (see *table* 43 – *44*).

| ***Alert*** | ***Description*** |
|---|---|
| ***Alert 1*** | *"Occurrence of one or more events detected as critical on the risk map.* |
| ***Alert 2*** | *Generation of a group of «steps» that overtakes the set of identified thresholds* |
| ***Alert 3*** | *Increasing trend of "General deterioration of the line"* |

***Table 43****: Priority matrix alert-OI example.*

| *Alert combination* | *Average evaluation* |
|---|---|
| *Alert 1* | ***Alert 1*** |
| *Alert 2* | ***Alert 2*** |
| *Alert 3* | ***Alert 3*** |
| *Alert 1 + Alert 2* | ***Alert 4*** |
| *Alert 1 + Alert 3* | ***Alert 5*** |
| *Alert 2 + Alert 3* | ***Alert 6*** |
| *Alert 1 + Alert 2 + Alert 3* | ***Alert 7*** |

***Table 44***: *Alert, combination of alerts list.*

Once gathered and processed the results coming from all the experts' interviews we have obtained what presented in *table 45.*

| *Final alert* | *Average evaluation* |
|---|---|
| ***Alert 1*** | *6* |
| ***Alert 2*** | *5* |
| ***Alert 3*** | *8* |
| ***Alert 4*** | *7* |
| ***Alert 5*** | *9* |
| ***Alert 6*** | *8,5* |
| ***Alert 7*** | *10* |

***Table 45***: *Alert, combination of alerts final evaluations "Capability to solve a critical situation".*

Now it is necessary to reorder them following their "capability to solve a critical situation" (ascendant order) (*see table 46*).

| *Final alert* | *Average evaluation* |
|---|---|
| ***Alert 2*** | *5* |
| ***Alert 1*** | *6* |
| ***Alert 4*** | *7* |
| ***Alert 3*** | *8* |
| ***Alert 6*** | *8,5* |
| ***Alert 5*** | *9* |
| ***Alert 7*** | *10* |

***Table 46***: *Alert, combination of alerts final evaluations "Capability to solve a critical situation".*

*Table 46* shows which alerts are considered more dangerous because of their ability to foresee a future critical situation on the line. The activation of the three basic alert concurrently (***Alert 7***) identify a very dangerous situation in which it is necessary to act in the fastest way possible.

Now the focus moves on the OIs. As explained in the initial part of this chapter the analysis of operational instruments' impact have to be done considering two main factors:

1. *Power to solve a critical situation*
2. *Impact on service level perception*

*Table 47* recaps all the operative instruments that will be used by the algorithm of the DMSS:

| *Operational instruments* |
| --- |
| ***Skipping stops*** |
| ***Deadheading*** |
| ***Headway control*** |
| ***Speeding up*** |
| ***Slowing down*** |
| ***Detours*** |
| ***Short turning*** |
| ***Vehicle holding*** |
| ***Ride elimination*** |
| ***Shift's duration flexibility*** |
| ***Break flexibility*** |
| ***Shift's structure flexibility*** |
| ***Change station flexibility*** |
| ***Stop at the terminals flexibility*** |

***Table 47***: *Operational instrument used by the DMSS.*

Once gathered and processed the results coming from all the experts' interviews we have obtained what presented in *table 48.*

| ***Operational instrument*** | ***Power to solve a critical situation [1-10]*** | ***Impact on service level perception [1-10]*** | ***OI overall impact [1-20]*** |
|---|---|---|---|
| ***Break flexibility*** | 5 | 0 | ***5*** |
| ***Shift's structure flexibility*** | 5 | 0 | ***5*** |
| ***Stop at the terminals flexibility*** | 5 | 0 | ***5*** |
| ***Headway control*** | 5 | 0 | ***5*** |
| ***Speeding up*** | 5 | 0 | ***5*** |
| ***Slowing down*** | 5 | 0 | ***5*** |
| ***Shift's duration flexibility*** | 6 | 0 | ***6*** |
| ***Change station flexibility*** | 6 | 0 | ***6*** |
| ***Vehicle holding*** | 7 | 5 | ***12*** |
| ***Ride elimination*** | 9 | 5 | ***14*** |
| ***Skipping stops*** | 8,5 | 8 | ***16,5*** |
| ***Detours*** | 9 | 8,5 | ***17,5*** |
| ***Short turning*** | 10 | 10 | ***20*** |

***Table 48***: *Operational instruments used by the DMSS, with processed evaluation (ascendant order).*

Once obtained the results it is possible to make some considerations about the characteristics of the different Operation instruments at disposition of support system created (see *figure 81*).

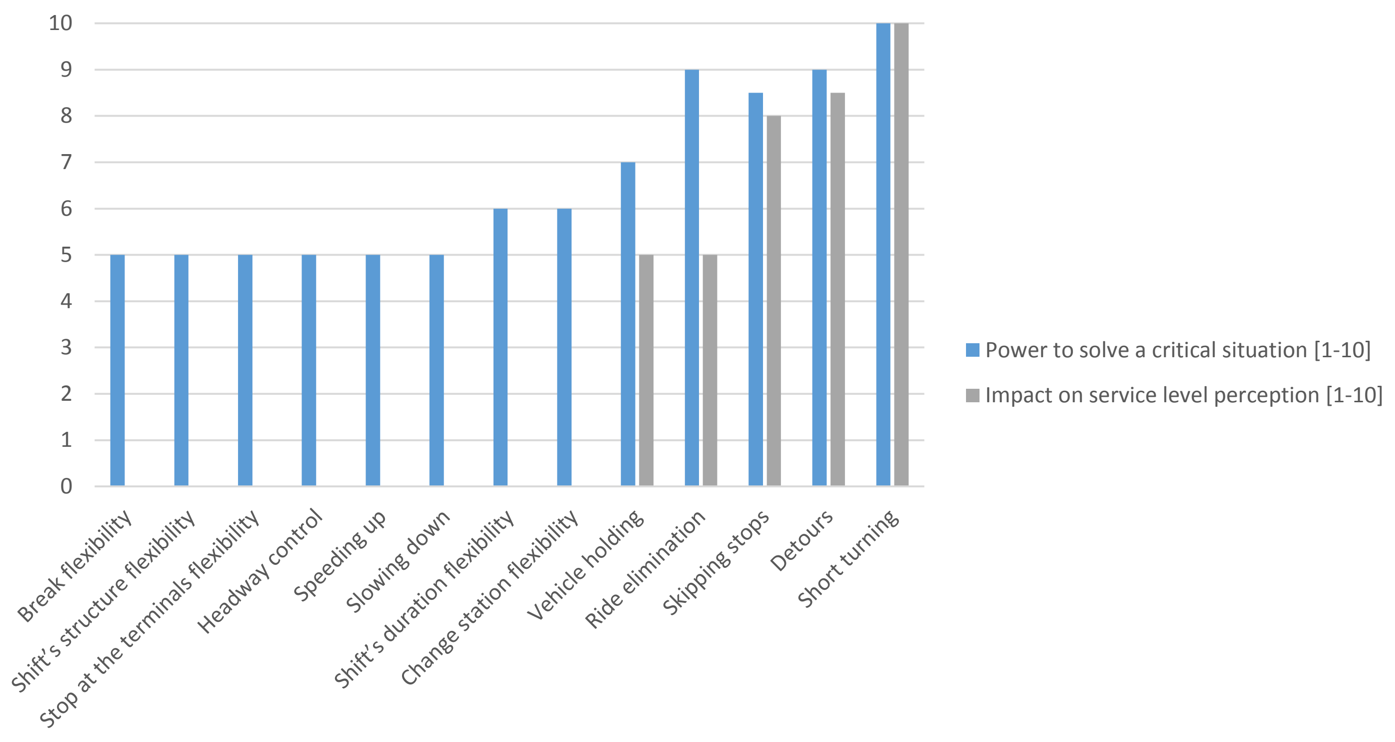



***Figure 81**: Operational instrument evaluation graph.*

As shown in *figure 81* it is possible to separate the operational instruments in ***two different categories:***

***1° - Fisrt Category***

- Ride elimination
- Skypping stops
- Detours
- Short turning
- Vehicle holding

***2° - Second category***

- Break flexibility
- Shift's structure flexibility
- Stop at the terminals flexibility
- Headway control
- Speeding up
- Slowing down
- Shift's duration flexibility
- Change station flexibility

***Categories***:

- ✓ *1° - First category:* This category it is composed by operational instruments that have high power to solve a critical situation but at the same time, once applied, they have a bad impact on the service quality perception of the clients that are obliged, for example, to get off the means because it will skip the stop they are aiming at.

- ✓ *2° - Second category*: The operational instruments that compose this category has a lower capacity to solve a critical situation, but the passengers are not involved during the application of these OIs.

As said previously all the elements that will constitute the columns and the rows of the matrix will be disposed following the criteria deeply explained previously in this section. *Figure 82* shows the final matrix after having processed the results coming from all the interviews.

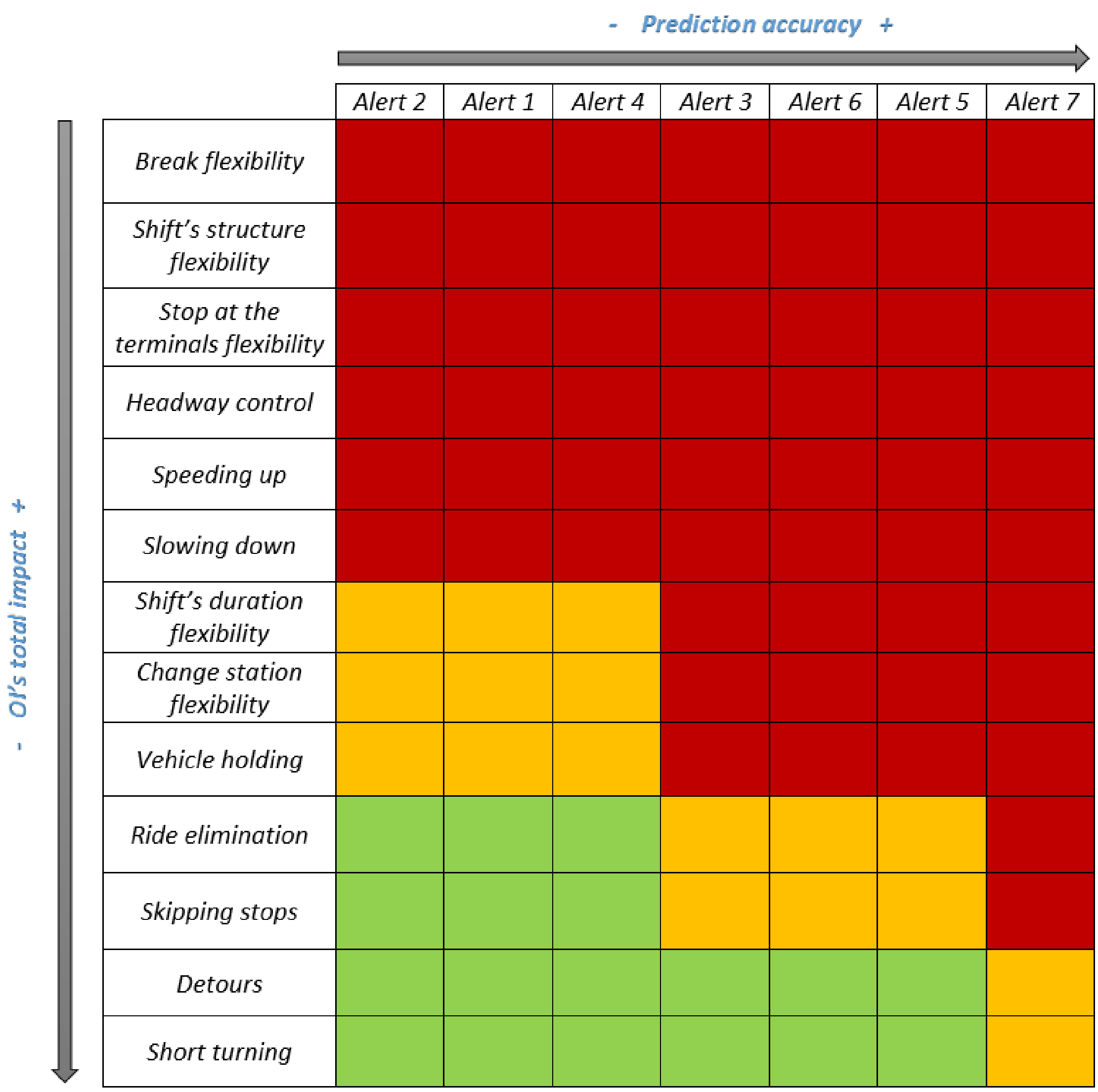



***Figure 82****: Final Alert/OIs matrix with different level of priority usage.*

***Notes***

- ✓ The different colors of the cells represent the intensity of usage with which a certain OI should be used by the algorithm to solve a critical situation detected by the activation of a certain alert.

- ✓ It is important to notice that the relations described by the matrix do not exclude the use of any OI in advance. But it gives priority rules to apply them. Alert that does not have a high power in predicting a future critical situation should not require the implementation of operational instruments that have a high impact on the system.

- ✓ With the introduction of the new DMSS we want to limit the usage of the OIs that have a negative impact on client's service quality perception. But it is not possible to completely avoid their usage because when the situation degenerate seriously and the performances of the line drops it is necessary to apply also this invasive OIs.

The studying just performed is qualitative, but it has been built on the experience of the interviewed professionals. This fact makes the matrix just presented a reliable tools that gives priority rules to link together the alerts, the operational instruments, the objective function and the SR algorithm.

## 5.3 Additional information side

Along this section we will analyze the third macro-side of the DMSS, the *additional information side*. The objective is to identify a system to make more effective and more helpful the suggestions generated by the disruption management support system. In order to achieve this goal it is necessary to give auxiliary information to dispatchers. This additional info will help them having a broader view on how the implementation of a certain operative instrument can affect passengers considering the part of the line and the part of the day in which the OI would be implemented.

In order to develop this studying it is necessary to follow two principal steps:

1. ***Influence diagram creation***: The objective of this first step is to analyze how the implementation of different operative instruments interact with the quality aspects considered valuable to passengers.

2. ***Definition of auxiliary information:*** The final achievement of this second step is the creation of logics, assumptions and reasoning that can be used to define the auxiliary information that are necessary to make the DMSS a helpful system well integrated with the dispatchers.

The main objective of the algorithm, that is the heart of the decision support system created, is to maximize the service reliability (*travel time reliability + comfort*) of the line. While the aim of this third macro-side is linking effectively the suggestions generated by the support system with the dispatcher, who is the actor that in the end has to decide if implementing or not the OI proposed (*see figure 83).*

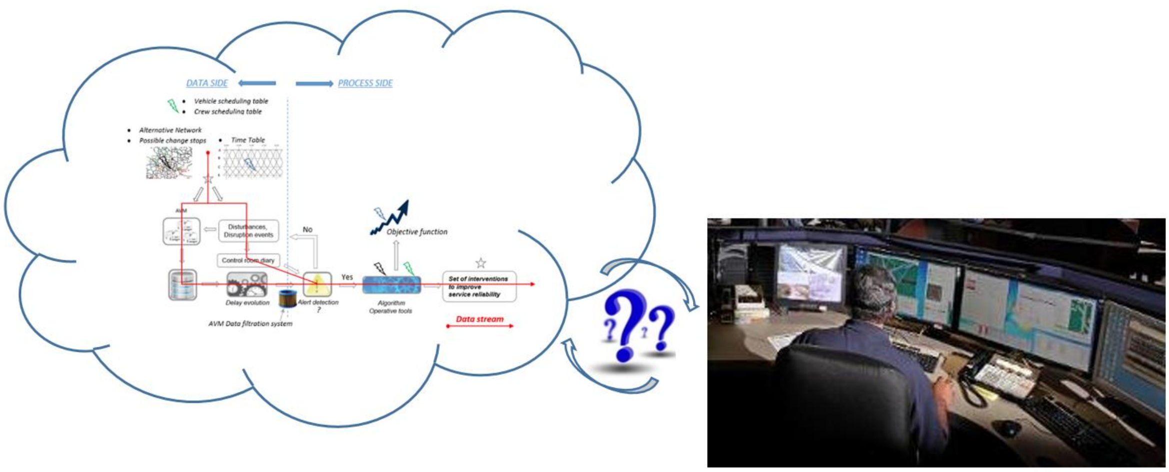



***Figure 83**: Thesis' section objective (how to link DMSS' suggestions with the dispatcher).*

### 5.3.1 Influence diagram creation and analysis

Influence diagrams are instruments used to describe the relationship between several elements that can affect the results of a decision. The diagram can be used as a basis for creating computer-based models that describe a system or as descriptions of mental models managers use to assess the impact of their actions.

***In this case we will use them to identify which are the relations between the different operational instruments and the different quality aspects that are evaluated important by passengers.***

The information and the knowledge gathered during the literary review and during the internship at ATM S.p.A. combined with the expertise of the TU Delft's professors that supported me during the development of this project's part are at the base of the reasoning that allowed me to build the *influence diagrams (ID)*. These diagrams describe the relations between the implementation of a certain group of operative instruments and the consequent repercussions that they have on the different passenger's quality aspects.

Now we describe in detail the elements of the ID that will be presented later on:

***Depicts an external influence*** (*an exogenous variable*) – these are variables whose values are not affected by the decision being made. For example, *the condition of the weather in which the transport system have to operate*.

***Depicts a decision*** (these *are decisions made by the management)*. In our case is the *implementation of a certain operational instrument on the line*.

***Depicts an intermediate variable*** (*an endogenous variable*) – these are variables that have a direct impact on the result node and they vary according to the kind of ***decision variable*** taken. For example, the *travel time variability* that is something in between the ***decision variable*** considered and the ***result node***.

***Depict a results node*** – showing the result of the interaction of the various elements of the model. In some situations the model may provide more than one result, but this is not our case.

***<u>Shows the influence between variables</u>*** – The ***green arrow*** represents a positive relation between two variables (*the increase of one correspond to the increase of the other*), while the ***red arrow*** represents a negative relation between two variables (*the increase of one correspond to the increase of the other*). When the relation has a negative impact on passengers' service quality perception the arrow will be represented in ***bold***.

***<u>Shows information being communicated between elements</u>***. For example, *in order to select a certain OI it is needed to know in advance which the network design of the line is.*

Now we represent a summary table in which we will present a legend with all the symbols described up to now (See *table 84*).

| ***Symbol*** | ***Description*** |
|---|---|
| | *Positive influence between elements ( ↑ ↑ )* |
| | *Negative influence between elements ( ↑ ↓ )* |
| | *Information communicated between elements* |
| | *This symbol depicts an external influence (an exogenous variable)* |
| | *This symbol depicts a decision* |
| | *This symbol depicts an intermediate variable (an endogenous variable). $1^{st}$ level.* |
| | *This symbol depicts an intermediate variable (an endogenous variable). $2^{nd}$ level.* |
| | *This symbol depicts the intermediate variable that the DMSS aims to maximize (an endogenous variable). $3^{rd}$ level.* |
| | *This symbol depicts the result node* |

***Figure 84**: Summary table with the symbols used in the influence diagram and relative short description*

Now it is possible to introduce all the influence diagrams created to describe the relations between the ***Operational instruments*** suggested at disposition of the DMSS, the various ***quality aspects*** considered valuable by passengers and the ***result node*** (***Overall passengers' appreciation of quality aspects influenced by the DMSS).*** (*See figure 85 – 92*).

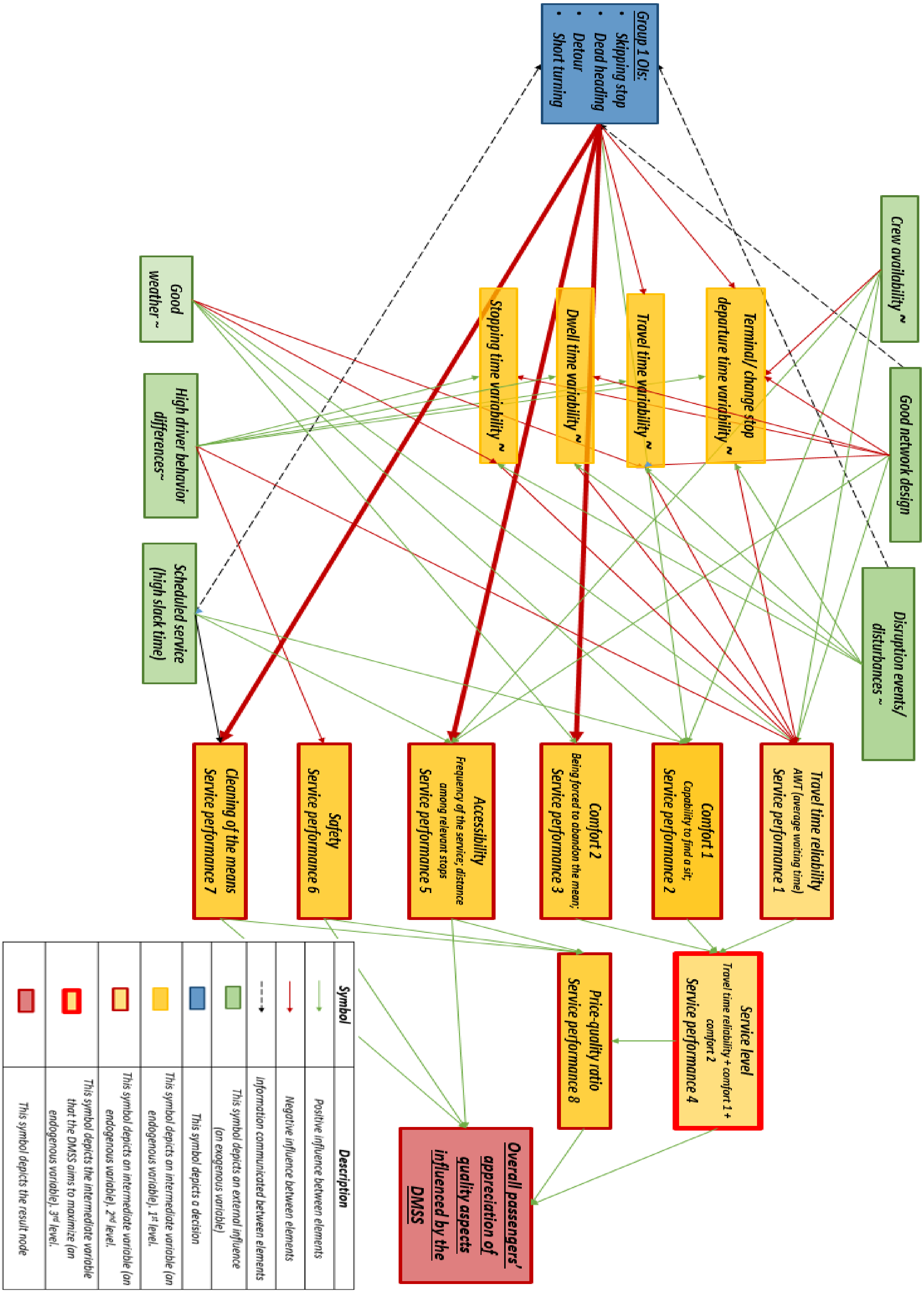



***Figure 85***: *Influence diagram "Group 1 OIs"*

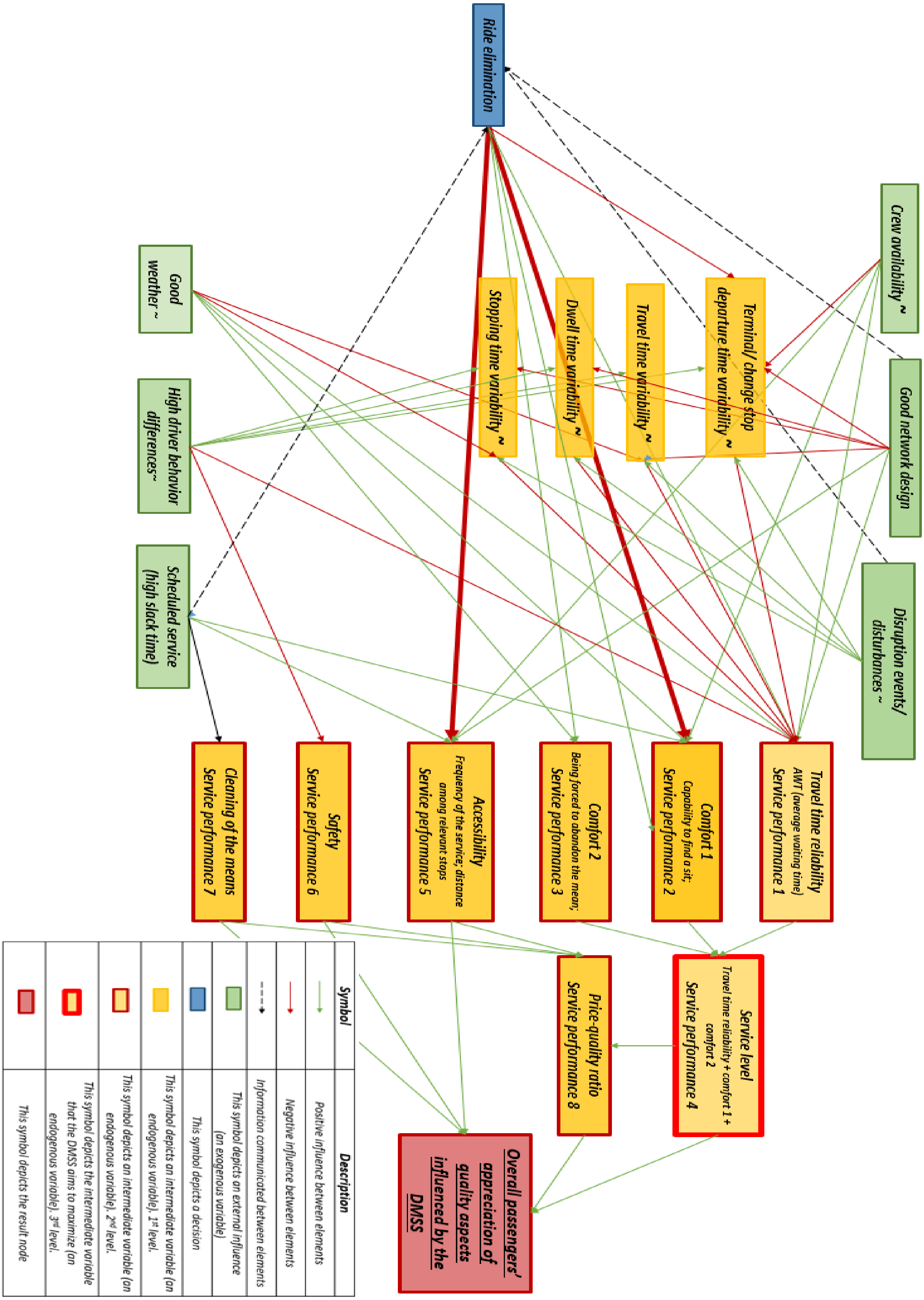



***Figure 86**: Influence diagram “<u>Ride Elimination</u>”.*

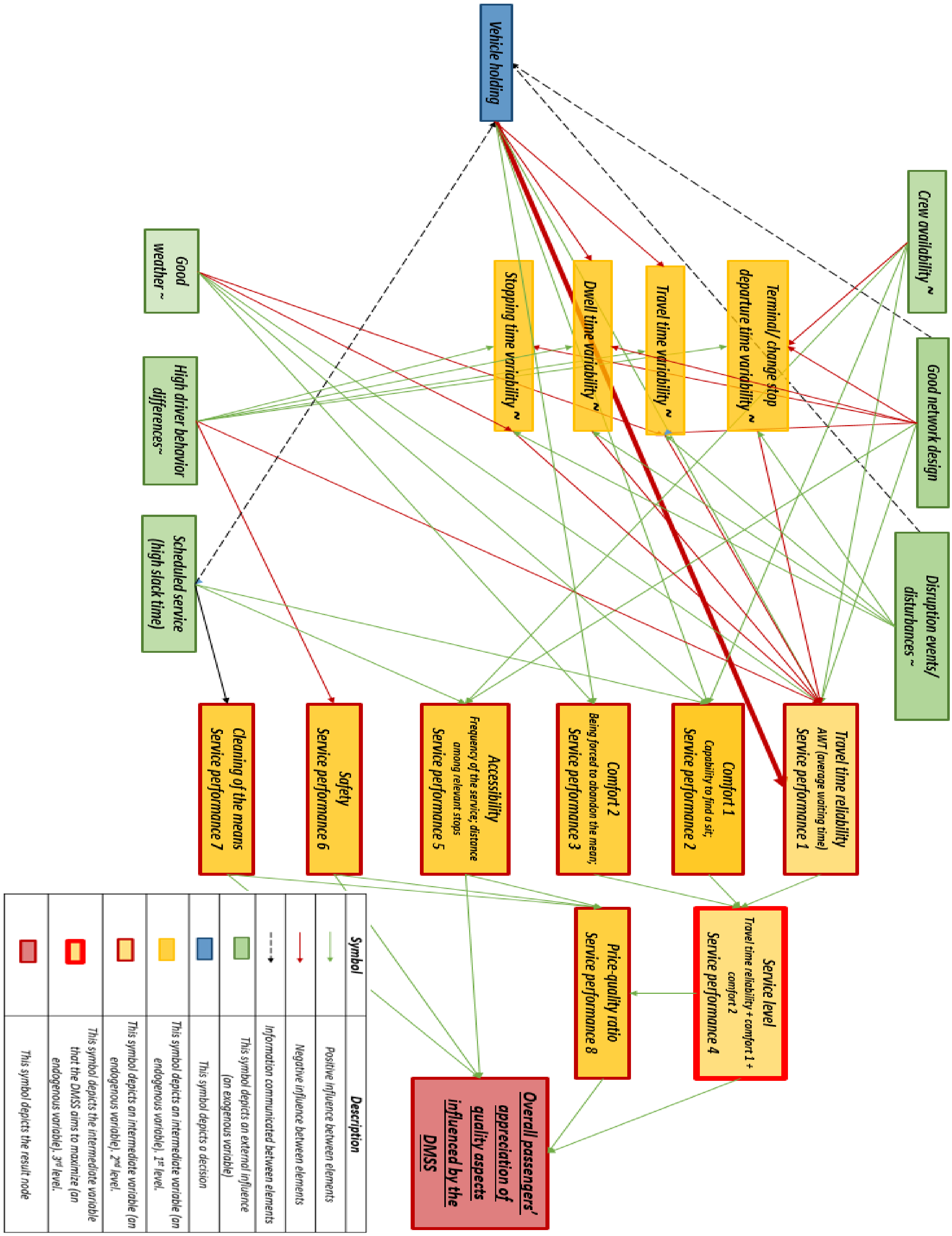



***Figure 87**: Influence diagram “Vehicle Holding”.*

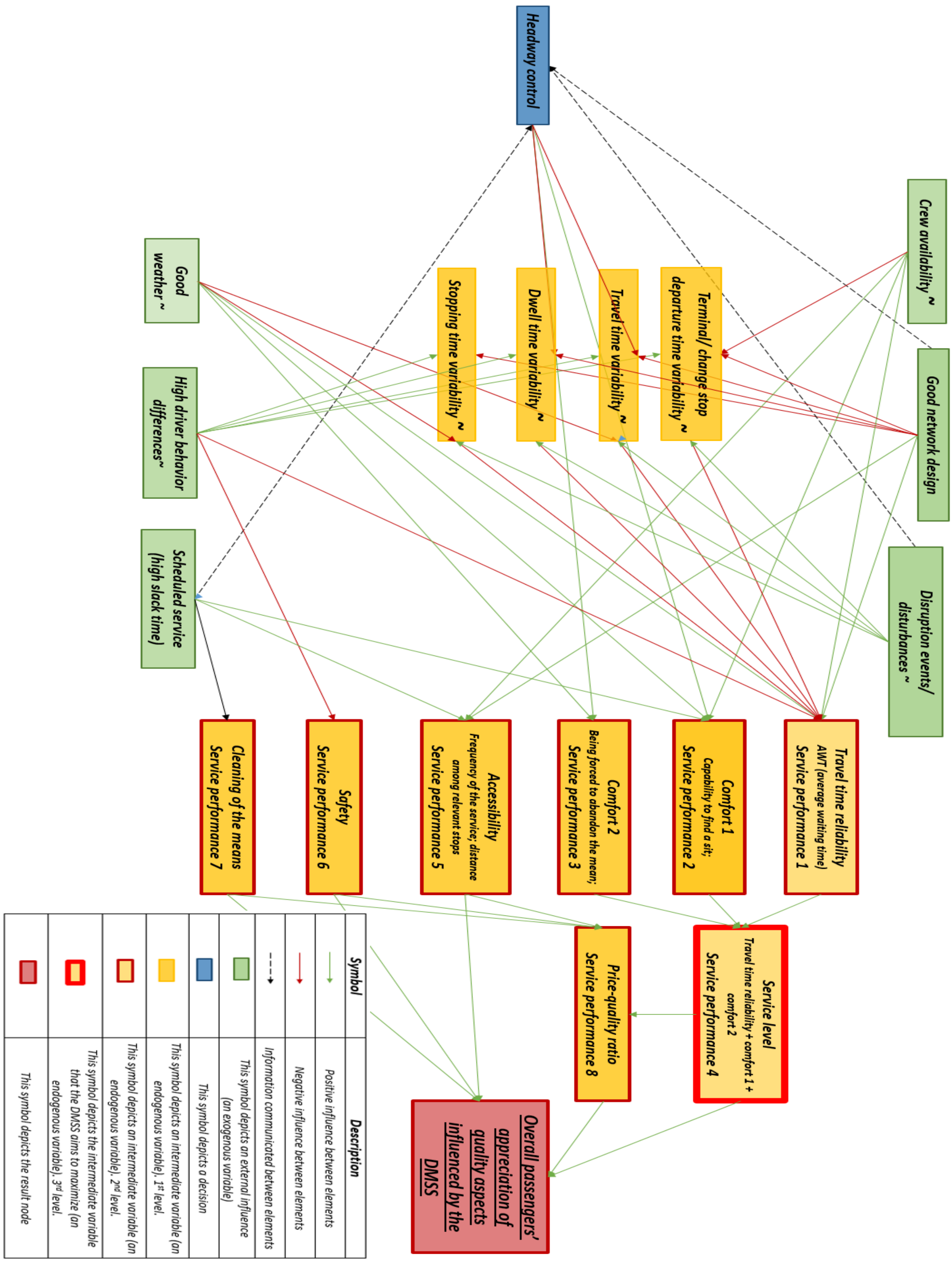



***Figure 88**: Influence diagram "<u>Headway control</u>".*

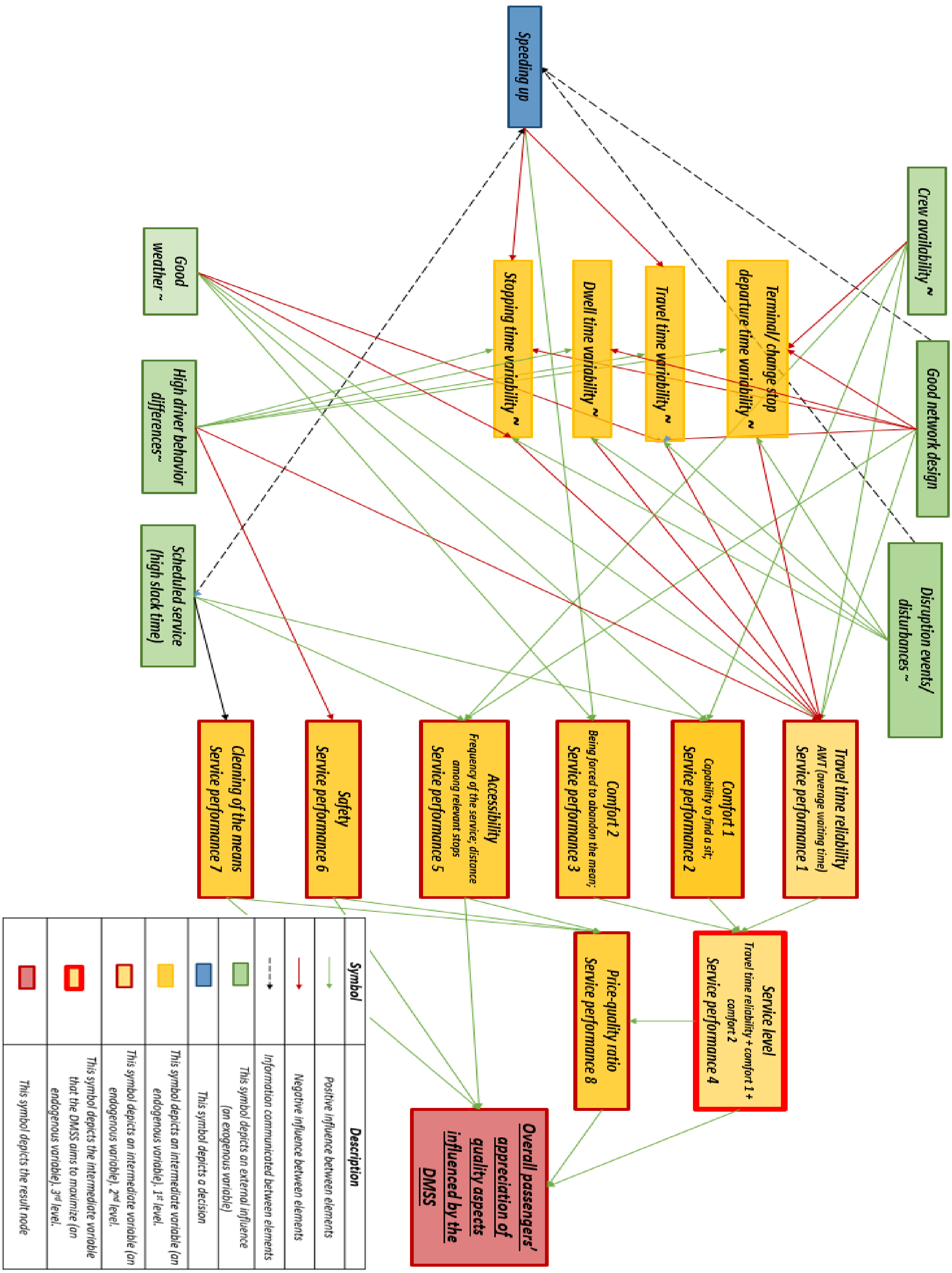



***Figure 89**: Influence diagram "<u>Speeding up".</u>*

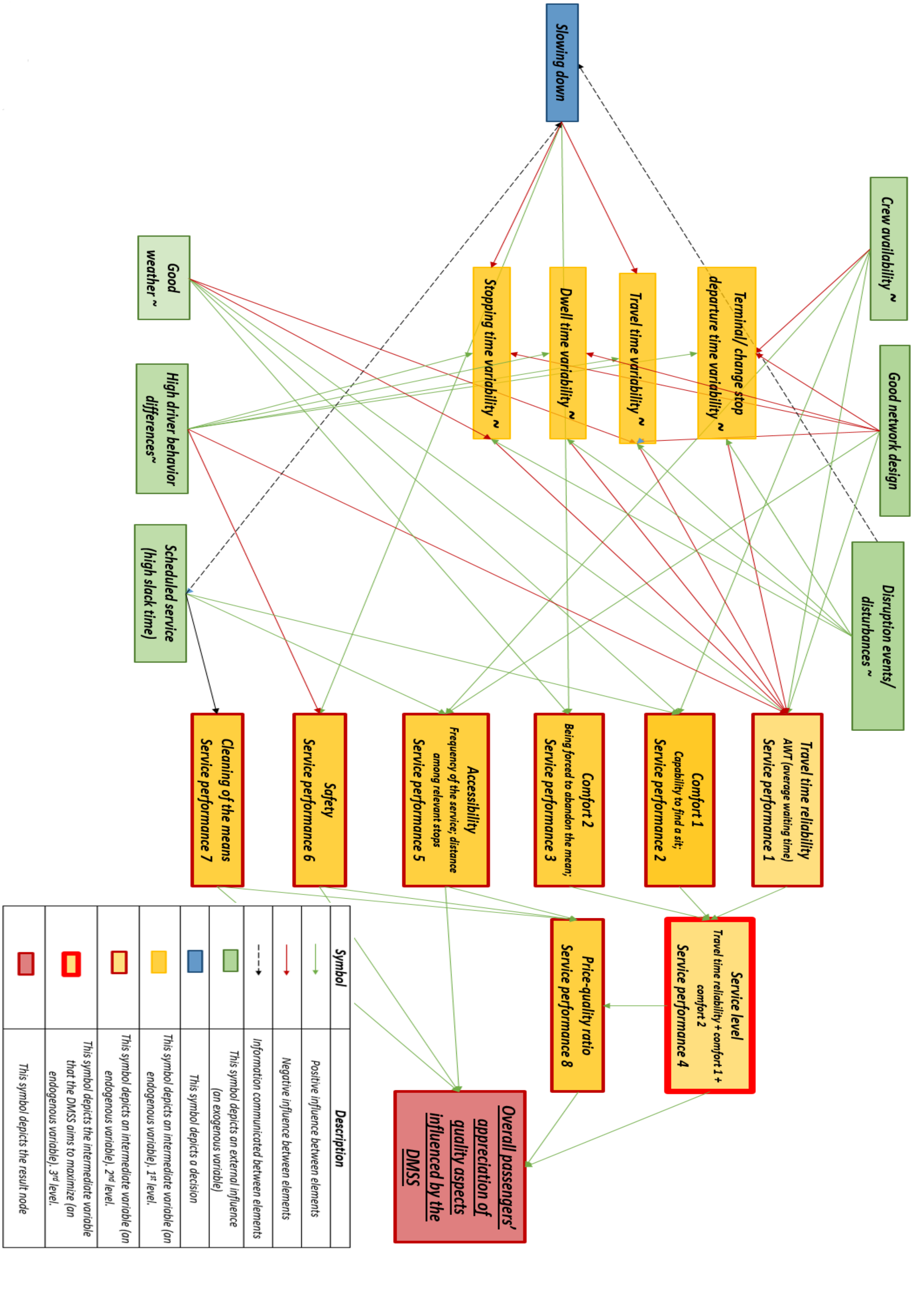



***Figure 90***: *Influence diagram “<u>Slowing down</u>”.*

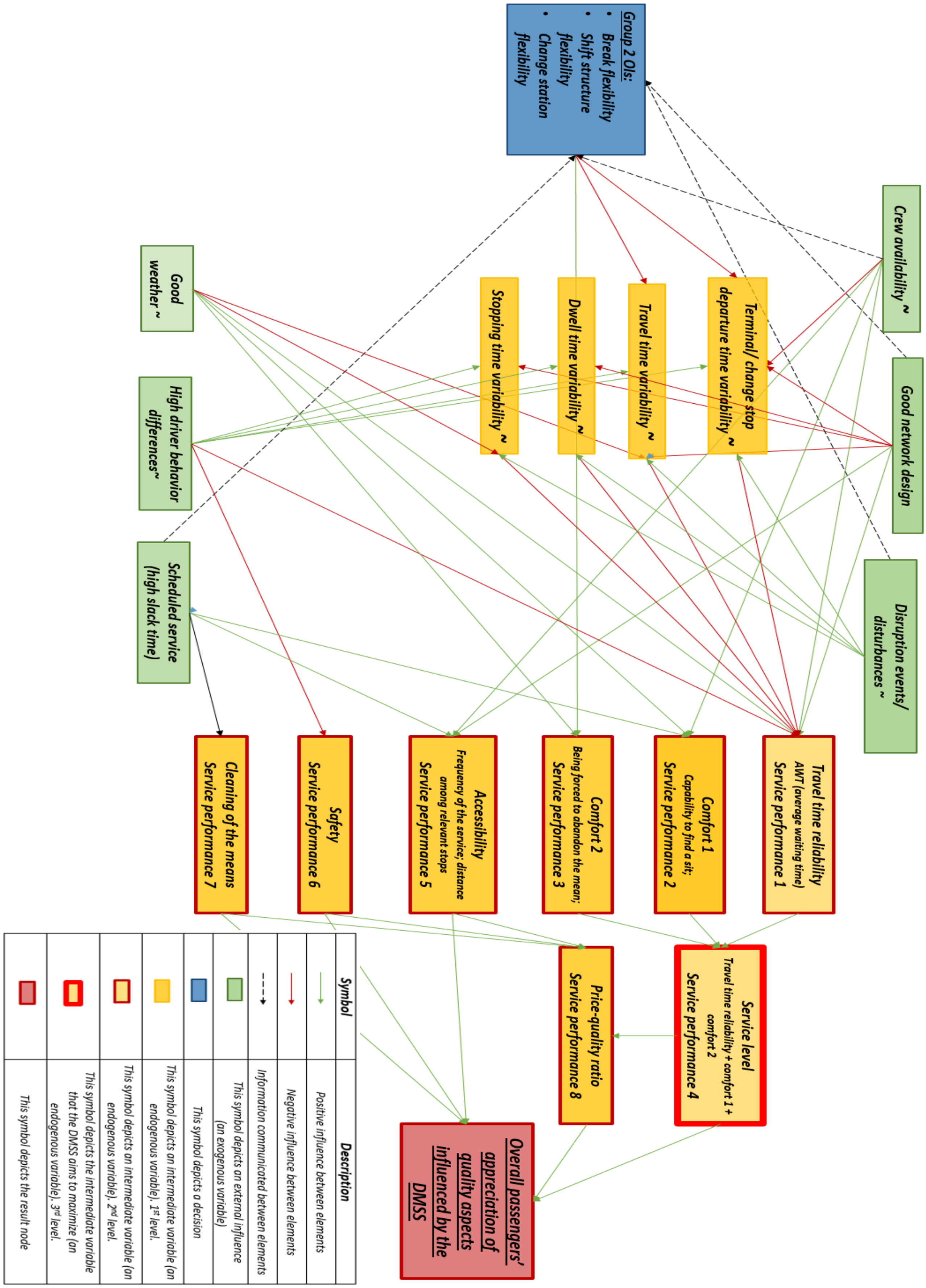



***Figure 91**: Influence diagram "<u>Group 2 OIs</u>".*

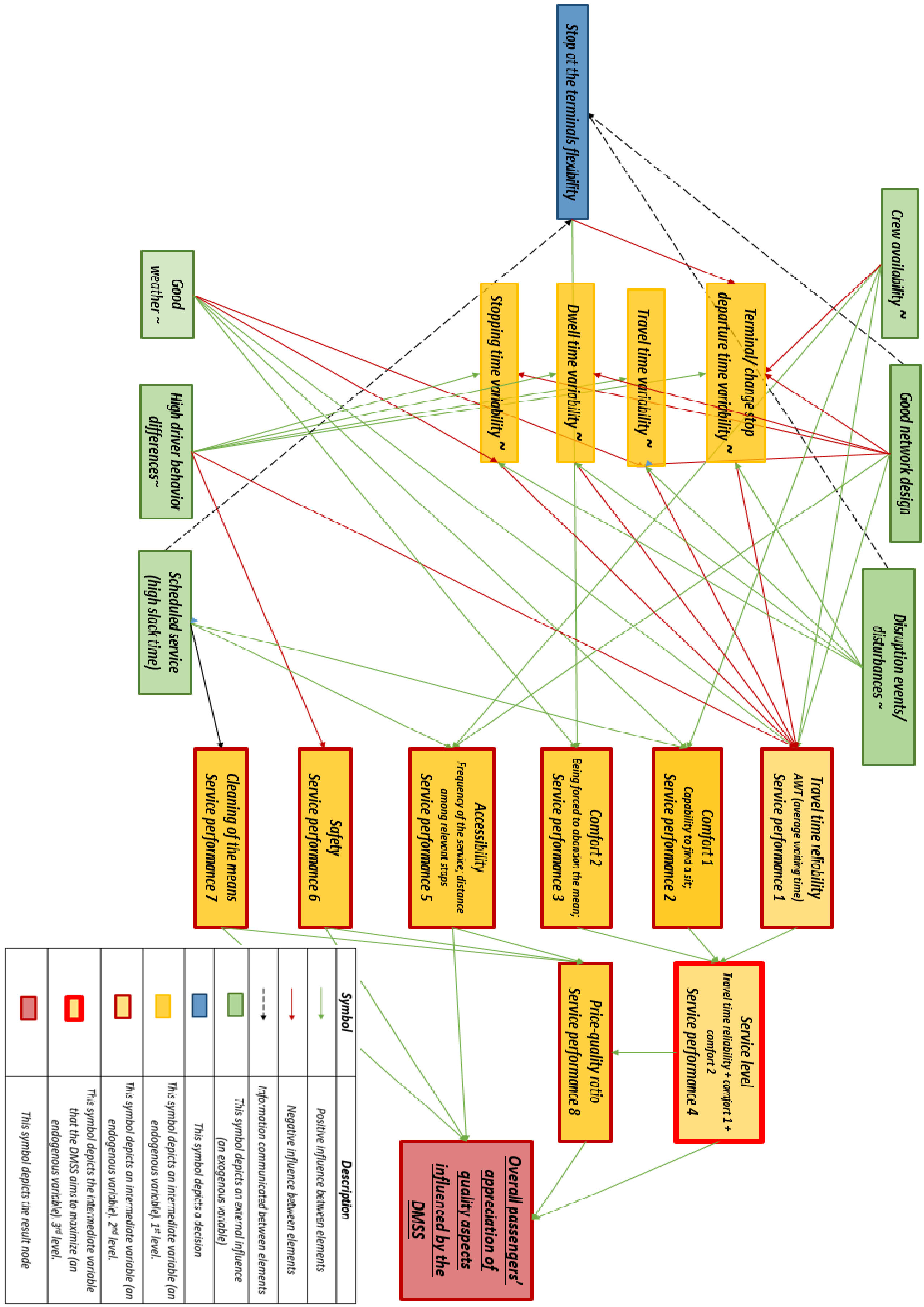



***Figure 92:*** *Influence diagram "<u>Stop at the terminals flexibility</u>".*

After having built an influence diagram for each kind of operational instruments at disposition of the operators it is worth to make some analysis about what found. The first thing that it is possible to identify is that it is possible to divide the operational instrument in ***two main categories:***

***1) Invasive operational instruments;***

***2) Neutral operational instruments.***

The main differences that there are between this two categories is that the first one produces also negative effects on some of customers' quality aspects while the operational instruments that constitute the second one don't have any impact on them. On the other hand, it is possible to say that the instruments of the first category are more powerful respect to the instruments of the second one in solving critical situations and restoring the regularity of the line. (*See also Set of priority rules for applying OIs, 5 – Thesis model*).

## *1) Invasive operational Instruments*

Now it is worth to list which are the positive and the negative aspects that characterize the OIs that constitute this first group.

PROs

- *High capability to restore the regularity of the line;*
- *High capability to restore delay;*
- *High capability to tackle any kind of inefficiency that can be present on the line* (*accident, part of the road blocked*).

CONs

- *Impact on passenger comfort perception that in some cases are obliged to abandon the mean;*
- *Impact on passenger that are waiting at the stop that experience a decrease of service accessibility*

  (e.g. *See the mean passing without stopping → negative perception of the service*).

The operative instruments that have been identified as part of this group are the following:

- ***"Group 1 OIs"*** *(See figure 85):*
  - *Skipping stop;*
  - *Dead heading;*
  - *Detour;*
  - *Short turning.*
- ***"Ride elimination"*** *(See figure 86)*;
- ***"Vehicle holding"*** *(see figure 87)*;

Looking at *figure 85 – 86 – 87* it is possible to note that these operational instruments bring many benefits to customers, but at the same time there are some aspects that have a negative effect on passenger's service quality perception *(**red bold arrows** that directly connect the <u>operational instrument</u> with the <u>intermediate variable 2nd level</u>).* Now we want to explain why this happens, *figure 93; 94 and 95* resume which are the quality aspect that are negatively influenced by the application of the three OIs just listed

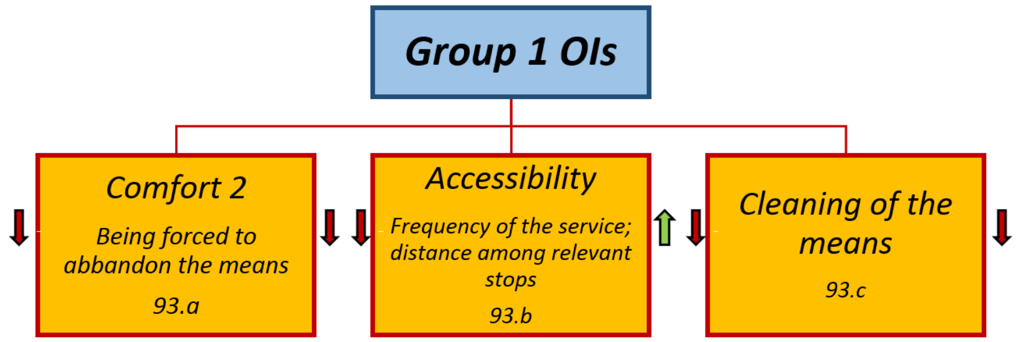



***Figure 93****: Quality aspects that experience a level decrease due to the implementation of <u>Group 1 OIs</u>*.

- **<u>Comfort 2</u>** (*figure 93.a*): The implementation of one of these operative instruments oblige the passenger to get off the vehicle. This happens because the mean does not serve some stops to recover a delay or to round some obstacles and the passengers that aim to go at one of the skipped stops are obliged to alight and wait for the arrival of another mean that brings them at destination. The perception of inefficiency of the service can be worsen according to the weather conditions. In case of bad weather the sensibility of the passengers increases a lot.

- **Accessibility** (*figure 93.b*): Customers experience a decrease in accessibility because they could see the vehicle passing in front of them without stopping. Furthermore the application of these operational instruments can deny passengers to get to their destination station because the vehicle on which are driving skips it. The perception of inefficiency of the service can be worse according to the weather conditions. In case of bad weather the sensibility of the passengers increases a lot. It is necessary to say that the application of this kind of operational instruments have also a positive impact on accessibility level perception because they are really effective in bring back the regularity of the line.

- ***Cleaning of the means*** *(93.c):* customers can experience a decrease in the level of means' cleaning if one of the skipped stop is one of the station in which the vehicle has to be cleaned. This denies the possibility to the cleaning team to intervene on the vehicle.

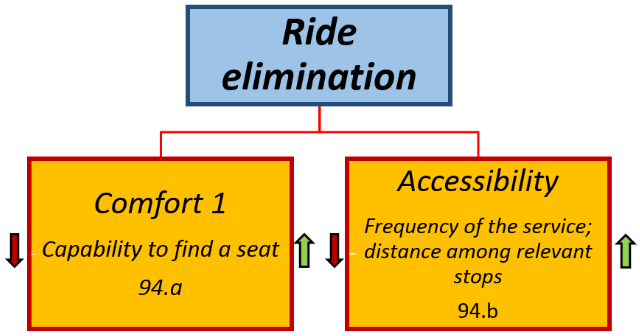



***Figure 94***: *Quality aspects that experience a level decrease due to the implementation of Ride elimination.*

- ***Comfort 1*** *(figure 94.a):* The fact to eliminate one ride generates an extraordinary load of people on the vehicle that departs after, because the number of passengers that are waiting at the various stops increases. This generates a decrease in the level of comfort perceived by customer that are obliged to travel standing on a crowded vehicle and in the worst case they are not even able to get on the mean because there is no space left. On the other hand the implementation of this operational instrument bring also benefits from the comfort point of view, because it is used to maximize the regularity of the line, this means generation of constant headways that is translated an increase in the possibility to find a seat for a higher number of passengers.

- ***Accessibility*** *(94.b):* Passengers experience a decrease in the level of accessibility because eliminating a ride means decreasing the optimal frequency of the service. For this reason, customers experience the happening as an inefficiency of the service because they have to wait at the stop in average for a longer time. It is necessary to say that the application of this kind of operational instruments have also a positive impact on accessibility level perception because they are really effective in bring back the regularity of the line, that means having constant headway, that means offer to the customer the optimal frequency possible.

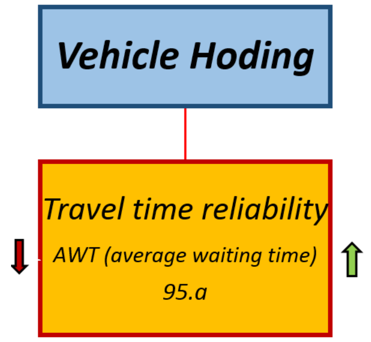



***Figure 95****: Quality aspects that experience a level decrease due to the implementation of* <u>*Vehicle holding*</u>*.*

- <u>***Travel time reliability***</u> *(95.a):* As we have seen for other operative instruments also vehicle holding has a double effect on customer's quality perception. On one hand we have an improvement in service time reliability because this instrument is applied to increase the level of service reliability that means an increase in regularity of the headways that in the end can be translated in the decrease of average waiting time for a great number of the passengers. On the other hand, we have to consider that the passengers on the held means experience a sense of inefficiency because they see the vehicle completely still without any external cause that keeps it in that condition.

Since the operational instruments of this category generate also negative effects on passengers' quality aspect perception it is necessary to provide the dispatchers with further information in order to help them in ***taking the decisions that improve the overall passengers experience and not only the regularity of the line***. We will go further in details on this aspect in the following chapter (*Definition of auxiliary information*).

### *2) Neutral operational instruments*

These are operational instruments that do not generate any negative impact on passengers' quality aspects perception, but at the same time they are not effective in tackling complex situation.

PROs

- *No negative impact on passenger's quality aspect perception;*
- *Capable of maintaining a good level of service reliability in presence of service disturbances.*

CONs

- *Incapable to tackle a situation that is generated by a big disruption that for example blocks part of the line for long time.*

The operational instruments that have been identified as a part of this group are the following:

- ***Headway control*** (*See figure 88*);
- ***Speeding-up*** (*See figure 89*);
- ***Slowing-down*** (*See figure 90*);
- ***Group 2 OIs*** (*See figure 91*);
  - *Break flexibility*
  - *Shift structure flexibility*
  - *Change station flexibility*
- ***Stop at the terminals flexibility*** (*See figure 92*).

In order to recap all the concepts introduced up to now we introduce a summary table (*table 49*):

1. On the ***vertical axe*** will be listed the operational instruments at disposition of the control room operator following an ascendant order dictated by the power of the OI to solve a critical situation on the line. (*See 5.2.2, table 48*).

2. On the ***horizontal axe*** will be listed the passengers' service quality aspects following an ascendant order dictated by the importance that passenger assign to them. (*See 2.1.1 figure 6*).

− ***Quality aspect importance*** +

− ***Ability to solve a critical situation*** +

| | Safety | Cleaning of the means | Accessibility | Comfort 2, *Being forced to abandon the mean* | Comfort 1, *Capability to find a sit* | Travel time reliability, *Average waiting time* |
|---|---|---|---|---|---|---|
| Group 2 OIs | | | | ↑ | | ↑ |
| Stop at the terminals flexibility | | | | | | ↑ |
| Headway control | | | | ↑ | ↑ | ↑ |
| Speeding up | | | | ↑ | | ↑ |
| Slowing down | ↑ | | | ↑ | | ↑ |
| Vehicle holding | | | | | | ↑ ↓ |
| Ride elimination | | | ↓ ↑ | | ↓ ↑ | ↑ |
| Group 1 OIs | | ↓ | ↓ | ↓ | ↑ | ↑ |

***Table 49****: Summary table relations between operative instruments applied and quality aspects.*

### 5.3.2. Definition of auxiliary information

The main objective of the first two macro-sides is to generate suggestions to provide to the control room operators in order to maximize the service reliability of the lines (*travel time reliability + travel comfort).*

While the objective here is to identify which is the additional information to provide to dispatchers in order to make the suggestions generated by the DMSS more complete and effective in maximizing passengers' experience. We have to remember that the last achievement is to enable dispatchers to take better decisions in order to increase the overall service quality given to passengers and consequently increase customers acquisition and retention. *Figure 96* shows schematically the components that constitute this part of the DMSS and how it interacts with the rest.

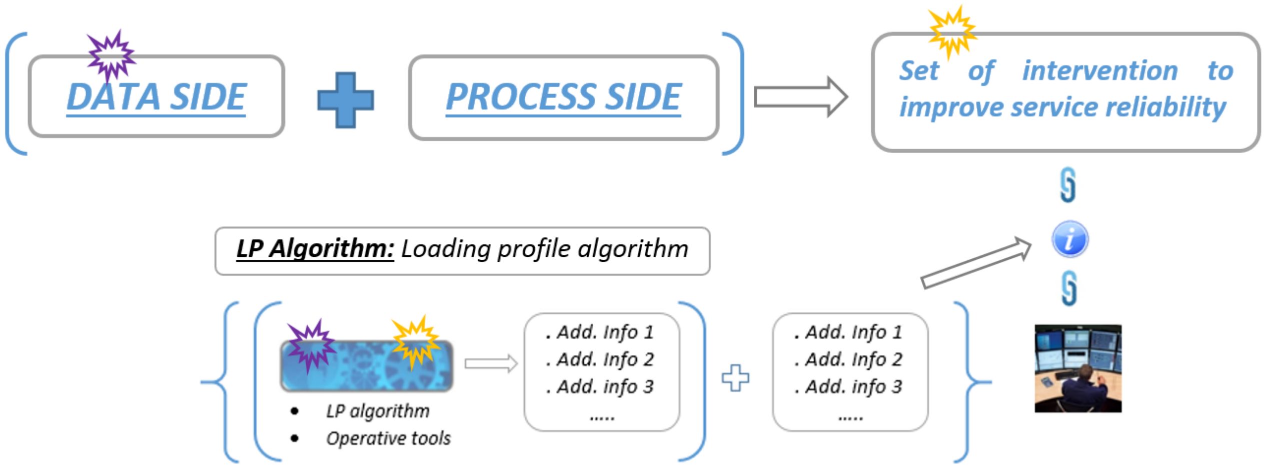



***Figure 96***: *Schematically representation of the components that compose the Additional information side and their interaction with the whole system.*

The idea is to make the out-put generated by the DMSS more effective by giving further information when are suggested *invasive operational instruments* in order to enable the control room operators to have a wider view about the effects generated by the implementation of this kind of OIs. During the Model definition, we have introduced a taxonomy that prioritizes the use of different operative instruments according to the inefficiency level that is identified by the activation of a specific alert/group of alert. The goal of introducing this kind of prioritization is to limit the implementation of invasive operational instrument, but unfortunately it is not always possible avoid their usage.

To reach this objective we have identified different additional information to provide to the dispatcher:

5. *Loading profile and number of passenger alighting and boarding*;
6. *Weather condition*;
7. *Cleaning of the vehicle*;
8. *Impact on accessibility*.

Now we will introduce a set of logics, assumptions, models and indicators to generate all the information that will help the dispatchers in taking the decisions that will generate the lower impact on customers' service quality perception.

## *1. Loading profile and number of passenger alighting boarding*.

In order to obtain this kind of information it is necessary to have as input the historical data that describes in average the loading profile of the vehicle along the line and the number of passengers alighting and boarding at each stop. The ***Automatic passenger counting systems (APC)*** generates the data we need.

This kind of systems, collecting data for long periods, are used to generate ridership information on a stop by stop basis providing as final output the information presented in *table 50.* To be clearer we introduce a fictitious line (*figure 97*) that will support in the understanding the columns headings' meaning.

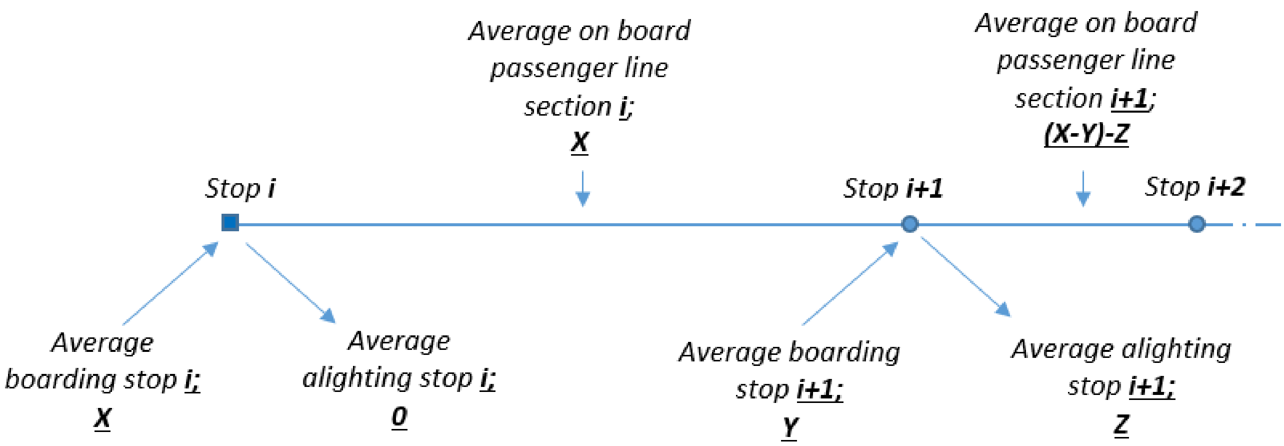



***Figure 97***: *Explanatory fictitious line.*

| *Time slot **u*** | *Average boarding stop **i*** | *Average alighting stop **i*** | *Average on board passenger line section **i*** | *Average boarding stop **i+1*** | *Average alighting stop **i+1*** | *Average on board passenger line section **i+1*** | … |
|---|---|---|---|---|---|---|---|
| 1 | ***X*** | ***0*** | ***X*** | ***Y*** | ***Z*** | ***(X+Y)-Z*** | … |
| 2 | … | … | … | … | … | … | … |
| … | … | … | … | … | … | … | … |

***Notes:***

- ✓ ***Average boarding stop i***: The average number of people getting on the vehicle in a certain period of the day (*Usually the day is divided in time slots of an hour*), at a certain stop ***i***;
- ✓ ***Average alighting stop i**:* The average number of people getting off the vehicle in a certain period of the day (*Usually the day is divided in time slots of an hour*), at a certain stop **i**;
- ✓ All this data are available for all the stops that compose the line along all the service period;
- ✓ In this table we are assuming to deal with a regular system (regular headways); this is reasonable due to the abundance of data analyzed (*normalization process).*

***Table 50****: It represents the data at disposition of public transport operators related to boarding and alighting at the different stops along the line in the different part of the day.*

At this point our objective is to create the mathematical formulas that will allow us to provide to dispatchers some of the additional information needed to optimize the integration between them and the disruption management support system. The model that it will be presented below it is the fruit of the collaboration and the support of Oded Cats (*assistant professor at TU Delft University, Civil engineering faculty*).

For our purposes, it is not possible to assume to deal with a regular line (constant headways) since this assumption is excessively far from what happens in the real life and because the final objective of the support system created is to help dispatchers dealing with lines inefficiencies generated by irregularities.

Before to present the mathematical formulas it is worth explain the ***assumptions on which we will build all the following reasoning***:

1. We are considering *high frequency service*, in this case it is possible to describe the arrival of passenger at the stop with a random distribution;
2. We will consider *irregular lines (irregular headways);*

3. We assume to have *AVL data real time for all vehicles* (*headways between vehicles in real time)*;

4. We will use historical data for what concern *Average boarding stop* ***i,*** *Average alighting stop* ***i,*** *On board passenger line section* ***i.***

To explain better the meaning of the various variables of the mathematical formulas that we are going to introduce we will use the help of a fictitious line (*see figure 98*).

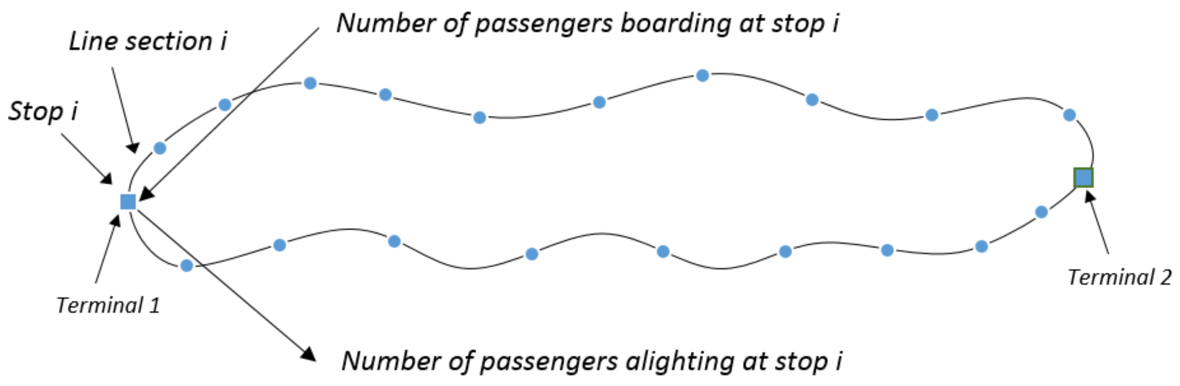



***Figure 98****: Fictitious line example.*

$$l_{i,k,j} = l_{i-1,K,j} - a_{i,k,j}\left(l_{i-1,k,j}\right) + b_{i,k,j}\left(h_{i,k,j}\right) \qquad \textit{Equation 6}$$

$$a_{i,k,j} = l_{i-1,K,j} * \gamma_{i,u} \qquad \textit{Equation 7}$$

$$\gamma_{i,u} = \frac{\overline{a_{i,u}}}{\overline{l_{i-1;u}}} \qquad \textit{Equation 8}$$

$$b_{i,k,j} = \overline{b_{i,k}} * \frac{h_{i,k,j}}{\overline{h_i}} \qquad \textit{Equation 9}$$

***Legend:***

$\boldsymbol{l_{i,k,j}}$ **:** This term represents the <u>*number of passengers travelling on the mean*</u> per line section **i**, time **k,** vehicle **j**. This value is different for every vehicle that is serving the line because in its computation are considered also the effects generated by irregular headways. Computing this term is an iterative process that starts at terminal 1 and keeps on being updated at every stop/line section along all the line.

$\boldsymbol{a_{i,k,j}}$ : This term represents the *number of passengers alighting* at stop **i**, time **k**, vehicle ***j***. This value is different for every vehicle that is serving the line because in its computation are considered also the effects generated by irregular headways. Computing this term is an iterative process that starts at terminal 1 and keeps on being updated at every stop/line section along all the line.

$\boldsymbol{\gamma_{i,u}}$ **:** This term represents the *average ratio of passengers that alight* at a certain stop **i**, time slot **u**. This value it is equal for all the vehicles serving the line.

$\overline{\boldsymbol{a_{i,u}}}$ **:** The average number of passenger alighting at stop **i**, time slot **u**;

$\overline{\boldsymbol{l_{i-1,k}}}$: The average number of passenger on board at stop **i**, time slot **u**;

$\boldsymbol{b_{i,k,j}}$ **:** This term represent *the number of passengers boarding* at stop **i**, time slot **k**, vehicle ***j***. This value is different for every vehicle that is serving the line because in its computation are considered also the effects generated by irregular headways. Computing this term is an iterative process that starts at terminal 1 and keeps on being updated at every stop/line section along all the line.

$\overline{\boldsymbol{b_{i,k}}}$ **:** *The average number of passenger alighting* at stop **i**, time slot **u**;

$\overline{\boldsymbol{h_{i,k}}}$ **:** *The scheduled headway* between means at stop **i,** time slot **u** *(in case there are not missing trips)*;

$\boldsymbol{h_{i,k,j}}$ **:** *The actual headway* at stop **i**, time **k** between the vehicle **j** and the one ahead of it

Thanks to these mathematical formulas and the historical values generated by the APC system, we have at disposition all the ingredients to generate the following information:

1. *A reliable figure that shows the number of people traveling on a specific line* ***i**, time* ***k**,* *vehicle* **j**;
2. *A reliable number of passenger alighting the vehicle at stop* ***i**, time* ***k**, vehicle* ***j;***
3. *A reliable number of people boarding the vehicle at stop* ***i**, time* ***k**, vehicle* ***j.***

## 2. Weather condition

Another information that it is considered important to provide to dispatchers in order to enable them to take the decision that maximize the passengers satisfaction is the condition of the weather. If we consider the application of an invasive operational instrument with the aim to bring back the regularity of the line we have to take into account that the impact that it generates on passengers can be way worse in case of adverse weather conditions. In fact, if we think about the application of a short turning during a nice day it will create less discomforts to the passenger that are obliged to alight than if the same operational instrument it is applied during a storm. So after this analysis the information that will be given to the dispatcher will be also:

1. *The outside temperature [°C]*
2. *The condition of the weather (Rain, drizzle, sun, cloudy …)*

## 3. Cleaning of the means

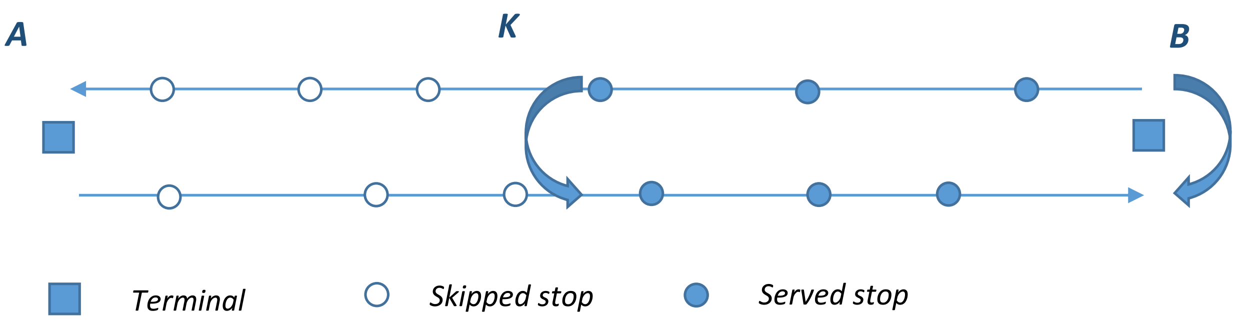
Another information that it is important to give to control room operators is related to the cleaning level of the mean. The idea in this case is to inform the dispatcher if the mean on which will be applied the invasive operational instrument have already skipped the cleaning operation previously and for how many times in a row. In the end, the information provided to the control room operators will be the following:

1. ***Vehicle i:*** *skipped **n** cleaning operation*
    - This means the vehicle was supposed to stop to be cleaned but at the end it didn't do it;
    - Also if in the past the mean skipped the cleaning operation activities its count is brought to 0 once it does it;
    - This information will be shown only if one of the skipping stops suggested by the DMSS is one in which the vehicle it is supposed to be cleaned.

## *4. Impact on accessibility*

In the end we have to consider also accessibility. It is a combination of the ***frequency of the service*** and the ***distance between relevant stops***. Consequently the implementation of certain kind of invasive operational instruments can have a bad influence on this two aspects. Now we will introduce an example to better explain and show practically what just stated.

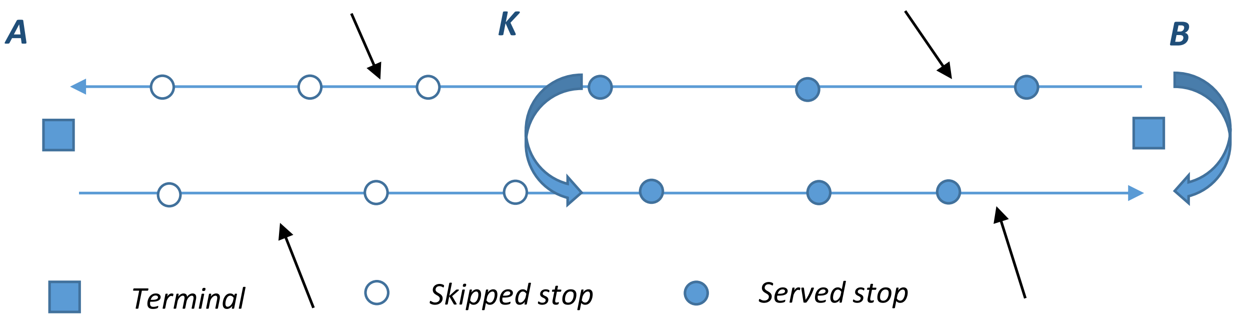
### *2. Example*




*During a **certain hour X** there are **10 means** serving the line and they are scheduled to do **2 passages** per stop. If a vehicle it is short turned, as showed in the example above, for that hour I will have an increasing of the frequency in the left part of the line respect to the right part.*

***Frequency***: 60 [min]/ (9 [means]* 2 [passages per stop * means]) = ***<u>3.33 [min/passage]</u>***

***Frequency***: 60 [min]/ (10 [means]* 2 [passages per stop * means]) = ***<u>3 [min/passage]</u>***




***Frequency***: 60 [min]/ (9 [means]* 2 [passages per stop * means]) = ***<u>3.33 [min/passage]</u>***

***Frequency***: 60 [min]/ (10 [means]* 2 [passages per stop * means]) = ***<u>3 [min/passage]</u>***

The information needed to the dispatcher to assess quickly the impact on this quality aspect after the implementation of invasive operational *instrument is* the same presented in point *1 "Loading profile and number of passenger alighting boarding."* But in this case it is considered the number of passengers that will be oblige to travel on an overcrowded vehicle and that experience an increase in the frequency of the service.

In order to conclude this section we introduce *table 51* that summarizes all the additional information as far described.

| ***Category*** | ***Information*** |
|---|---|
| ***1-4*** | ***Number of passengers on board*** line section **i**, time **k**, vehicle **j** |
| | ***Number of passengers alighting*** at stop **i**, time **k**, vehicle ***j*** |
| | ***Number of passengers boarding*** at stop **i**, time **k**, vehicle ***j*** |
| **2** | ***Outside temperature*** |
| | ***Condition of the weather*** |
| ***3*** | ***Cleaning of the vehicle*** |

***Table 51****: List of the additional information identified to make the DMSS more integrated with the control room operator.*

### 5.3.3. Combination of auxiliary information and operative instrument

After having identified how to generate all the different information that is considered important to support the dispatchers in taking their decisions it is important to identify which are the information that has to be provided when the single kind of operational instrument is suggested by the DMSS.

As said previously the auxiliary information will be given only in relation to the invasive operative instruments that are the ones that generate also negative impact on passengers' quality aspect. In the previous chapter we have identified three of them:

- ***"Group 1 OIs"*** *(Figure 85)*
    - *Skipping stop;*
    - *Short turning;*

- *Dead heading;*
- *Detour;*

- ***"Ride elimination"** (see figure 86);*

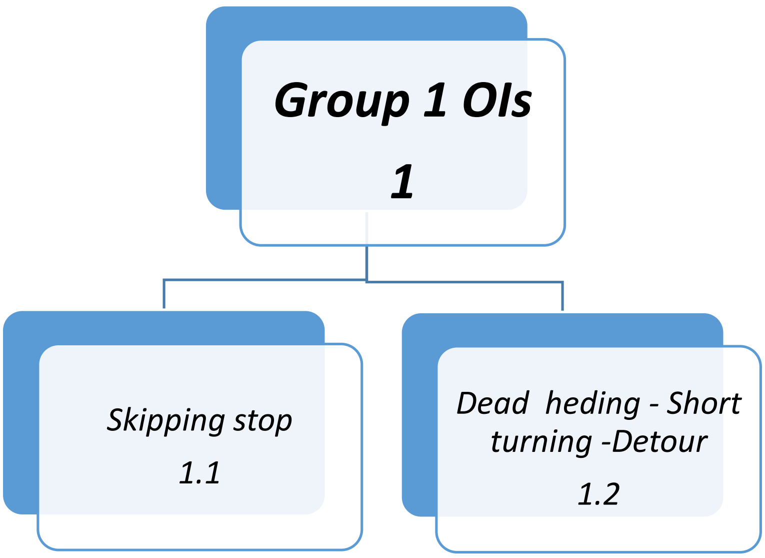
- ***"Vehicle holding"** (see figure 87);*

## Group 1 OIs

This is the first invasive operational instrument that we are going to analyze, as we studied in the first section this operative instrument generate a negative impact on the three quality aspects:

1. ***Comfort 2 :** Being forced to abandon the mean;*
2. ***Accessibility**: Frequency of the service; distance among relevant stops;*
3. ***Cleaning of the means** (Only if the skipped stop is one of the stops in which the vehicle have to be cleaned).*

Now it is necessary to divide this group of operational instruments in two subgroups because even if the OIs that compose it generates a negative impact on the same quality aspects the additional info to provide to dispatcher is different.




The next step is to analyze the two subgroups just identified and describe which are the additional information needed in each specific case to support the control room operator in the best way possible.

## *1.1 Skipping stop*

When the DMSS will suggest this kind of operational instrument the dispatcher will be provided with additional information that will help him in understanding the negative impact generated on passengers' quality aspect after its implementation. We will use the help of *table 52* to present in a clear way all the additional info needed. To recall the dynamic of a skipping stop it is introduced also *figure 99*.

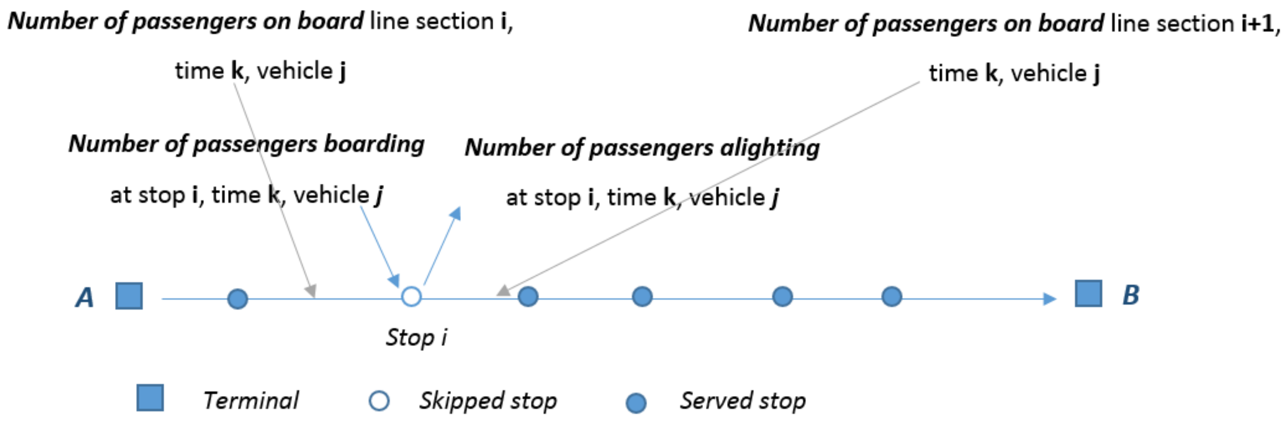



***Figure 99***: *Fictitious line with the explanation of skipping stop dynamics.*

| *Vehicle interested* | *Skipped stop* | *Quality aspects* | *Additional info 1* | *Additional info 2* |
|---|---|---|---|---|
| ***Vehicle J*** | ***Stop i*** | **Accessibility** ⬇ | 1) ***Number of passengers boarding*** *at stop* ***i****, time* ***k****, vehicle* ***j;*** | *1) Outside temperature [C°] ; 2) Weather condition* |
| | | **Comfort 2,** *Being forced to abandon the vehicle* ⬇ | ***2) Number of passengers alighting*** *at stop* ***i****, time* ***k****, vehicle* ***j*** | |
| | | **Cleaning of the means** ⬇ | *Skipped* ***n*** *cleaning operation* | |

***Table 52****: Table with the additional information needed to dispatcher to understand the impact that the implementation of a* ***skipping stop*** *generates on passengers' quality aspects.*

## *1.2 Dead heading – Short turning –Detour*

Since these three operational instruments are similar it is possible to describe at the same time the additional information needed to better support control room operators. As skipping stop (they all come from the same group of operative instruments *"Group 1 OIs")* these operative instruments generate a negative impact on the three quality aspects:

1. ***Comfort 2 :*** *Being forced to abandon the means;*
2. ***Accessibility***: *Frequency of the service; distance among relevant stops;*
3. ***Cleaning of the means*** *(Only if the skipped stop is one of the stops in which the vehicle have to be cleaned).*

In order to make *table 53* clearer we will introduce *figure 100 – 101 – 102*. Contrary to what said for the skipping stop in this case when one of these operational instruments is applied all the passengers have to leave the vehicle at stop i (i=1).

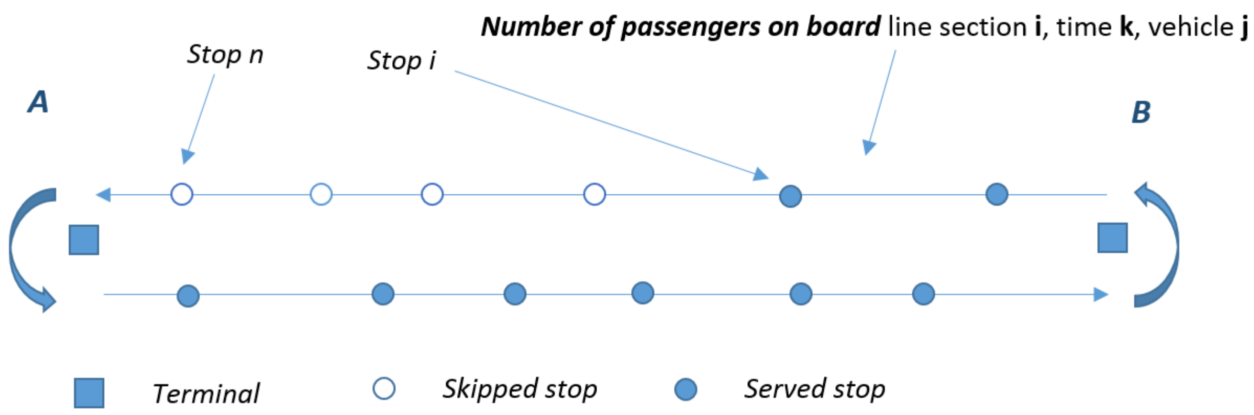



***Figure 100**: Fictitious line with the explanation of detour dynamics.*

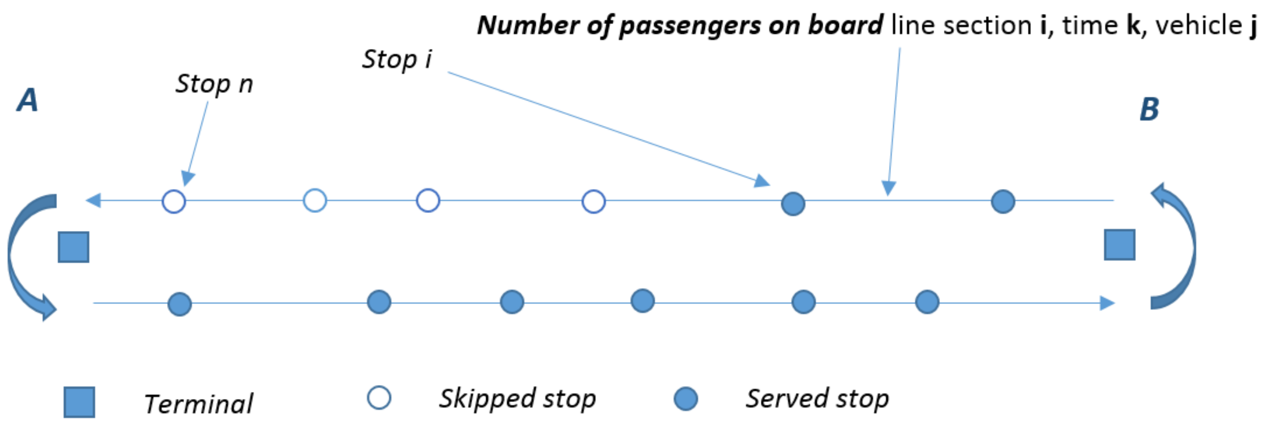



***Figure 101**: Fictitious line with the explanation of deadheading dynamics.*

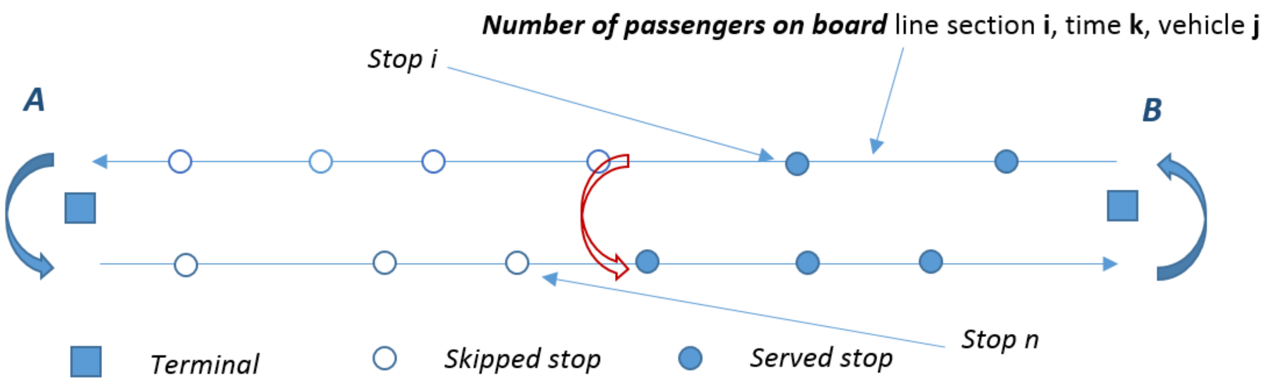



*Figure 102: Fictitious line with the explanation of short turning dynamics.*

| ***Vehicle interested*** | ***Skipped stop*** | ***Quality aspect*** | ***Additional info 1*** | ***Additional info 2*** |
|---|---|---|---|---|
| ***Vehicle j*** | $\sum_{i=2}^{n} stop\ i$ | **Accessibility** ⬇ | ***1)Number of passengers on board*** *line section* ***i****, time* ***k****, vehicle* ***j;*** <br><br> ***2) Average number of passenger waiting for boarding*** *at the various skipped stop, time slot* ***u****.* | *1) Outside temperature* [C°]; *2) Weather condition.* |
| | | **Comfort 2,** *Being forced to abandon the mean* ⬇ | | |
| | | **Cleaning of the means** ⬇ | *Skipped* ***n*** *cleaning operation* | |

***Table 53***: *Table with the additional information needed to dispatcher to understand the impact that the implementation of* ***detour-dead heading and short turning*** *generates on passengers' quality aspects.*

## *Ride elimination*

As we analyzed this kind of invasive operative instrument has an ambiguous effect on two quality aspects:

1. ***Comfort 1***: Capability to find a seat;
2. ***Accessibility***: Frequency of the service; distance among relevant stops.

We have said that this operational instrument has an ambiguous impact, this means that it generates both a positive and negative effect on the two quality aspects over listed. Our objective is to provide the dispatchers with the information related to the bad effects because the good influences generated by the application of the OI are already showed by the changings of the objective function (*It shows the increase of line's regularity generated by the application of a certain OI*).

The application of this kind of operational instrument generates a decrease in the capability to find a seat for the passengers that are going to take the bus after the one eliminated. This because eliminating a ride generates an exceptional load for the vehicle departing after the one suppressed.

The kind of information that will be provided to the dispatcher is an estimation of the number of stops in which the vehicle will be overcrowded. We use the help of *table 54* to show which is the additional information provided to dispatchers when ride elimination is suggested by the DMSS.

| ***Vehicle interested*** | ***Skipped stop*** | ***Quality aspect*** | ***Additional info 1*** | ***Additional info 2*** |
|---|---|---|---|---|
| ***Vehicle j*** | ***Entire line*** | **Accessibility** ⬆ ⬇ | $\frac{\sum_{i=1}^{n} stop_i \; in \; which \; \frac{average \; load \;\; stop \; i}{capacity \; of \; the \; vehilce \; j} \geq X}{Nuber \; of \; stops \; along \; the \; entire \; line}$ | *1) Outside temperature* [C°]<br>*2) Wheatear condition* |
| | | **Comfort 1,** *Capability to find a seat* ⬇ ⬆ | $\frac{\sum_{i=1}^{n} stop_i \; in \; which \; \frac{average \; load \;\; stop \; i}{capacity \; of \; the \; vehilce \; j} \geq 1}{Nuber \; of \; stops \; along \; the \; entire \; line}$ | |

***Notes:***

✓ The two indicators consider the historical data at disposition and accordingly with the period of the day in which the operative instrument will be applied they will highlight:

***Equation 10 describes the average crowding level along the entire line, time slot u, vehicle j***

$$\frac{\sum_{i=1}^{n} stop_i \; in \; which \; \frac{average \; load \;\; stop \; i}{capacity \; of \; the \; vehilce \; j} \geq X/1}{Nuber \; of \; stop \; along \; the \; entire \; line} \qquad \text{Equation 10}$$

- Where ***X*** represents a threshold of crowding acceptability that can be different according to the acceptability level set by the specific public operator;
- Where ***1*** Shows the extreme case in which there will be some passengers that will not be even able to get on the vehicle because there is no space left.

***Table 54****: Table with the additional information needed to dispatcher to understand the impact that the implementation of* ***<u>ride elimination</u>*** *generates on passengers' quality aspects.*

## *Vehicle holding*

As already analyzed in the beginning of this section this kind of invasive operative instrument has an ambiguous effect on one quality aspect:

1. ***Travel time reliability***

We have said that this operational instrument have an ambiguous impact, this means that it generates both a positive and negative effect on the quality aspect just mentioned. Our objective is to provide the dispatchers with the information related to the bad effects created by the implementation of this OI. The positive influences generated by the application of such operational instrument are already shown by the changings of the DMSS' objective function (*It shows the increase in the regularity of the line generated by the application of a certain OI*).

## *Travel time reliability*

The application of this kind of operational instrument generates a sense of inefficiency in the passengers  that are travelling on the held mean because they see it remaining still without any external reason that keeps it in that condition. Due to this the control room operator will be provided with the number of passenger on board line section i, time k, vehicle j that is held. Another info to be communicated is the average number of passengers waiting at the downstream stops (stop following the one in which the vehicle will be held) because they will experience an increase in the waiting time. We introduce *figure 103* to better explain which is the information provided to the dispatcher

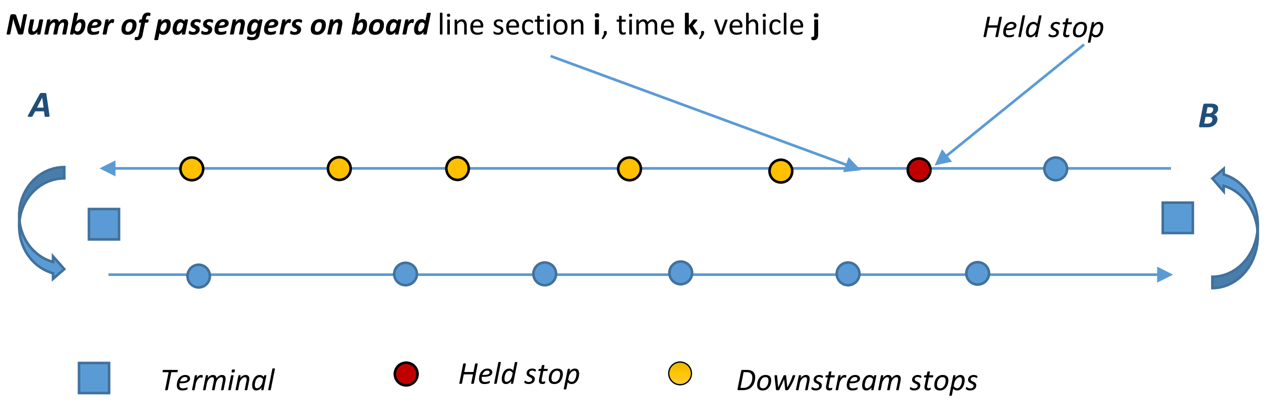



***Figure 103****: Fictitious line with the explanation of skipping stop dynamics.*

*Table 55* shows the additional information provided to dispatchers in case of *vehicle holding* implementation.

| *Vehicle interested* | *Stop held* | *Quality aspect* | *Additional info 1* | *Additional info 2* |
|---|---|---|---|---|
| ***Vehicle j*** | ***Stop i*** | **Accessibility** ⬆ ⇩ | ***1) Number of passengers on board*** line section **i**, time **k**, vehicle **j;** ***2)Average number of passenger waiting*** *downstream after the held stop at the various stops, time slot* ***u*** | *1) Outside temperature* [C°] ; *2) Wheatear condition* |

***Table 55****: Table with the additional information needed to dispatcher to understand the impact that the implementation of* ***vehicle holding*** *generates on passengers' quality aspects.*

The objective of this third section was to create, define and describe the set of logics and assumptions on which is built the additional information to provide to the dispatcher in order to make the disruption management support system a more effective tool able to really support them in their decisions. An important quality aspect of the equations presented in this study is their robustness; in fact they are able to provide valuable information always considering the variability of the system they try to describe. All the info can be seen as an alert that enable the operator to understand the repercussion on passengers' quality aspect if one invasive operational instrument will be implemented.

# 6. Thesis simulation

The aim of this last part of the thesis is to verify if the assumptions, logics and variables introduced along the model section are confirmed analyzing the data coming from the reality. In order to explain all the passages done to perform the validation phase we will introduce few case studies to be clear and concise in the explanation.

To develop this phase we will follow the same logic that we have already used for the model creation. We will tackle the different components that constitute the disruption management support system (DMSS) following the flow of data inside it (*see figure 104*).

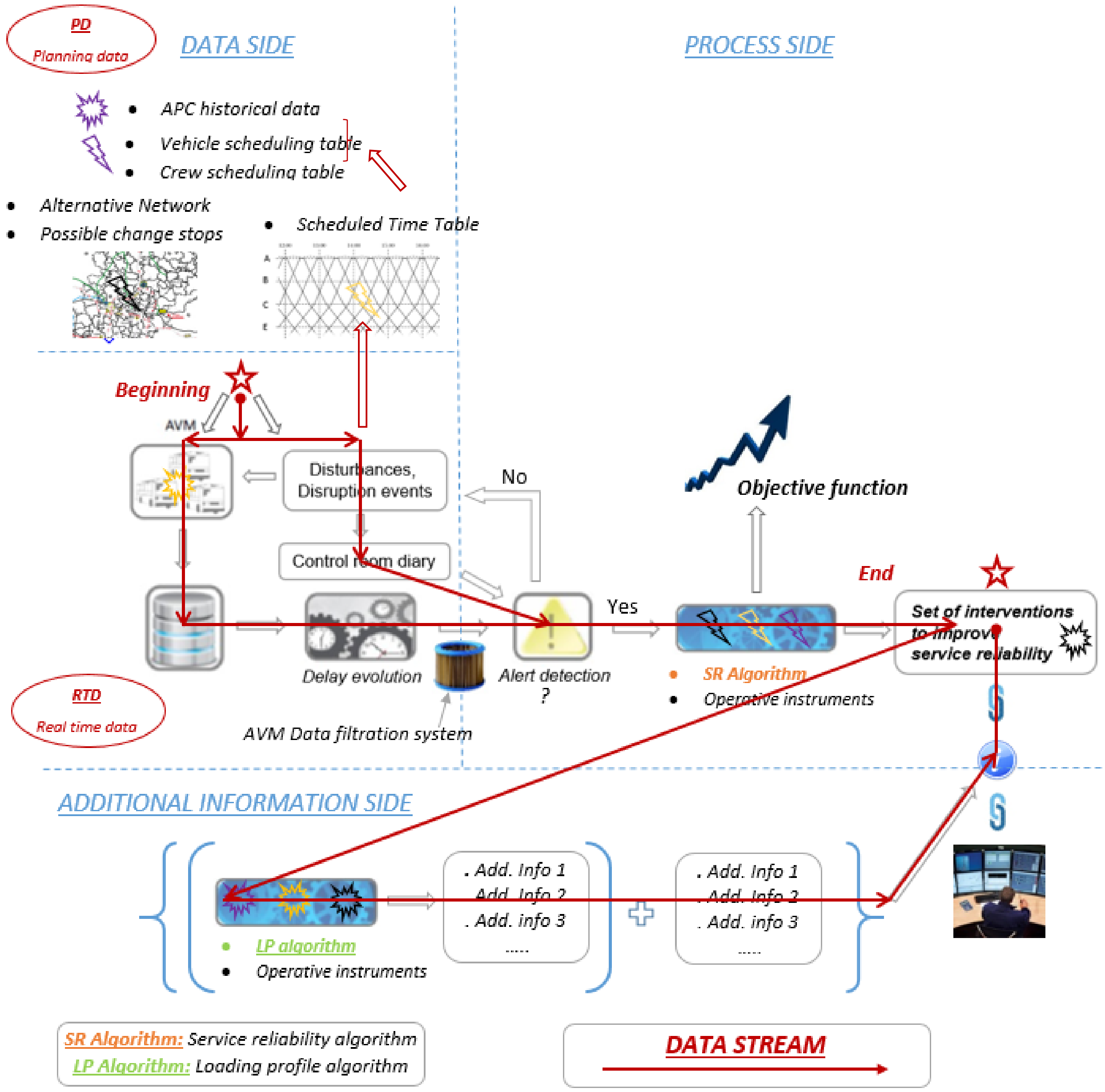



***Figure 104**: Disruption management support system (DMSS) overview, with data stream.*

## 6.1 Data side

Concerning the Data side the greatest part of the job was about the validation, filtration and elaboration of the different kind of data that will be the in-put of the DMSS hence the validation of the *AVM data filtration system*. The objective is to provide the process side of the system with high quality data in order to be able to provide dispatchers with valuable suggestions.

### *6.1.1 AVM data filtration system*

According to the data flow stream presented in *figure 104* the first component created from scratch to satisfy the DMSS' needs is the **AVM Data filtration system** (*see figure 105*). To explain better the validation process that has been used to validate the set of rules, logics and assumptions that constitute this component we analyze ***Line 14, on the 21-02-2013.*** The line selected is one of the 4 lines of power *(high demand; high frequency; low performances*) on which it will be used the DMSS; while the day selected is the one with the worse performances along February (*February is the most critical month of the year*). Another reason for which we have selected this line is that it is a *tram lime*, so we are focusing on the vehicle that has the highest number of constraints; it needs overhead cable and railway to operate.

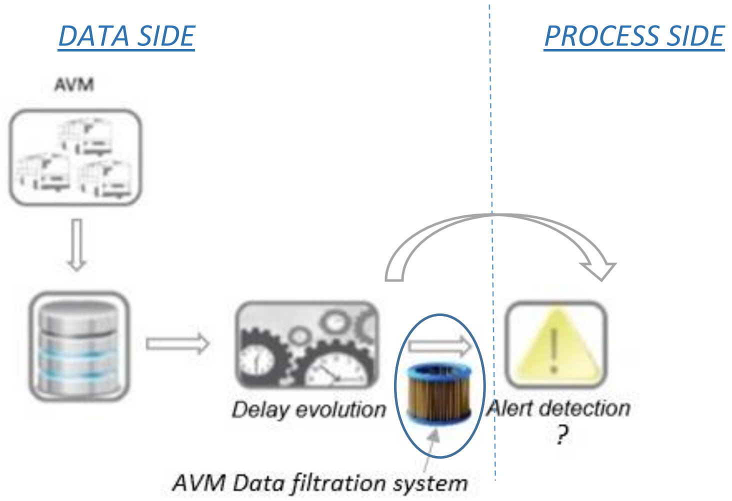



***Figure 105****: AVM data filtration particular; link between DATA SIDE and PROCESS SIDE.*

To start we will develop a numerical example that shows how we have selected the day on which perform the validation phase of the data filtration system (*the days chosen for the other case studies presented for the validation of the system's component will follow the same logic*).

1. The ***first step*** is to compute the *weighted daily average regularity in frequency (wdaRiF)* of the line selected (*L 14*) for all the workdays of the month selected (*February*) (see *table 56*).

2. ***Second step*** is to select the day of the month in which the line considered (*L 14*) performed the worse. That day is selected to perform the in deep analysis (see *table 56*).

| ***Feb-13*** | |
|---|---|
| ***Data*** | ***wdaRiF*** |
| *22/02/2013* | *82%* |
| *26/02/2013* | *82%* |
| *05/02/2013* | *82%* |
| *04/02/2013* | *81%* |
| *01/02/2013* | *81%* |
| *18/02/2013* | *81%* |
| *20/02/2013* | *80%* |
| *08/02/2013* | *80%* |
| *15/02/2013* | *79%* |
| *06/02/2013* | *79%* |
| ***Average Feb*** | ***78%*** |
| *14/02/2013* | *78%* |
| *27/02/2013* | *78%* |
| *07/02/2013* | *77%* |
| *19/02/2013* | *76%* |
| *25/02/2013* | *76%* |
| ***11/02/2013*** | ***75%*** |
| ***12/02/2013*** | ***74%*** |
| ***13/02/2013*** | ***73%*** |
| ***28/02/2013*** | ***73%*** |
| ***21/02/2013*** | ***72%*** |

***Table 56***: *wdaRiF of all the weekdays of February, ordered in ascendant order.*

Once selected the day of interest the next phase is to track how the line selected (*L 14*) performed along the different time slots of the day selected *(e.g. time slot 4, 4:00 a.m. to 4:59 a.m.) (see figure 106).*

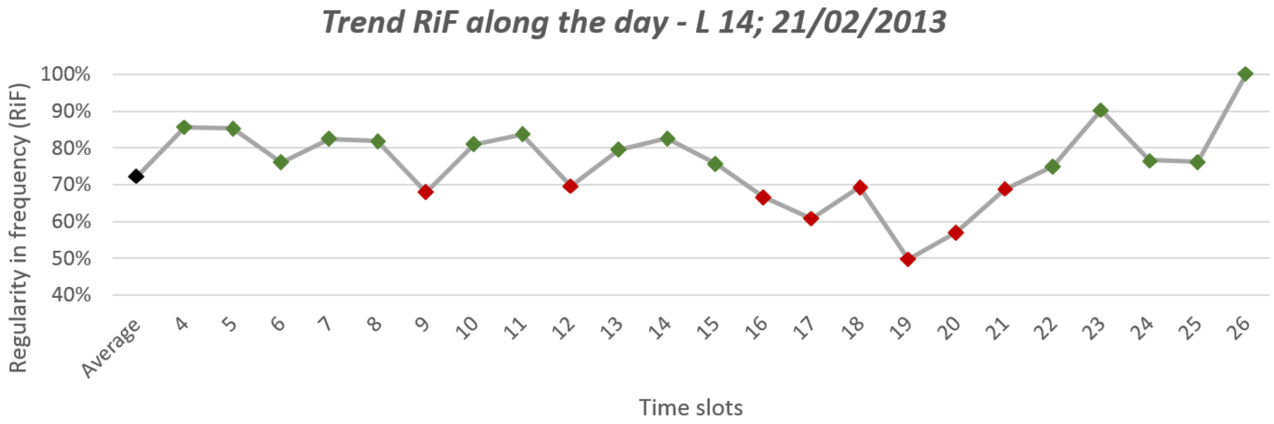



***Figure 106***: *RiF trend along the day – L14; 21/02/2013.*

Once we have this information it is possible to start analyzing in detail all the different kind of records that have been registered along the day selected (21/02/2013) to understand which of them can be considered valid to be processed and which not. We want to understand which real time data the system will process and which not.

As already presented along *chapter 5.1.1* there are some codes that have been discarded from a first qualitative analysis performed by the experts that compose the Disruption management team. (*see table 57).*

| ***Initial discarded code*** | |
|---|---|
| ***Error_code*** | ***Description*** |
| ***Code1*** | *Planned deviation* |
| ***Code 2*** | *No functioning transmission system* |
| ***Code 1024*** | *No transmission in the center of the line* |

***Table 57***: *Initial discarded code.*

A more detailed analysis has been performed on codes that have been judged critical by the expert because we were not able to assess without a numerical analysis their validity *(see table 58).*

| *Critique code* | |
|---|---|
| ***Error- code*** | ***Description*** |
| ***Code 16*** | *The mean stops at least 3 minutes at the terminal* |
| ***Code 64*** | *The mean stops at least 3 minutes on the line* |
| ***Code 128*** | *The mean doesn't transmit during the final 5 stops* |
| ***Code 256*** | *The mean doesn't transmit during the initial 5 stops* |

***Table 58***: *critique codes.*

Once identified the critique code we have analyzed them in detail using the data coming from the worst day identified previously (*for L 14 → day 21/02/2014*). Now we will apply, on the case study considered, the variables the logics and the assumptions widely described in the model phase.

Under are reported the tables (*table 59; table 60; Table 61*) with the **registration made by the system (all the codes)** and the **registration made by the system (codes i-l)** along the all day (*21/02/2012, L14*) divided in time slots of 4 hours each.

| *Time slot* | *registrations made by the system (all the codes)* | *%* |
|---|---|---|
| *5_8* | *843* | *8%* |
| *9_12* | *2647* | *24%* |
| *13_16* | *2573* | *23%* |
| *17_20* | *3028* | *27%* |
| *21_24* | *2085* | *19%* |
| ***Somma*** | ***11176*** | ***100%*** |

***Table 59***: *Registration made by the system (all the codes) along the day. Case study L14; 21/02/2013.*

| *Time slot* | *Registration made by the system ( codes 16-64)* | *%* |
|---|---|---|
| *5_8* | *90* | *6%* |
| *9_12* | *328* | *22%* |
| *13_16* | *362* | *24%* |
| *17_20* | *487* | *33%* |
| *21_24* | *218* | *15%* |
| ***Somma*** | ***1485*** | ***100%*** |

***Table 60***: *Registration made by the system (code 16-64) along the day. Case study L14; 21/02/2013.*

| *Time slot* | *Registration made by the system ( codes 128-256)* | *%* |
|---|---|---|
| *4 _8* | *138* | *11%* |
| *9_12* | *182* | *15%* |
| *13_16* | *52* | *4%* |
| *17_20* | *586* | *47%* |
| *21_24* | *278* | *22%* |
| ***Somma*** | ***1236*** | ***100%*** |

***Table 61***: *Registration made by the system (codes 128 – 256) along the day. Case study L14; 21/02/2013.*

Once obtained all the **% values** presented in the previous tables it is time to put them in a chart in order to compare the trend of the *registration made by the system (critique codes i-l)* with the trend of *registration made by the system (all the codes)* (*see figure 107; figure 108*). From their comparison it is possible to consider if the critique codes can be consider valid or not.

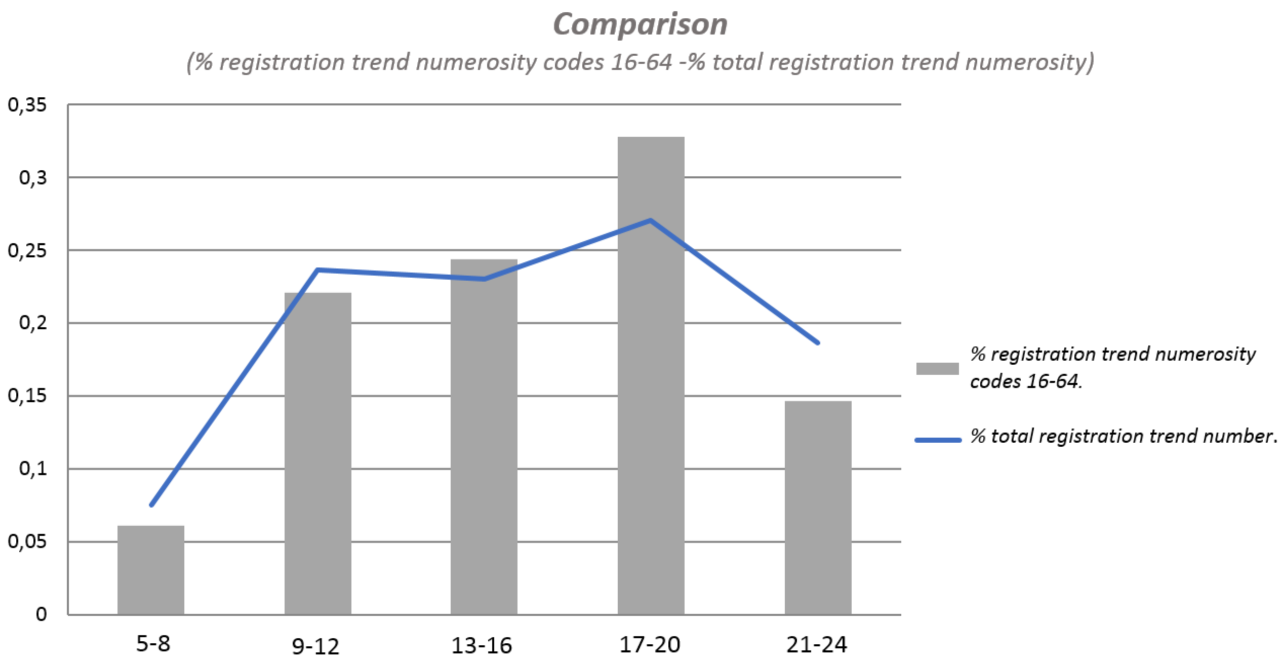



***Figure 107***: *Comparison between % numerosity registrations codes 16-64 - % total registration trend number. Case study L14; 21/02/2013.*

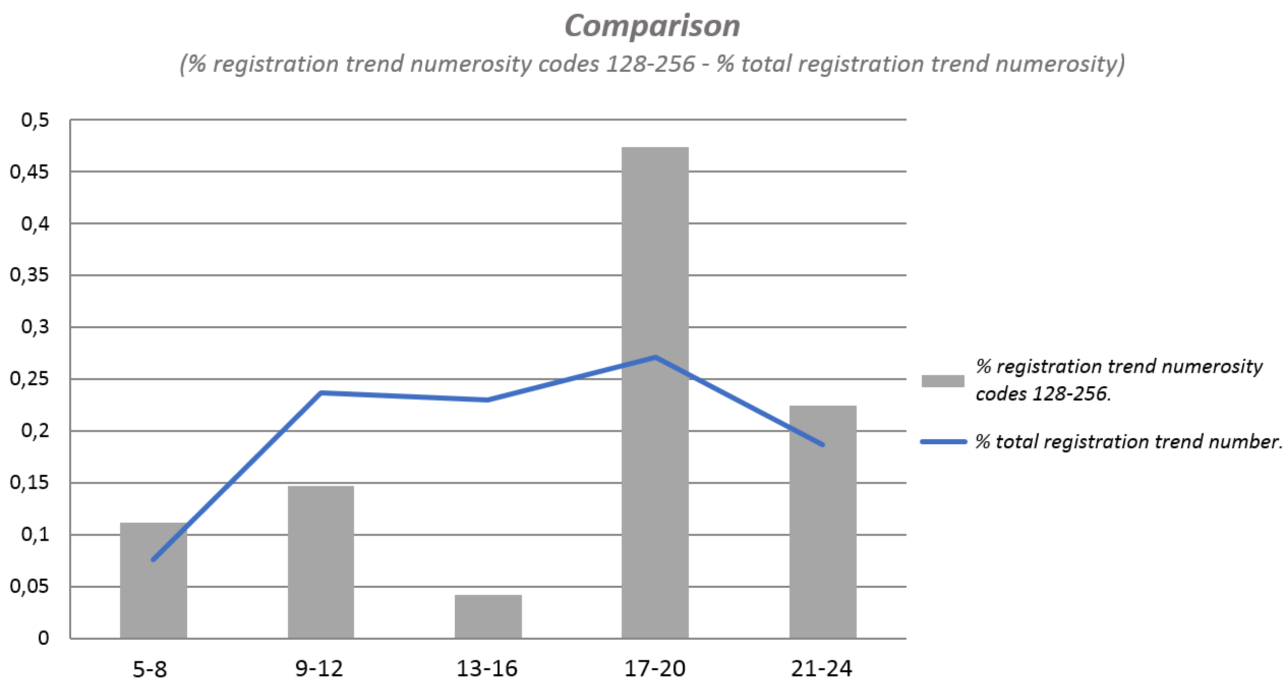



***Figure 108***: *Comparison between % numerosity registrations codes 128-256 - % total registrations trend number. Case study L14; 21/02/2013.*

At this point it is possible to make the final considerations on the results obtained:

1. Data related to the *code 16 -64* can be considered valid because they follow a trend strictly related to the total numerosity of data recorded, hence it is probable that this two codes are due to transmission problems or to common situations that happens on the line (e.g. a traffic light particularly long). If the number of registration increases it is logical assume a similar increase in the number of transmission problems.

2. The *codes 128-256* are concentrated between the $16^{th}$ and the $20^{th}$ time slot where there was also the great inefficiency of the day (*see figure 106*). This means that the record with this codes cannot be considered valid because they are generated because of unusual maneuvers of the means that travel part of the ride out of the line to cope with critical situations (*e.g. an accident that block the viability of a street*).

   In the following tables (*see Table 62, Table 63*) are reported all the codes that can be considered valid and hence used by the process side and the ones that cannot.

| Discarded code | |
|---|---|
| ***Error _ code*** | ***Description*** |
| ***Code1*** | *Planned deviation* |
| ***Code 2*** | *No functioning transmission system* |
| ***Code 1024*** | *No transmission in the center of the line* |
| ***Code 128*** | *The mean doesn't transmit during the final 5 stops* |
| ***Code 256*** | *The mean doesn't transmit during the initial 5 stops* |

***Table 62***: *Final table with discarded codes.*

| Valid codes | |
|---|---|
| ***Error _ code*** | ***Description*** |
| ***Code 0*** | *Correct transmission* |
| ***Code 4*** | ........................................................ |
| ***Code 8*** | ........................................................ |
| ***Code 16*** | *The mean stops at least 3 minutes at the terminal* |
| ***Code 64*** | *The mean stops at least 3 minutes on the line* |
| ***Code 512*** | ........................................................ |
| ***Code 16384*** | ........................................................ |

***Table 63***: *Final table with valid codes.*

The same approach will be applied also on other case studies identifies along chapter *4 (Thesis Methodology).*

## 6.1.2 Time table design quality

Another important aspect that we need to verify is the **quality of the scheduled travel time** because the algorithm generates suggestions to maintain high reliability based on the headways generated dividing the total scheduled travel time of the line per the number of means that are serving the line (*see figure 109*).

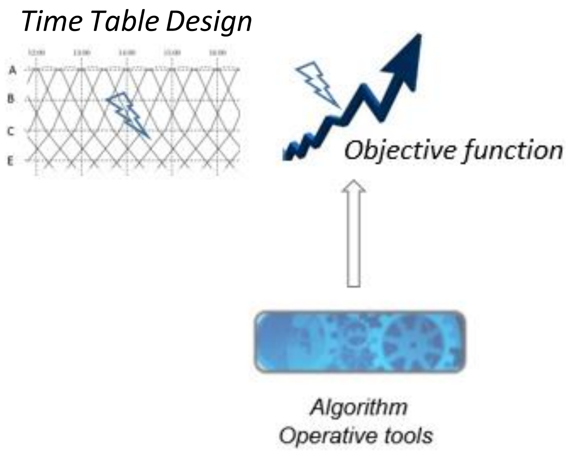



***Figure 109****: Interaction of the Time Table (it gives the scheduled travel time) with the other components of the DMSS.*

Among the case studies identified to validate this data we have selected ***Line 14 on the 21/02/2013.***

As already explained during the model's specification section, the analysis is performed in two different parts:

1. *Overall quality of the scheduled trip time;*
2. *Daily trend travel time deviation %.*

***1. Overall quality of the scheduled trip time***

The first step is to divide and cluster all the various trips performed by the various means along the day according to their *travel time deviation %* respect to the scheduled travel time.

| ***Total trip*** | ***TTD% > 10%*** | ***-10% < TTD% < 10%*** | ***TTD% < -10%*** |
|---|---|---|---|
| 324 | 34 | 286 | 4 |
| ***%sul totale*** | 10% | 88% | 1% |

***Table 64****: Table travel time deviation (TTD) % repartition. Case study L14; 21/02/2013.*

Once obtained the results presented in the *table 64* we need to put them in a graph (*figure 110* ) to verify if they follow the minimum thresholds provided by the operational research department of Politecnico di Milano that guarantee a correct functioning of the algorithm, which is the core of the disruption management support system.

***Threshold*** → *< 10 % of the trips recorded has to have a Trip Time Deviation (TTD) % higher than 10%*

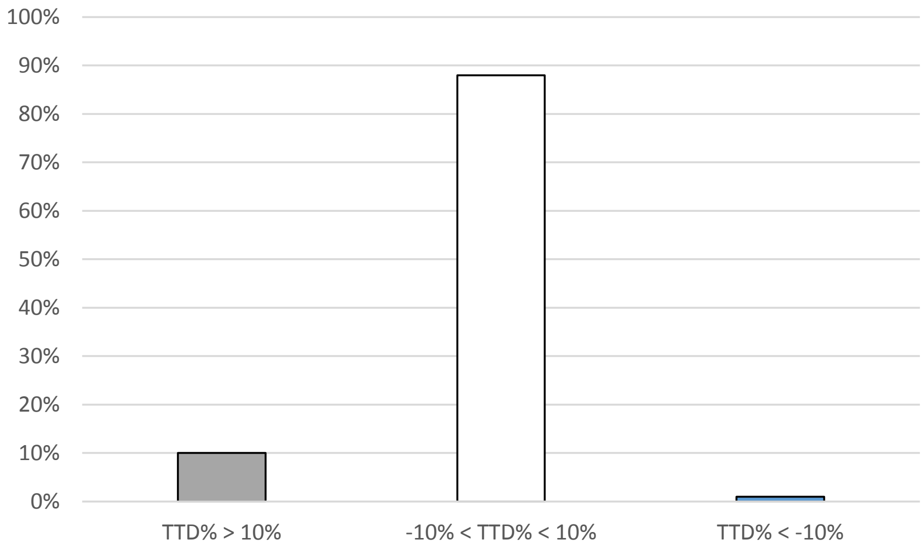



***Figure 110***: *Table travel time deviation (TTD) % graphic representation. Case study L14; 21/02/2013.*

As it is possible to see the case study (*L 14 – 21/02/2013*) selected respects the minimum threshold.

### ***2. Daily trend travel time deviation %***

The objective of this second part of analysis is to understand how are distributed along the day the event in which the travel time deviation % is higher than 10%. In the following graphic (*figure 111*) are presented three lines that aim at represent three different meanings:

- ***Blue Line***: *Daily trend travel time deviation %* (we put in the graph every single trip performed during the day).
- ***Black Line***: *Simple moving average (5 periods)* to see the trend of the *trip time deviation %* mitigating the episodes that have an extremely high TTD% *(generated by a big accident or similar events*).

- ***Red line***: *Exponential trend-line (grade 6):* This analysis has the aim to track the trend of the travel time quality along the day. This studying is important to understand the daily ***distribution of the travel time deviation***.

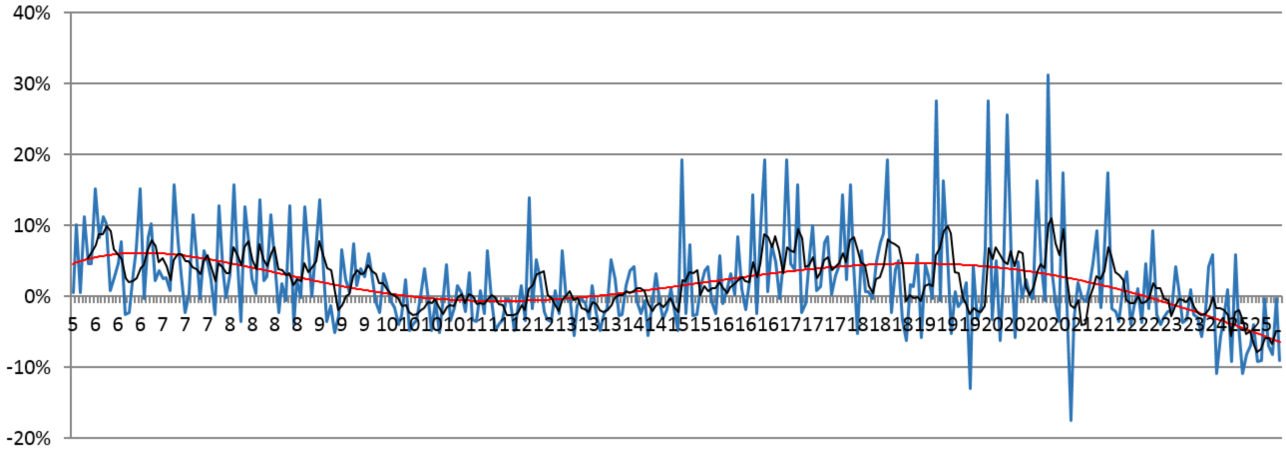



***Figure 111****: Graphic with the distribution of the travel time deviation (TTD) %. Case study L14; 21/02/2013.*

- ***Black Line:*** *The simple moving average (5 periods)* graph confirms what already found in the first analysis. The line never overtake the 10% threshold, this show a good level of data quality.

- ***Red line:*** *The Exponential trend-line (grade 6)* shows that the worse data quality is around the 6$^{th}$ and the 19$^{th}$ time slots. Particularly our attention goes on the 19$^{th}$ slot because at that time there are both the highest traffic and the personnel change shift hours. It is possible to notice that the greatest part of the low quality data is concentrated between the 15$^{th}$ and the 20$^{th}$ time slot. In any case the level of distribution of the poor quality data it is consider sufficiently good by the Operative reseach department who asked for this specific of analysis.

Similar analysis will be performed also on the other case studies identified during *chapter 4* – thesis methodology.

## 6.2 Process side

Now our attention goes to the ***process side***, in this second part of the system all the data is elaborated and processed into valuable information. In the end the support system will give suggestions to controllers for maintaining a high level of line's service reliability. Also for this side we will follow the data flows inside the system (*see figure 104*) as rule to prioritize the element to validate.

### 6.2.1 Alert detection component

The alert detection component (*figure 112*) is the part of the system that links the Data side with the core of the DMSS, the service reliability Algorithm. It is composed by a set of rules, variables, and indicators that have the task to detect in advance possible critical situations of the line that without a prompt intervention can irremediably degenerate. Among the identified case studies we have chosen the ***L 14 on the 21-02-2013*** to validate this component**.**

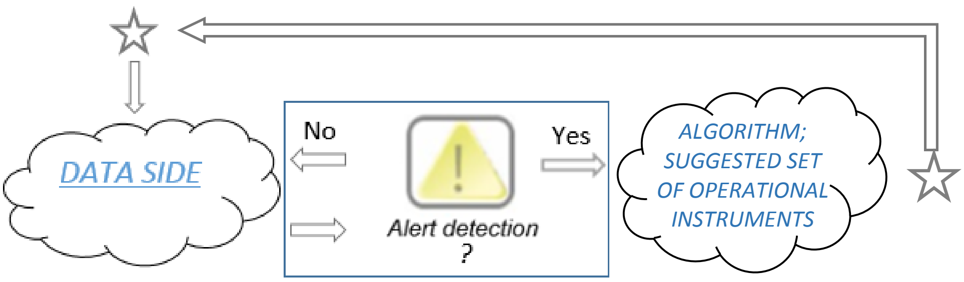



***Figure 112****: Alert detection component with context.*

*Table 65* recaps the 3 different alerts already described and explained in the model specification section.

| ***Alert*** | ***Description*** |
|---|---|
| ***Alert 1*** | *Occurrence of one or more events detected as critical on the risk map* |
| ***Alert 2*** | *Generation of a group of «steps» that overtakes the set of identified thresholds* |
| ***Alert 3*** | *Increasing trend of General deterioration of the line* |

***Table 65****: Alerts presentation with short introductive description.*

## *Alert 1: "Occurrence of one or more events detected as critical on the risk-map."*

In order to verify the validity of the components, logics and assumption that constitute this alert is necessary to follow two steps:

1. ***First level (RISK-MAP CREATION):*** In this first part we will cluster the different events happened on the line 14 sub-network (*L 14, L19, L 12, L2, L4, L1, L3*). The historical data used are the ones of *March and February (only workdays are considered)*.

2. ***Second level (Alert Definition):*** In this second part we will validate in detail the ***Alert 1***, analyzing the single day 21/02/2013 and the single line 14.

### 1. First level (RISK MAP CREATION)

1. *The First step* is to aggregate the data related to the different events happened on *L 14 sub-network*, during the first period of analysis (*March and February*). (*See table 66*).

| *Kind of event* | *Sum PASSENGER-ALIGHT* | *Sum ELIMINATED-RIDES* | *Sum SHORT TURNED-RIDES* | *Average DURATION OF THE EVENT (min)* | *EVENT-FREQUENCY occurrence* |
|---|---|---|---|---|---|
| ***Aggressions*** | 7 | 2 | 3 | 12,7 | 21 |
| ***Cause event*** | 400 | 3 | 588 | 52,3 | 435 |
| ***Cause event other ATM's mean*** | 588 | 77 | 966 | 59,7 | 742 |
| ***Connections*** | 4 | 5 | 2 | 135,3 | 21 |
| ***Bad weather conditions*** | 14 | 5 | 28 | 5,5 | 14 |
| ***Transmission system failure*** | 3 | 2 | 4 | 293,7 | 21 |
| ***Means' equipment failure*** | 14 | 7 | 21 | 17,9 | 189 |
| ***Previous failure same means*** | 28 | 5 | 56 | 16,5 | 28 |
| ***Means failure*** | 595 | 371 | 1211 | 94,9 | 1337 |
| ***Grounding*** | 77 | 21 | 189 | 51,7 | 217 |
| ***Previous grounding same mean*** | 84 | 14 | 154 | 22,0 | 84 |
| ***Slow roads*** | 2667 | 84 | 6013 | 25,4 | 3073 |
| ***Illness*** | 35 | 4 | 42 | 29,9 | 56 |
| ***Rolling stock issues*** | 35 | 35 | 98 | 41,3 | 70 |
| ***Passenger on the ground*** | 7 | 6 | 3 | 0,7 | 84 |
| ***Injured passenger*** | 14 | 4 | 56 | 40,4 | 63 |
| ***Personnel*** | 126 | 98 | 259 | 103,0 | 147 |
| ***Crash*** | 70 | 21 | 112 | 99,1 | 98 |
| ***Dirty mean*** | 28 | 7 | 77 | 69,8 | 42 |

***Table 66**: Table with events' aggregated data. Case study sub-network L 14; March/February.*

2. *The second step* aims is to define a set of weights that will be used to gather the sub-indicators that describe the impact of the single event in the macro indicator "Event Magnitude". In order to obtain the set of weights we will apply a correlation function in Excel between the *weighted daily average regularity in frequency (wdaRiF)* during the month of February and the sub-indicators value's trend of *L 14*. (See *table 67/68*).

| Day | wdaRiF | Sum ELIMINATED-RIDES | Sum SHORT TURNED-RIDES | Sum PASSENGER ALIGHT | Average DURATION OF THE EVENT |
|---|---|---|---|---|---|
| **22/02/2013** | *82%* | *0* | *6* | *4* | *73,9* |
| **26/02/2013** | *82%* | *0* | *0* | *0* | *17,8* |
| **05/02/2013** | *82%* | *0* | *4* | *3* | *20,0* |
| **04/02/2013** | *81%* | *2* | *8* | *4* | *110,4* |
| **01/02/2013** | *81%* | *0* | *6* | *3* | *117,0* |
| **18/02/2013** | *81%* | *4* | *6* | *3* | *115,3* |
| **20/02/2013** | *80%* | *0* | *6* | *4* | *23,9* |
| **08/02/2013** | *80%* | *0* | *6* | *4* | *52,4* |
| **15/02/2013** | *79%* | *1* | *15* | *6* | *100,2* |
| **06/02/2013** | *79%* | *1* | *11* | *5* | *22,4* |
| **14/02/2013** | *78%* | *3* | *20* | *10* | *54,7* |
| **27/02/2013** | *78%* | *4* | *14* | *5* | *55,9* |
| **07/02/2013** | *77%* | *4* | *14* | *6* | *64,5* |
| **19/02/2013** | *76%* | *3* | *18* | *10* | *83,8* |
| **25/02/2013** | *76%* | *3* | *22* | *12* | *91,0* |
| **11/02/2013** | *75%* | *3* | *17* | *9* | *44,3* |
| **12/02/2013** | *74%* | *3* | *31* | *16* | *42,8* |
| **13/02/2013** | *73%* | *1* | *21* | *4* | *37,3* |
| **28/02/2013** | *73%* | *2* | *32* | *17* | *60,2* |
| **21/02/2013** | *73%* | *2* | *26* | *13* | *65,1* |

***Table 67****: Table with daily data of the events related to the month of February; Case study L 14.*

| *Kind of correlation* | *Level of correlation* | *Absolute value* |
|---|---|---|
| Correlation ***wdaRiF/*** ***Sum SHORT TURNED-RIDES*** | -93% | ***93%*** |
| Correlation ***wdaRiF/*** ***Sum PASSENGER-ALIGHT*** | -81% | ***81%*** |
| Correlation ***wdaRiF/*** ***Sum ELIMINATED RIDES*** | -47% | ***47%*** |
| Correlation ***wdaRiF/*** ***Average EVENT-DURATION*** | 13% | ***13%*** |

***Table 68****: Table with the results after applying the correlation function between the wdaRiF and the values of the daily aggregated result of the sub-indicators. February, L 14.*

3. The third step consists in the definition of the indicator "*Medium event" (the average of the results coming from all the kind of events for each sub-indicators). (See table 69).*

| *Kind of event* | *Sum PASSENGER-ALIGHT* | *Sum ELIMINATED-RIDES* | *Sum SHORT TURNED-RIDES* | *Average DURATION OF THE EVENT* | *EVENT-FREQUENCY occurrence* |
|---|---|---|---|---|---|
| ***Aggressions*** | 7 | 2 | 3 | 12,7 | 21 |
| ***Cause event*** | 400 | 3 | 588 | 52,3 | 435 |
| ***Cause event other ATM's mean*** | 588 | 77 | 966 | 59,7 | 742 |
| ***Connections*** | 4 | 5 | 2 | 135,3 | 21 |
| ***Bad weather conditions*** | 14 | 5 | 28 | 5,5 | 14 |
| ***Transmission system failure*** | 3 | 2 | 4 | 293,7 | 21 |
| ***Means' equipment failure*** | 14 | 7 | 21 | 17,9 | 189 |
| ***Previous failure same means*** | 28 | 5 | 56 | 16,5 | 28 |
| ***Means failure*** | 595 | 371 | 1211 | 94,9 | 1337 |
| ***Grounding*** | 77 | 21 | 189 | 51,7 | 217 |
| ***Previous grounding same mean*** | 84 | 14 | 154 | 22,0 | 84 |
| ***Slow roads*** | 2667 | 84 | 6013 | 25,4 | 3073 |
| ***Illness*** | 35 | 4 | 42 | 29,9 | 56 |
| ***Rolling stock issues*** | 35 | 35 | 98 | 41,3 | 70 |
| ***Passenger on the ground*** | 7 | 6 | 3 | 0,7 | 84 |
| ***Injured passenger*** | 14 | 4 | 56 | 40,4 | 63 |
| ***Personnel*** | 126 | 98 | 259 | 103,0 | 147 |
| ***Crash*** | 70 | 21 | 112 | 99,1 | 98 |
| ***Dirty mean*** | 28 | 7 | 77 | 69,8 | 42 |
| ***Average event*** | ***252,4*** | ***40,6*** | ***520,1*** | ***61,7*** | ***354,8*** |

***Table 69****: Table average event; case study sub-network L14, February/March.*

*4. The forth steps* consist in performing an analysis on the *% deviation* between the values of the sub-indicators generated by the single kind of event and the average event. (*see table 70*)

| *Kind of event* | *Sum PASSENGER-ALIGHT* | *Sum ELIMINATED -RIDES* | *Sum SHORT TURNED-RIDES* | *Average DURATION OF THE EVENT* | *EVENT-FREQUENCY occurrence* | *FREQUENCY* | *IMPACT* |
|---|---|---|---|---|---|---|---|
| ***Aggressions*** | -97% | -95% | -99% | -79% | -94% | -226% | -94% |
| ***Cause event*** | 58% | -93% | 13% | -15% | 23% | ***14%*** | ***23%*** |
| ***Cause event other ATM's mean*** | 133% | 90% | 86% | -3% | 109% | ***190%*** | ***109%*** |
| ***Connections*** | -98% | -88% | -100% | 119% | -94% | -134% | -94% |
| ***Bad weather conditions*** | -94% | -88% | -95% | -91% | -96% | -118% | -96% |
| ***Transmission system failure*** | -99% | -95% | -99% | 376% | -94% | -125% | -94% |
| ***Means' equipment failure*** | -94% | -83% | -96% | -71% | -47% | -115% | -47% |
| ***Previous failure same means*** | -89% | -88% | -89% | -73% | -92% | -113% | -92% |
| ***Means failure*** | 136% | 814% | 133% | 54% | 277% | ***493%*** | ***277%*** |
| ***Grounding*** | -69% | -48% | -64% | -16% | -39% | -79% | -39% |
| ***Previous grounding same mean*** | -67% | -65% | -70% | -64% | -76% | -85% | -76% |
| ***Slow roads*** | 957% | 107% | 1056% | -59% | 766% | ***85%*** | ***77%*** |
| ***Illness*** | -86% | -90% | -92% | -52% | -84% | -112% | -84% |
| ***Rolling stock issues*** | -86% | -14% | -81% | -33% | -80% | -76% | -80% |
| ***Passenger on the ground*** | -97% | -85% | -99% | -99% | -76% | -119% | -76% |
| ***Injured passenger*** | -94% | -90% | -89% | -34% | -82% | -119% | -82% |
| ***Personnel*** | -50% | 142% | -50% | 67% | -59% | 26% | -59% |
| ***Crash*** | -72% | -48% | -78% | 61% | -72% | -81% | -72% |
| ***Dirty mean*** | -89% | -83% | -85% | 13% | -88% | -111% | -88% |

***Table 70****: table FREQUENCY – IMPACT; Sub network L14, February, March.*

5. The fifth step consists in the creation of the Risk-Map using the values of impact and Frequency found in *table 70*, in the end we create a summary table in which are contained all the harmful events identified. *(See figure 113, table 71).*

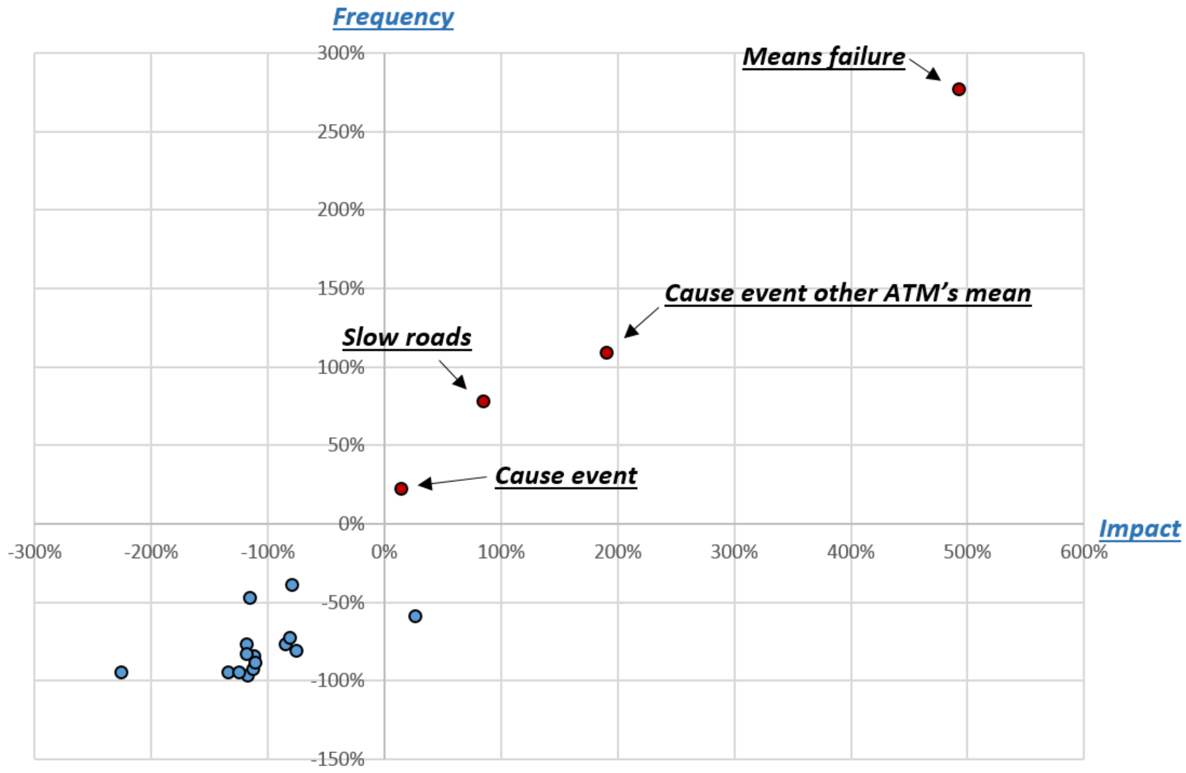



***Figure 113***: *Risk map events; Case study sub-network L14, February/March.*

| *Event* | *Frequency* | *Impact* |
|---|---|---|
| ***Means failure*** | *493%* | *277%* |
| ***Cause event other ATM's mean*** | *190%* | *109%* |
| Slow roads | *85%* | *77%* |
| Cause event | *14%* | *23%* |

***Notes***

- ✓ It is important to observe the ***slow roads*** event. From the analysis done using historical data we have identified that the slow road event in the 90% of the cases is caused by other events. It is not the primary cause of the inefficiencies but it is a consequence produced by the occurrence of another event. Due to this the DMSS team decided reasonable to consider only the 10% of its value.

***Table 71:*** *Summary table containing harmful events, Sub-network L 14 –March/February.*

## 2. Second level (Alert Definition)

Now that we have identified the harmful events of the *sub-network line 14* we can focus our attention on the validation of the first alert. The objective is to analyze if there is a relation between the alleged activation of the alert and the period of the day in which are registered the biggest inefficiencies. Now we will analyze the specific case of ***Line 14 on the 21/02/2013***.

1. The first step is to introduce the RiF trend along the day of interest (*figure 114*), it will be used to verify if there is a relation between the alleged alert activation and the period of the day in which the line performed the worse.

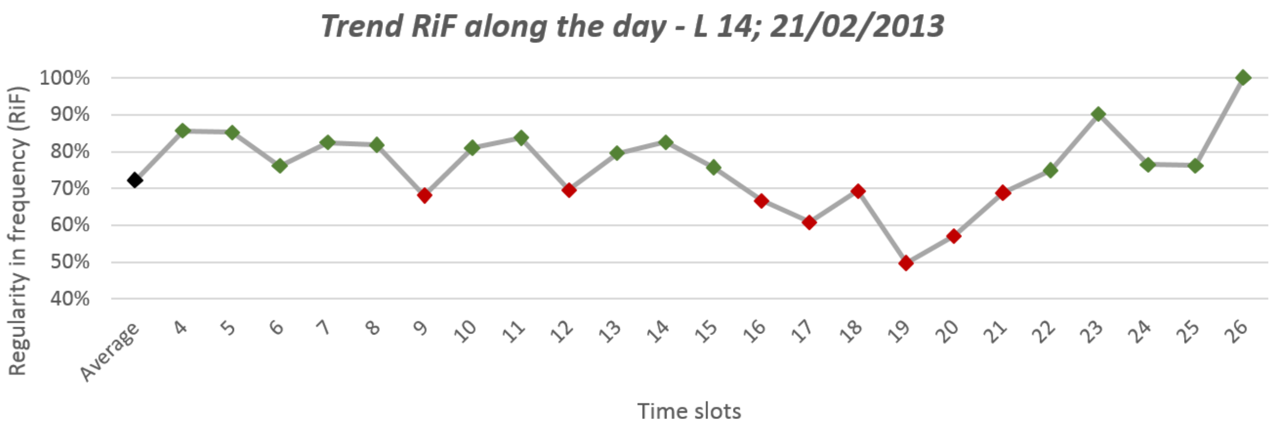



***Figure 114***: *RiF trend along the day. Case study L14; 21/02/2013.*

2. The second point is gather all the events happened on the line and report them in a table highlighting the harmful events that have been detected during the risk-map analysis. We will highlight the ones of them that happened close to an inefficiency *(see table 72).*

| EVENT | TABLE | TIME SLOT START | TIME SLOT END | DURATION (MIN) |
|---|---|---|---|---|
| Mean's equipment failure 1 | 3 | 9 | 9,6 | 2 |
| Mean failure 1 | 1 | 8 | 11,8 | 242 |
| Mean failure 2 | 9 | 11 | 12,2 | 49 |
| Illness 1 | 45 | 15 | 16,4 | 63 |
| Cause event other ATM's mean 1 | 46 | 16 | 17,8 | 92 |
| Mean's equipment failure 2 | 15 | 16 | 16,3 | 0 |
| Cause event other ATM's mean 2 | 7 | 16 | 17,5 | 71 |
| Cause event other ATM's mean 3 | 47 | 16 | 19,6 | 192 |
| Slow roads 1 | 1 | 18 | 18,3 | 14 |
| Slow roads 2 | 43 | 19 | 19,5 | 59 |

***Table 72***: *Events registered during the day, highlighting the ones defined as harmful during the risk-map analysis. Case study L14; 21/02/2013.*

- Mean failure (time span: 8 - 11,5)
- Mean failure (time span:12 - 15,2)

*Cause inefficiency time slot 12 and 9*

- Cause event other ATM's vehicle (time span: 16 – 17,5)
- Cause event other ATM's vehicle (time span: 16 – 17,5)
- Cause event other ATM's vehicle (time span: 16 – 19,5)

*Cause inefficiency time slot 19*

Even if the RiF (*regularity in frequency*) is not the objective function optimized by the disruption algorithm it is evaluated positively as KPI able to evaluate the quality of the service performed by the line (explained in detail in the *Model Specification*).

As it is possible to see in the graph presented in *figure 114* the moment of the day in which we have the worst performance is in the time span that goes from the 16th to the 22th time slot.

Furthermore we can see three meaningful deterioration in the 9th, 12th and in the 19th slot, this suggests that probably previously happened an event that successively degenerated.

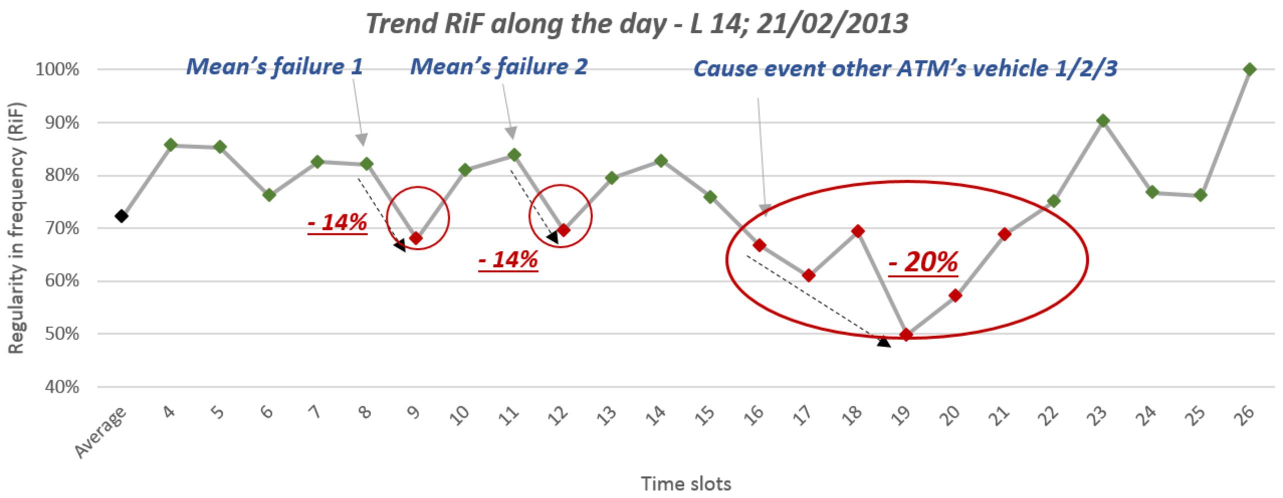



***Figure 115***: *Relation between the events occurred on the line and the quality of the service level. Case study L14; 21/02/2013.*

From *figure 115* it is possible to see the relation that there is between the RiF and the occurrence of one or more events that have been evaluated harmful in the risk-map analysis. When such an event occurs it is possible to notice a degradation of the line in the following hours (*problem is accentuated during the change shift hour → around 8th, 12th and 19th time slot*). It is possible to notice that in case of multiple harmful events in the same time slot the deterioration of the line service level is much more severe.

Similar analysis will be performed also on the other case studies identified during *chapter 4* – thesis methodology.

### Alert 2: "Generation of a group of «steps» that overtakes the set of identified thresholds."

Once computed all the ***steps*** generated on the line by the various couple of means along all the day the alert 2 is activated if:

- *In an hour more than the 70% of the steps recorded are higher than +/- 300 sec (5');*
- *In an hour at least the 10% of the steps are recorded are higher than +/- 600 sec (10');*
- *In an hour at least the 5% of the steps recorded are higher than +/- 900 sec(15').*

**Note:**

- ✓ For the validation phase we used historical data, but once we will have a functioning decision support system it will be feed with real time data.
- ✓ The case study tackled to demonstrate the process followed to validate this alert is focused on ***L 14 the 21/02/2013.***

Now we show the ***steps*** trend during the day highlighting where the alert it would have been activated if the DMSS had been operative (*see figure 116).*

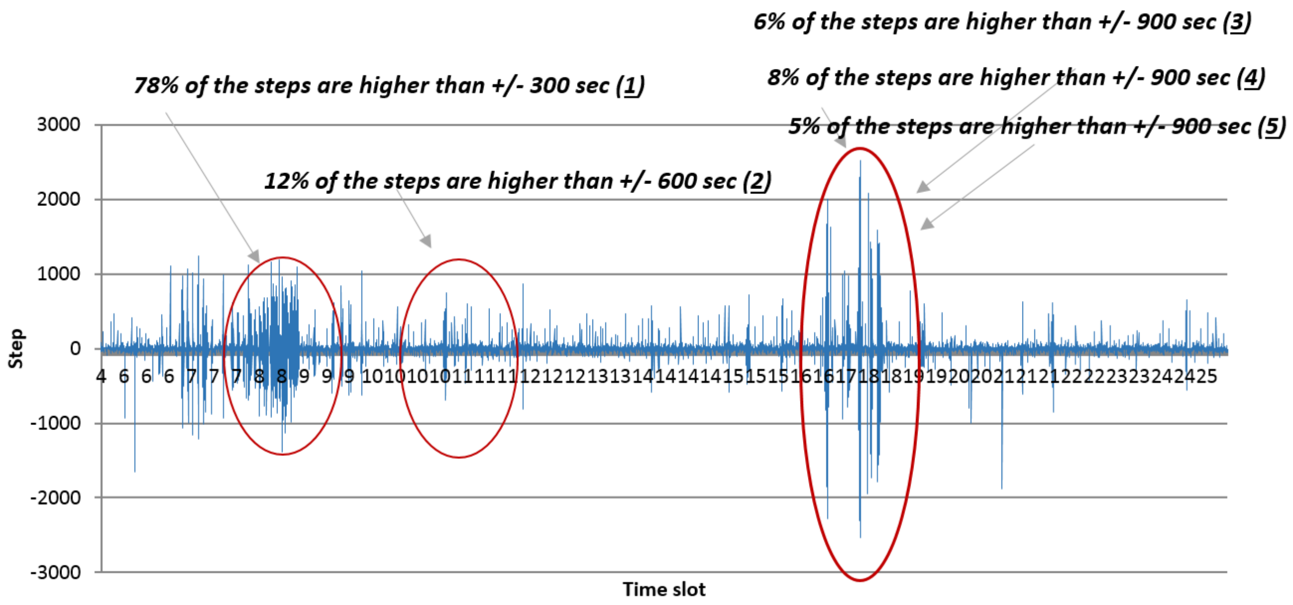



***Figure 116:*** *Steps trend highlighting the part of the day in which are overtaken the safety thresholds. Case study L14; 21/02/2013.*

1. *$8^{th}$ time slot: the 78% of the steps are higher than +/- 300 sec;*
2. *$10.5^{th}$ to $11.5^{th}$ time slot: the 12% of the steps are higher than +/- 600 sec;*
3. *$16^{th}$ time slot: the 6% of the steps are higher than +/- 900 sec;*
4. *$17^{th}$ time slot: the 8% of the steps are higher than +/- 900 sec;*
5. *$18^{th}$ time slot: the 5% of the steps are higher than +/-900 sec.*

At this point in order to validate the predictive capacity of the ***alert 2*** it is necessary to compare what found during the steps analysis (*figure 116*) with the ***hourly RiF trend*** during the day (*see figure 117*).

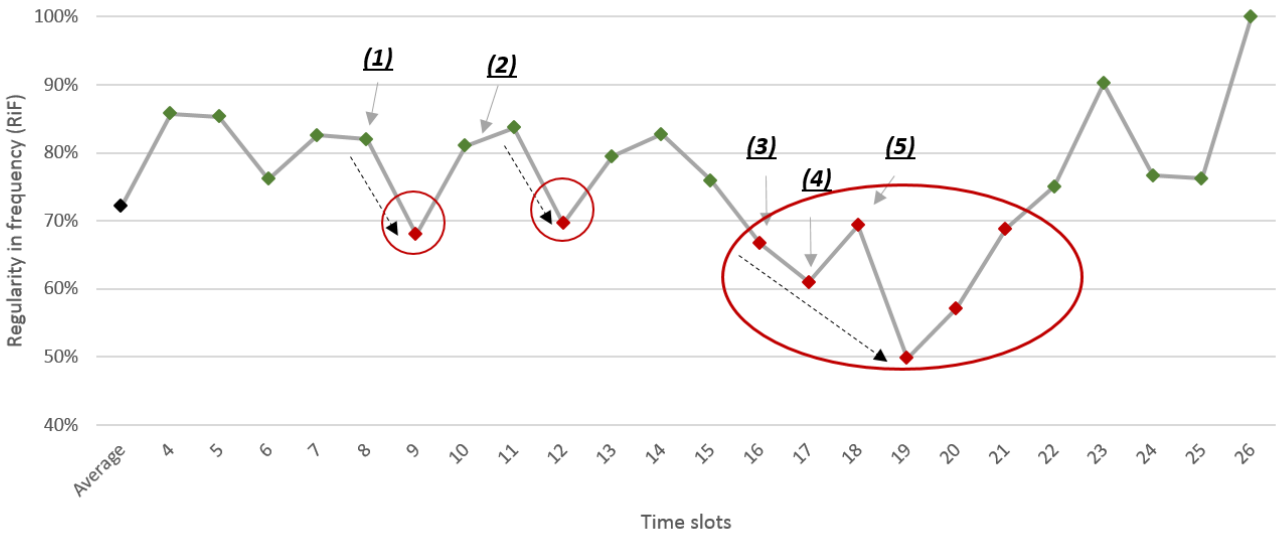


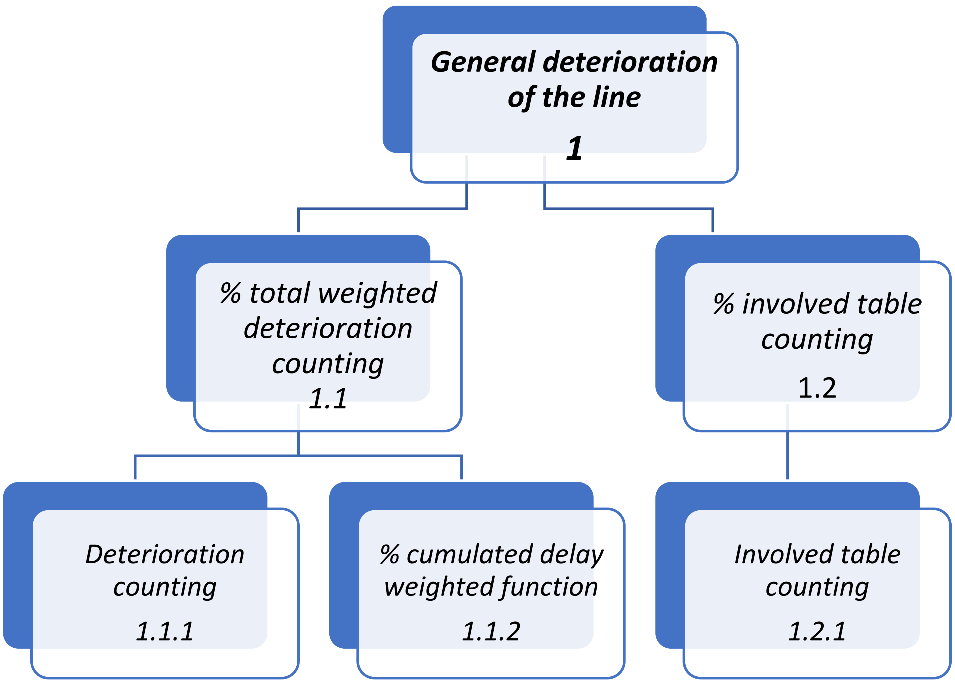

***Figure 117**: Relation between the step's threshold overtaken and the quality of the service level. Case study L14; 21/02/2013.*

From *figure 117* it is possible to see the relation that there is between the *RiF* trend and the overtaken of a step's safety threshold. When such a situation occurs on the line it is possible to notice a degradation of its performance in the following hours (*problem is accentuated during the change shift hour, → around $8^{th}$, $12^{th}$ and $19^{th}$ time slot*). It is possible to notice that in case of multiple threshold overtaken in time slots close one from the other the deterioration of the line is much more severe (see *figure 117*; episodes ***3***, ***4***, ***5*** lead to the big inefficiency of the day in the $17^{th}$ time slot *50%*)

The other case studies that will be performed to complete the validation of this alert will follow the same logics presented above.

### *Alert 3: "Increasing trend of "General deterioration of the line"*

Now we want to validate the variables, logics and assumptions that form the third alert ***"Increasing general deterioration of the line".*** Before to start developing the case study it is worth to recap the sub-indicators hierarchical structure that constitute ***General deterioration of the line***:




The concept of ***deterioration** is identified as the delay accumulation of a single mean for at least 5 consecutive stops*. From this concept derives the two sub-indicators *"% total weighted deterioration counting"* and *"% involved table counting"* that are in the end merged in *"General deterioration of the line ".*

The case study selected to perform the validation phase of this alert is focused on ***line 14 on the 21/02/2013***.

1. The ***first step*** to perform the validation of this alert is to compute the two sub-indicators "*% total weighted deterioration counting 1.1* " and " *% involved table counting 1.2*".

   a. ***Computation "% total weighted deterioration counting 1.1" (see table 74)***

Before to start with the computation of this sub-indicator we introduce the weighted function that will be used to weight the delays generated by different deterioration events (*we will weight differently a deterioration episode that generates in the end a delay of 3 minutes respect to one that generates 6 minutes of delay*). (*see table 73, figure 118*).

| *% cumulated delay* | *Weighted associated* |
|---|---|
| *0-74%* | *1* |
| *75%-84%* | *2* |
| *85%-94%* | *3* |
| *95%-98%* | *4* |
| *99%-100%* | *6* |

***Table 73****: Relation between* "% cumulated delay" *and* "weighted associated".

***Notes:***

- ✓ To have further information about this function check *chapter 5.2.1*.

*Figure 118* shows graphically the trend of the weighted function respect to the % cumulated delay.

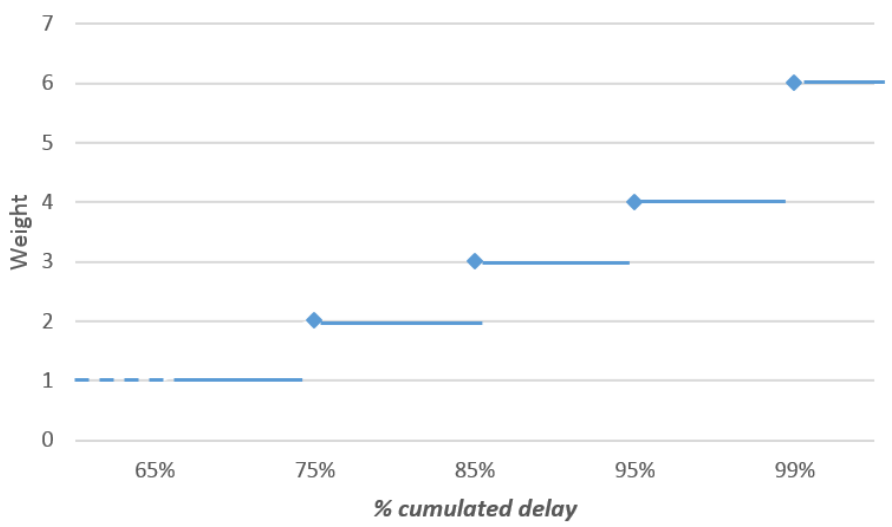



***Figure 118****: Graphical representation weighted function - % cumulated delay.*

| ***Weight*** | 1 | | 2 | | 3 | | 4 | | 6 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***% cumulated delay(x)*** | 0%<x<74% | | 74%<x>84% | | 85%<x<94% | | 95%<x<98% | | 99%<x<100% | | | |
| ***Time slot*** | ***Det. Cou.*** | ***Wei. Det. Cou.*** | ***Det. Cou.*** | ***Wei. Det. Cou.*** | ***Det. Cou.*** | ***Wei. Det. Cou.*** | ***Det. Cou.*** | ***Wei. Det. Cou.*** | ***Det. Cou.*** | ***Wei. Det. Cou.*** | ***Tot. wei Det. Cou.*** | ***%*** |
| ***5*** | 1 | 1 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | ***1%*** |
| ***6*** | 4 | 4 | 10 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 24 | ***4%*** |
| ***7*** | 8 | 8 | 2 | 4 | 3 | 9 | 0 | 0 | 0 | 0 | 21 | ***4%*** |
| ***8*** | 5 | 5 | 4 | 8 | 3 | 9 | 5 | 20 | 2 | 12 | 54 | ***9%*** |
| ***9*** | 8 | 8 | 2 | 4 | 3 | 9 | 0 | 0 | 0 | 0 | 21 | ***4%*** |
| ***10*** | 15 | 15 | 2 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | ***3%*** |
| ***11*** | 14 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14 | ***10%*** |
| ***12*** | 15 | 15 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | ***3%*** |
| ***13*** | 13 | 13 | 3 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | ***3%*** |
| ***14*** | 5 | 5 | 2 | 4 | 2 | 6 | 0 | 0 | 0 | 0 | 15 | ***3%*** |
| ***15*** | 15 | 15 | 2 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | ***3%*** |
| ***16*** | 14 | 14 | 4 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 22 | ***4%*** |
| ***17*** | 1 | 1 | 11 | 22 | 3 | 9 | 1 | 4 | 12 | 72 | 108 | ***18%*** |
| ***18*** | 2 | 2 | 0 | 0 | 2 | 6 | 0 | 0 | 5 | 30 | 38 | ***6%*** |
| ***19*** | 9 | 9 | 1 | 2 | 0 | 0 | 1 | 4 | 1 | 6 | 21 | ***4%*** |
| ***20*** | 12 | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | ***2%*** |
| ***21*** | 21 | 21 | 7 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 35 | ***6%*** |
| ***22*** | 17 | 17 | 9 | 18 | 0 | 0 | 0 | 0 | 0 | 0 | 35 | ***6%*** |
| ***23*** | 29 | 29 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 31 | ***5%*** |
| ***24*** | 11 | 11 | 3 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | ***3%*** |
| | | | | | | | | | | ***Total*** | 588 | |

***Figure 119****: Table "% total weight deterioration counting 1.1". Case study L 14; 21/02/2013.*

***Notes:***

- ✓ ***Det. Cou.*** : *Deterioration counting;*
- ✓ ***Wei. Deg. Cou.*** *: Weighted deterioration counting;*
- ✓ ***Tot. Wei. Det. Cou. :*** *Total weighted deterioration counting;*
- ✓ ***%*** : *% total weighted deterioration counting;*

### *b. Computation " % involved table counting 1.2"*

In this second part we compute how much the deterioration is spread on the line *(see table 74).*

| *Time slot* | *Involved table counting* | *% involved table counting* |
|---|---|---|
| ***5*** | 2 | ***1%*** |
| ***6*** | 6 | ***3%*** |
| ***7*** | 10 | ***5%*** |
| ***8*** | 15 | ***8%*** |
| ***9*** | 8 | ***4%*** |
| ***10*** | 10 | ***5%*** |
| ***11*** | 9 | ***5%*** |
| ***12*** | 10 | ***5%*** |
| ***13*** | 18 | ***10%*** |
| ***14*** | 5 | ***3%*** |
| ***15*** | 9 | ***5%*** |
| ***16*** | 28 | ***15%*** |
| ***17*** | 9 | ***5%*** |
| ***18*** | 6 | ***3%*** |
| ***19*** | 6 | ***3%*** |
| ***20*** | 6 | ***3%*** |
| ***21*** | 7 | ***4%*** |
| ***22*** | 7 | ***4%*** |
| ***23*** | 8 | ***4%*** |
| ***24*** | 4 | ***2%*** |
| *Total* | 183 | |

***Table 74****: Table "% involved table counting 1.2". Case study L 14; 21/02/2013.*

2. ***The second step*** consists in aggregate the values of the two sub indicators "*% total weighted deterioration counting 1.1*" and "*% involved table counting 1.2*" in the main indicator *"General deterioration of the line 1" (see table 75).*

| *Time slot* | *% total weighted deterioration counting 1.1* | *% involved table counting 1.2* | *General deterioration of the line 1* | *RiF* |
|---|---|---|---|---|
| ***5*** | 1% | 1% | 2% | 85% |
| ***6*** | 4% | 3% | 7% | 76% |
| ***7*** | 4% | 5% | 9% | 83% |
| ***8*** | 9% | 8% | 17% | 82% |
| ***9*** | 4% | 4% | 8% | 68% |
| ***10*** | 3% | 5% | 9% | 81% |
| ***11*** | 10% | 5% | 15% | 84% |
| ***12*** | 3% | 5% | 8% | 70% |
| ***13*** | 3% | 10% | 13% | 79% |
| ***14*** | 3% | 3% | 5% | 83% |
| ***15*** | 3% | 5% | 8% | 76% |
| ***16*** | 4% | 15% | 19% | 67% |
| ***17*** | 18% | 5% | 23% | 61% |
| ***18*** | 6% | 3% | 10% | 69% |
| ***19*** | 4% | 3% | 7% | 50% |
| ***20*** | 2% | 3% | 5% | 57% |
| ***21*** | 6% | 4% | 10% | 69% |
| ***22*** | 6% | 4% | 10% | 75% |
| ***23*** | 5% | 4% | 10% | 90% |
| ***24*** | 3% | 2% | 5% | 77% |

***Table 75****: Table "General deterioration of the line + hourly RiF". Case study L14; 21/02/2014.*

3. ***The third and last step*** is to verify if there is a relation between the trend of the indicator "*General deterioration of the line 1*" and the *"Rif"* trend . *Figure 6.2.8* shows the relation between the activation of alert 3 and the performance of the line along the day (expressed by RiF).

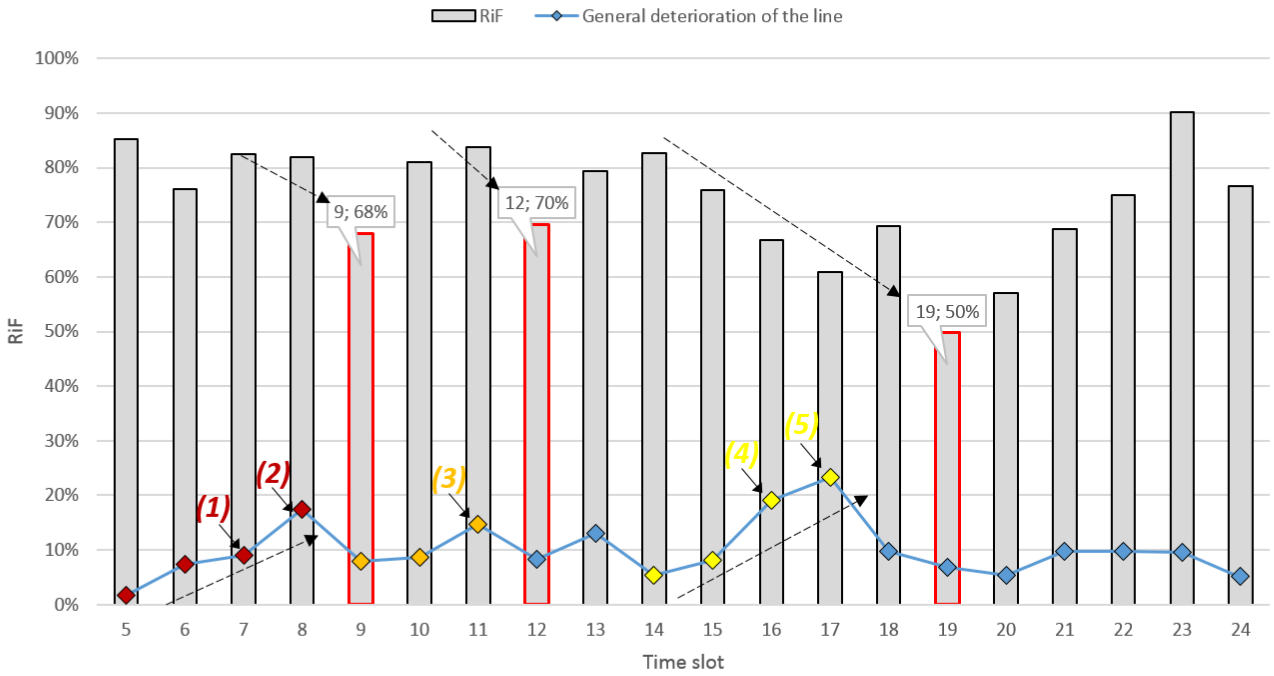



***Figure 120****: Relation between alert 3 activation and RiF hourly trend along the day.*

***Notes:***

- ✓ The numbers write in brackets represent the activation of alert 3, its activation follows the law presented under:

***Increasing trend GDL:*** $GDL\ t\ \ <> GDL\ t-1 <> GDL\ t-2 <> GDL\ t-3$

- o This symbol <> means that the relation between two element can be both of majority or minority;
- o The indicator activates the alert only and only if there are ***2/3 relation of majority.***

*Figure 120* shows the reliability of this alert. Another thing that it is possible to see from the chart is that more the function that represent the general deterioration on the line is steep worse is the forecasted inefficiency. Activation of alert 3 ***(4)*** and ***(5)*** predicts the high inefficiency of the 17$^{th}$ time slot. This analysis will be used as a guideline to conclude the validation of this alert using the case studies identified along *chapter 4*.

## 6.2.2 Algorithm

The last component we need to test is the algorithm. *Figure 121c*shows the main components of the algorithm, unfortunately in this first phase of the project the disruption management support system has been only created theoretically. All the components in terms of hardware and software will be operative for the beginning of the 2015. Due to this we were not able to validate the entire structure of the algorithm.

The part of the group coming from PoliMi (*operative research department*) created a simple simulator that works following the main logics on which the DMSS algorithm will be built (*Online combination approach*) and that tries to limit the short turning applied maximizing at the same time the service level of the line.

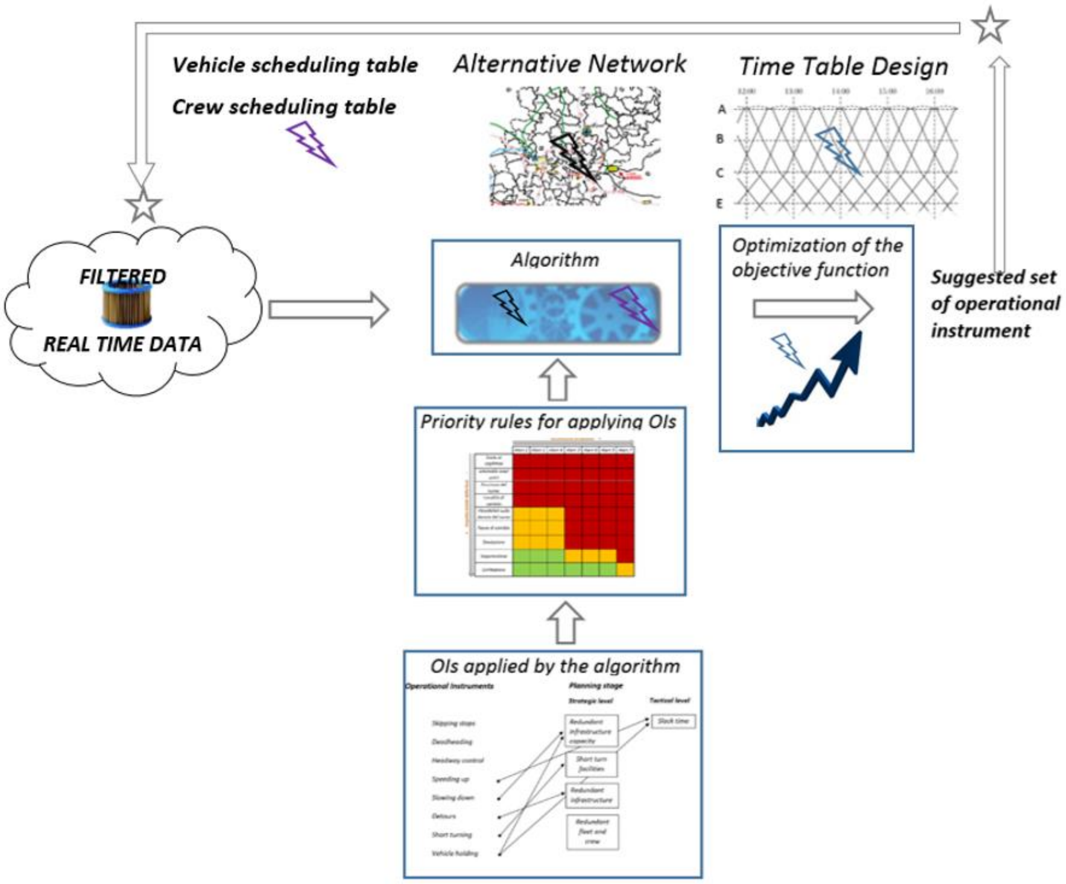



***Figure 121****: Algorithm side components.*

In order to assess the power of the algorithm we have analyzed a real case with the objective to study the development of the service along a determined time span. We have compared the action chosen by the operative room with the one that the algorithm would have suggested. The case study is related to ***line 37 on the 11/11/2011***. The DMSS team created a simulator that reproduces the actual service offered during the period of analysis and the scheduled one, and it permits to compare the trend of the two (*see figure 122*).

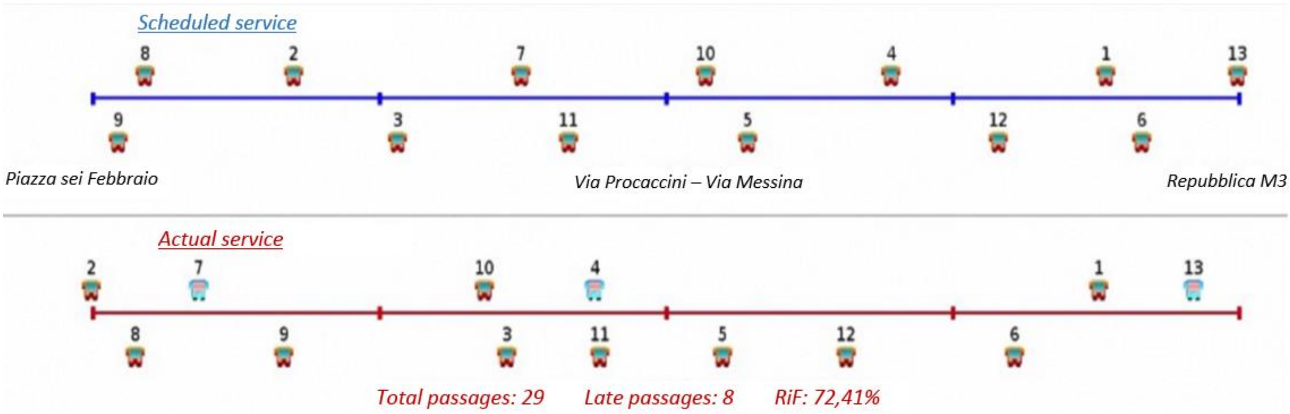



***Figure 122****: Comparison between the scheduled and the actual service. Line 37 hour 8:57 a.m.* ***;*** *11/11/2011.*

It is easy to notice that the scheduled service (along the *blue line*) has means perfectly, or almost, equidistant, while the one performed (along the *red line*) has lost part of the regularity (lower service level). In the instant considered in *figure 122* three means are not producing correct passages. Precisely the three means are the *7, 4* and *13* that are drawn in *light blue*. During the morning the situation evolves continuously, as shown in the following example (*figure 123*).

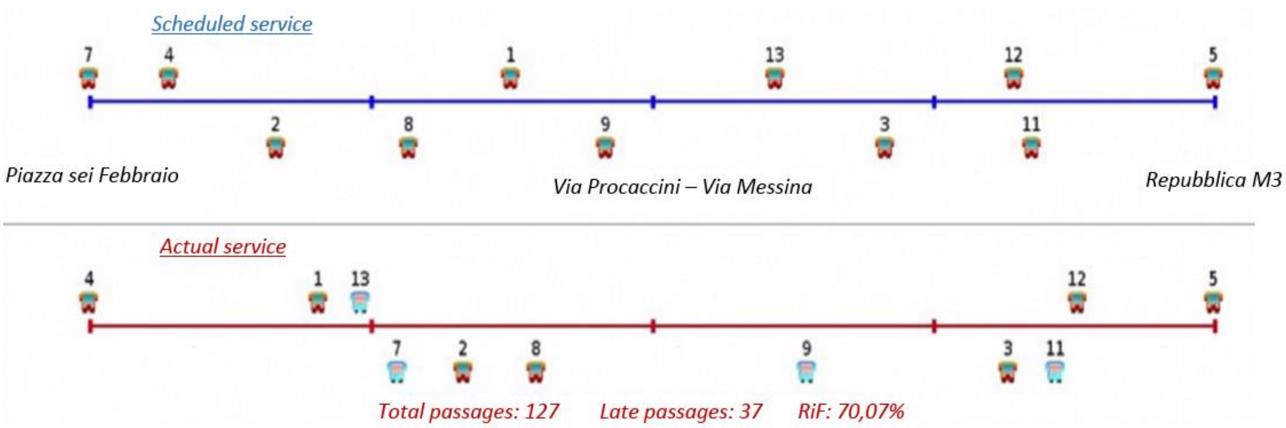



***Figure 123****: Comparison between scheduled and actual service. Line 37 hour 10:01 a.m.****;*** *11/11/2011.*

The means that are out of regularity are now four (*13,17,9,11*) with the *mean 3* that is moving out of the line ahead the number *11* to reduce an excessive time between two other means (*short turning*). The simulation considers also all the intervention made by the operators to keep the regularity of the line hence improve the service level offered to passengers. The operators implemented *8 interventions* in the period that goes from the 7:00 a.m. to thee 3 p.m. (8 short turning). Now it is worth to see and compare how it would be the RiF considering the three different scenarios listed under:

1. *67.9% without any intervention*;
2. *72.4% with the 8 interventions implemented by the control room's operator*;
3. *82.1% optimal result obtained with 5 interventions*.

The result is that the RiF would be higher if the operators would have acted in a different way.

The kind of short turnings that are possible to perform on the line 37 are presented in *table 76.* What presented in the table are also the alternative short turning maneuvers provided to the simulator system (*it is based on DMSS algorithm's logics*).

| ***Short turn beginning*** | ***Short turn finishing*** | ***Route*** | ***t Route*** | ***Stop possibility*** |
|---|---|---|---|---|
| ***1 Kind***<br>10962 - Domodossola direction P.za sei Febbraio | 16695 -Domodossola direction P.za Repubblica | C.so Sempione change direction in via Arona, c.so Sempione, Domodossola | 3' | ***NO*** |
| ***2 Kind***<br>11284 - C.so Sempione/via Procaccini direction P.za sei Febbraio | 11296 - Via Procaccini/via Lomazzo direction P.za Repubblica | C.so Sempione, Via Poliziaano, via Piero della Francesca, via Procaccini/via Lomazzo | 4' | ***NO*** |
| ***3 Kind***<br>15665 - via Procaccini/via Nono direction P.za Repubblica | 11306 - via Procaccini/via Lomazzo direction P.za Repubblica | Reversing in P.le Cim. Monumentale | 2' | ***YES*** |
| ***4 Kind***<br>11306 - P.le Cim. Monumentale direction P.za sei Febbraio | 11579 - P.le Cim. Monumentale direction P.za Repubblica | Reversing in P.le Cim. Monumentale | 2' | ***YES*** |

***Table 76****: Alternative network of the line 37, with possible short turning.*

In order to be more clear we report also two maps with the possible short turning maneuvers (*figure 124, figure 125*). They represent line 37 and its stops in the two different directions (P.za Repubblica → P.za sei Febbraio; P.za sei Febbraio → P.za Repubblica).

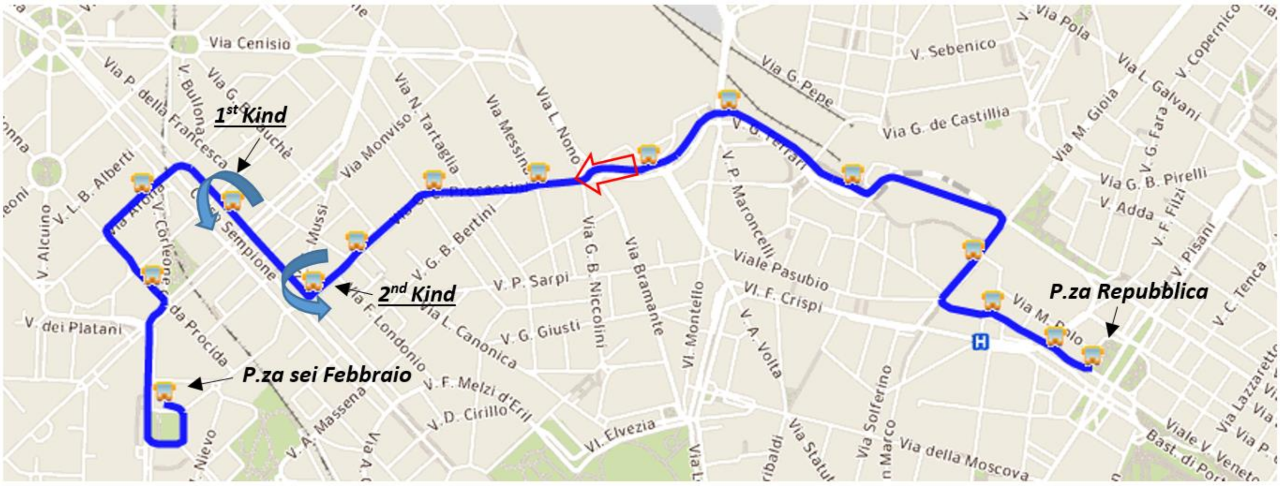



***Figure 124****: Line 37 direction from P.za Repubblica to P.za sei Febbraio with alternative network possibilities (short turning maneuvers).*

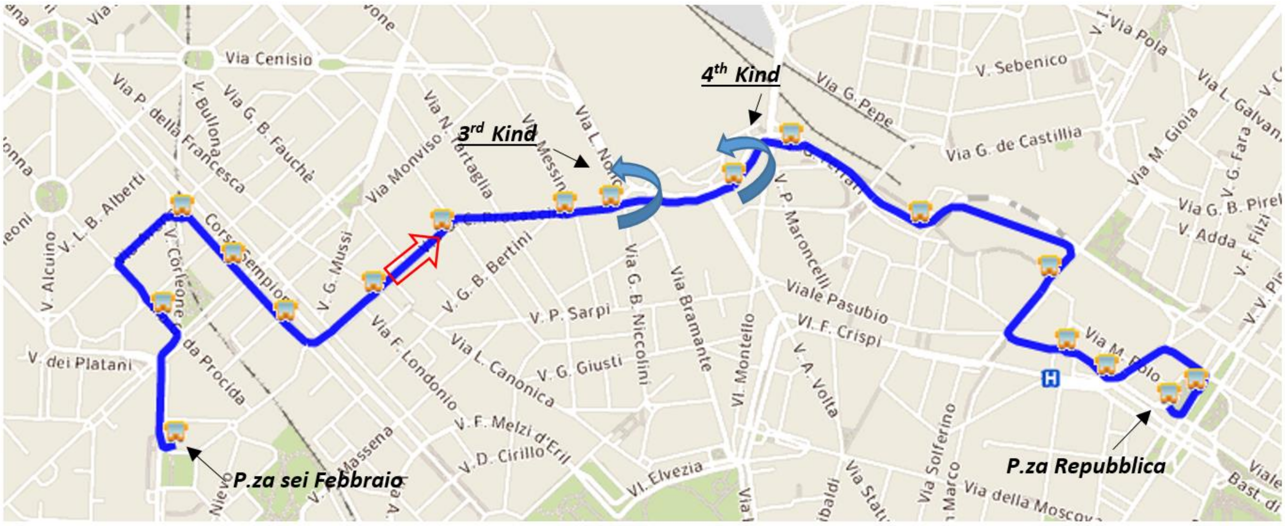



***Figure 125****: Line 37 direction from P.za sei Febbraio to P.za Repubblica with alternative network possibilities. (short turning maneuvers).*

With the objective to continue the analysis on line 37, we introduce another parameter that can give a better idea on how the application of the algorithm could bring benefits in increasing of service reliability of the line: *Average waiting time (AWT)* (*That is what optimized by the algorithm objective function).* As for the the *RiF* that is the indicator that we have used up to now for the validation it measures the delta between the scheduled frequency and the actual one. Instead of counting the number of times that this delta overtakes a certain threshold (as done by the ATM'S indicator), it computes the average. This indicators expresses in easy and understandable way what computed by the PRDM (*Percentage regularity deviation mean ;that is the algorithm objective function*). The best solution find by the algorithm to improve line 37 service level and consequently decrease the AWT is obtained with 5 interventions:

1. *Mean 3 hour 9:34:23 KIND 1 intervention;*
2. *Mean 1 hour 9:59:51 KIND 4 intervention;*
3. *Mean 7 hour 10:23:06 KIND 1 intervention;*
4. *Mean12 time 11:54:51 KIND 4 intervention:*
5. *Mean 4 time 14:27:14 KIND 4 intervention:*

Now it is worth to compare the AWT obtained (*figure 126, figure 127*) in the three different possible cases:

1. Without any kind of intervention *(No intervention);*
2. With the intervention done by the operative room *(Control room interventions-current state);*
3. With the intervention suggested by the algorithm *(Algorithm intervention).*

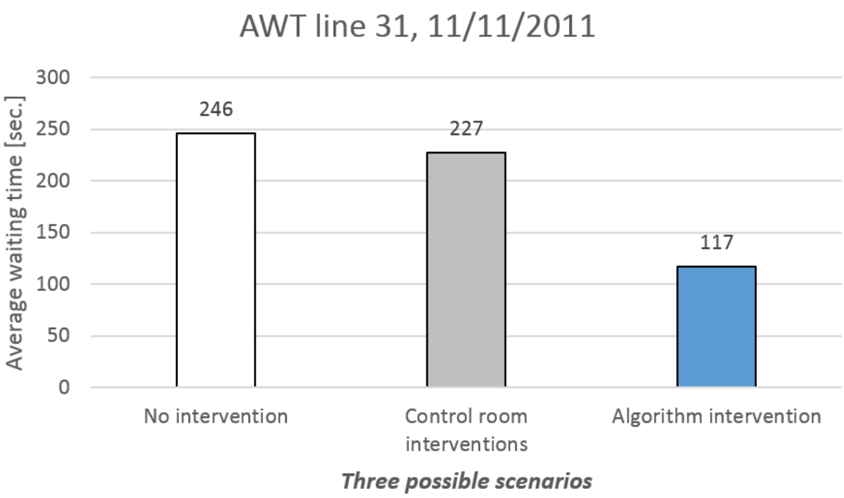



***Figure 126***: *Different AWT according to the different scenario considered. Case study L 37; 21/11/2011.*

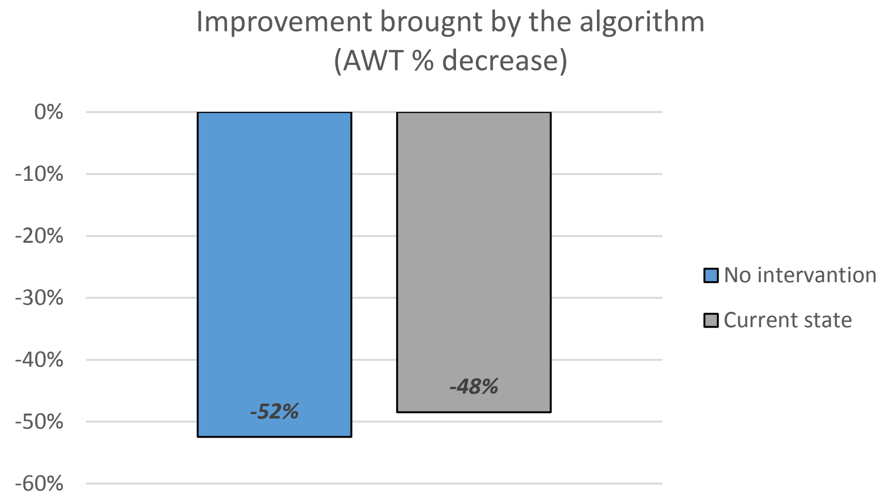



***Figure 127****: Different AWT % decrement comparing different scenarios. Case study L 37; 21/11/2011.*

Now it is possible to do some conclusion related to the case study just presented:

Also if the simulator at disposition to verify the case study is very simplistic because it uses only a minimal part of the logics and of the operational instruments that have been created to make the DMSS a powerful instrument the results obtained from this case study are impressive. ***It can improve the service level of the line of the 48% respect to actual operator's capability***.

These results rise our hopes, because the fact that many instruments have not been used let us thinking that there is stillroom for improvement respect to what obtained here.

*What obtained during the simulation phase shows how to carry out and complete the validation of all the logics, assumptions and variables that form the DMSS' components. Since this is the first phase, a prototype of the system will be ready for the beginning of 2015, we cannot validate the functioning of the entire decision support system yet. The prototype will be built using the logics showed along this thesis; once ready it will be possible to perform further analysis on them in order to validate and calibrate the entire system as a unique element.*

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