BDC

Università degli Studi di Napoli Federico II

14

numero 2 anno 2014

BDC

Università degli Studi di Napoli Federico II

14

numero 2 anno 2014

Towards an Inclusive, Safe, Resilient and Sustainable City: Approaches and Tools

BDC

Università degli Studi di Napoli Federico II

Via Toledo, 402
80134 Napoli
tel. + 39 081 2538659
fax + 39 081 2538649
e-mail info.bdc@unina.it
www.bdc.unina.it

Direttore responsabile: Luigi Fusco Girard
BDC - Bollettino del Centro Calza Bini - Università degli Studi di Napoli Federico II
Registrazione: Cancelleria del Tribunale di Napoli, n. 5144, 06.09.2000
BDC è pubblicato da FedOAPress (Federico II Open Access Press) e realizzato con Open Journal System

Print ISSN 1121-2918, electronic ISSN 2284-4732

Indice/Index

TECHNOLOGICAL SOLUTIONS AIMING AT RECOVERING METRO BRAKING ENERGY: A MULTI-CRITERIA ANALYSIS CASE STUDY

Annalia Bernardini, Ricardo Barrero, Cathy Macharis, Joeri Van Mierlo

Abstract

The transport sector, being responsible for a large share of fossil fuels consumption and emissions, mainly CO_2, is seeking for different ways of reducing their energy consumption and, especially, their dependency on fossil fuels. The purpose of this paper is to present the Multi-Criteria Analysis (MCA) of technological solutions recovering metro braking energy. The MCA PROMETHEE method endorsed to select the most suitable technological solution for the tram and metro network in Brussels. The MCA approach allowed to firstly evaluate the different technologies and afterwards to propose an individual decision to the public transport decision-maker based on the decision problem objectives and the MCA results.

Keywords: public transport, metro braking energy, PROMETHEE

SOLUZIONI TECNOLOGICHE PER IL RECUPERO DELL'ENERGIA CINETICA DI FRENATA: UN CASO-STUDIO DI ANALISI MULTICRITERIO

Sommario

Il settore dei trasporti, responsabile di un'ampia quota delle emissioni di gas serra di origine antropogenica (in particolare CO_2) e dell'utilizzo di combustibili fossili, sta individuando alternative per ridurre i consumi energetici e, soprattutto, la dipendenza dai combustibili fossili. Lo scopo di questa ricerca è di presentare un'Analisi Multi Criterio (AMC) per identificare la soluzione tecnologica che permetta di ridurre il consumo energetico, recuperando l'energia cinetica di frenata prodotta dai trasporti urbani. Tra le diverse metodologie MCA, si è scelto il metodo PROMETHEE al fine di individuare la soluzione tecnologica più efficiente da utilizzare per la rete tramviaria e metropolitana della città di Bruxelles. L'approccio AMC ha permesso di valutare in primo luogo le diverse tecnologie e, quindi, di proporre all'ente responsabile del trasporto pubblico una decisione univoca basata sugli obiettivi prescelti per il problema decisionale ed i risultati ottenuti dall'AMC.

Parole chiave: trasporto pubblico, energia cinetica di frenata, PROMETHEE

1. Introduction

In urban areas, where population density is very high and emissions present a higher risk to human health, electric powered vehicles such as trams, metros and trolley buses have already been in use for many years. These vehicles do not produce local emissions and are already efficient due to their low friction (rail vehicles) and to regenerative braking technologies that allow energy exchange among vehicles. Nevertheless, the efficiency of this system can be improved with the inclusion of energy recovery systems that capture the vehicles braking energy that could not be re-used.

When vehicles decelerate, usually an important amount of kinetic energy is lost in heat and dissipated in braking resistors. Power recovery techniques can be exploited to temporarily store this energy and use it for future accelerations or send it back to the electricity grid. Most of light rail vehicles in use of Direct Current (DC) networks nowadays are able to convert the vehicle kinetic energy into electrical energy during the braking phases of their driving cycles thanks to the dynamic braking technology, which uses the electric motor as a generator in order to stop the vehicle. One of the advantages of this system is that it avoids friction between the traditional braking pad and the wheels, reducing, thus, the wear of the braking components. In conventional DC networks, fed by irreversible rectifier substations, the braking vehicles attempt to send this energy back to the supply line. If the line is forming a hybrid train or it can be placed out of the train, connected to some part of the supply line. In this latter case, the RESS is known as wayside or stationary RESS (Rufer *et al.* 2004; Foiadelli *et al.* 2006). In both cases, several technologies could be used: batteries, Electric Double Layer Capacitors (EDLCs), flywheels, etc.

The last option is to retrofit the irreversible substation with an inverter so that they become reversible (Chuang *et al.* 2005; Han receptive at this moment, this energy will be re-used by other vehicles nearby, but if this is not the case, the vehicle voltage will increase until the maximum braking voltage is reached and this energy will be deviated to the braking resistors in the vehicle and dissipated as heat. This energy, dissipated in the braking resistors, will be the aim of different energy recovery technologies. There are several ways to re-use this energy: One of them consists in synchronizing the vehicles in such a way that when a vehicle brakes, another nearby one accelerates using that energy. This requires a very good control of the vehicles schedules and the automatization of the line and it can be altered by delays. Another option is the Rechargeable Energy Storage System (RESS) technology (also used in road hybrid vehicles) that would temporarily store this braking energy until it is needed again by the same or another vehicle. In the case of the light rail vehicles, the RESS can be installed on the vehicle (Destraz *et al.*, 2007; Hillmansen and Roberts, 2007; Allegre *et al.*, 2010) itself, Bae 2009; Cornic 2010). In this case, the energy is sent back to the network so that it can be used by any other consumer (if the transport operator owns the high voltage network, this energy could go to lighting, computers, escalators, air conditioning, other substations, etc.). This is a good solution if the transport operator is the owner of the high voltage network or if the electricity distributor is willing to buy this energy from the transport authority. These technologies have some advantages and disadvantages when compared to each other (Barrero, 2012).

The purpose of this paper is to present the Multi-Criteria Analysis of the technological energy recovery solutions, principally: EDLCs (also known commercially as supercapacitors or ultracapacitors), Flywheels and Reversible Substations, aiming at recovering metro braking energy for the public transport operator. In section two of this paper the applied methodology for the evaluation task is introduced, section three presents the stepwise procedure of the MCA and section 4 summarize the conclusions.

2. The Multi-Criteria Analysis application

MCA is increasingly used for decision-making in environmental policy evaluation due to the complexity of issues and the inadequacies of conventional tools such as the mono-criterion Cost-Benefit Analysis (CBA) used to compare the costs and benefits of the evaluated options in order to determine its economic "efficiency". The MCA allows to capture the full range of the decision problem impacts. The objectives (criteria) and preferences of the decision-maker(s) are considered in order to assess the different options (alternatives). MCA methods can conglomerate simultaneously in the decision-making support process qualitative and quantitative objectives. In the case of a sustainable MCA decision problem all the environmental and socio-economic objectives englobed in the decision problem can be considered. For a MCA evaluation the best compromise solution(s) should emerge (Brans, 2004; Munda, 2004; Figueira *et al.*, 2005; Hayez, *et al.* 2011; Roy and Słowiński, 2013).

3. MCA method: PROMETHEE

MCA techniques can be used to identify a single most preferred option, to rank options, to short-list a limited number of options for subsequent detailed appraisal, or simply to distinguish acceptable from unacceptable possibilities. The main role of these techniques is to deal with the difficulties that human decision-makers have in handling large amounts of complex information in a consistent way. Typically, most decision problems have a multi criteria nature and refer to several concerns at the same time: technological, economical, environmental, social etc. As there is no alternative optimizing all the criteria at the same time, a compromise solution should be selected.

The MCA Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) developed by Brans (1982), further extended by Brans and Vincke (1985), Brans and Mareschal (1994), Macharis *et al.* (1998), Figueira *et al.* (2004), Brans and Mareschal (2005) has been used for this study. The PROMETHEE method has been applied successfully in several domains covering topics such as environment, hydrology and water management, business and financial management, chemistry, logistics and transportation, energy management, etc. (Behzadian *et al.*, 2010). The choice of this method was mainly made regarding its simplicity and its capacity to approximate the way human mind expresses and synthesizes preferences in front of multiple contradictory decision perspectives (Diakoulaki and Karangelis, 2007).

A typical MCA procedure consists of several steps:

1. identification of the problem and selection of the alternatives (STEP 1);
2. translation of the objectives (concerns) into several criteria (STEP 2);
3. quantification of the relative importance of each criterion (weights) (STEP 3);
4. assessment of the performance of each alternative to the identified criteria (STEP 4) and the following categorisation. Tab. 1 presents the overall performance matrix, where the aggregation of each alternative contribution to the objectives is shown. Where a_1 to an represent the potential alternatives submitted for evaluation and where f_1 to f_j are the evaluation criteria;
5. sensitivity analysis (STEP 5).

Regarding the starting step of constructing the performance matrix, there is on one side a finite set (a set that has a finite amount of components) ***A*** and on the other side a coherent set of evaluation criteria ***F***. The family of criteria must be comprehensible (usually $n \geq 2$ and $n = 7 \pm 2$) and each criterion reflects the decision-maker preferences. ***F*** needs to satisfy three axioms. All theories are based on axioms. The simpler and fewer the axioms, the more general and applicable the theory (Forman and Gass, 2001). Correspondingly ***F*** should be sufficient to compare any two alternatives $(a, b) \in \boldsymbol{A}$ without loss of meaning, if this axiom is verified, two alternatives with the same vector performance are necessarily indifferent. It must be a minimal consistency between preferences on each criterion and the overall preferences. If *a* is preferred to b on each criterion of ***F***, then *a* should be globally preferred to *b*. Deleting a criterion of ***F*** leads to a questioning of the previous two axioms' (Meyer, 2005).

$\boldsymbol{A} = \{a_1, a_2, \ldots., a_i, \ldots, a_n\}$

$\boldsymbol{F} = \{f_1, f_2, \ldots., f_i, \ldots, f_j\}$

Table 1 – Performance matrix

	$\boldsymbol{f_1}$	$\boldsymbol{f_2}$	$\boldsymbol{f_3}$	**…**	$\boldsymbol{f_j}$
$\boldsymbol{a_1}$	$f_1(a_1)$	$f_2(a_1)$	$f_3(a_1)$	…	$f_j(a_1)$
$\boldsymbol{a_2}$	$f_1(a_2)$	$f_2(a_2)$	$f_3(a_2)$	…	$f_j(a_2)$
$\boldsymbol{a_3}$	$f_1(a_3)$	$f_2(a_3)$	$f_3(a_3)$	…	$f_j(a_3)$
…	…	…	…	…	…
$\boldsymbol{a_n}$	$f_1(a_n)$	$f_2(a_n)$	$f_3(a_n)$	…	$f_j(a_n)$

The advantage of using PROMETHEE here with respect to other MCA methods is that in the end it provides an overall ranking of the different alternatives with respectively positive and negative outranking flows expressing how an alternative is outranking or outranked by the other alternatives submitted for evaluation.

The use of the PROMETHEE method requires also additional information. First, a specific preference function needs to be defined ($P_j(a,b)$) that translates the deviation between the evaluations of two alternatives (a and b) on a particular criterion (f_j) into a preference degree ranging from 0 to 1. This preference index is a non-decreasing function of the observed deviation (*d*) between the scores of the alternatives on the considered criterion ($f_j(a)$-$f_j(b)$), as shown in Formula 1. In order to facilitate the selection of a specific preference function, six possible shapes of preference functions are proposed to the decision-maker by Brans *et al.* (1986) (Usual shape, U-shape function, V-shape function, level function, Linear function and Gaussian function) (Turcksin *et al.*, 2011). According to Brans and Mareschal (2005) these six shapes have been satisfactory in most real-world applications. Nevertheless new preference functions could always be projected.

$$P_j(a,b) = G_j\left\{f_j(a) - f_j(b)\right\} \quad (1)$$

Another preference parameter is the calculated or direct valued weight score for each criterion. It is the task of the analyst together with the decision-maker to try to come as close as possible to the "most appropriate value weight" of each criterion. Corresponding to the weights reflects a major part of the "brain" of the decision-maker (Mareschal, 2013).

In agreement with Mareschal (2013), the set of weights $\boldsymbol{W}$ $\{w_j, j = 1, 2,\ldots.k\}$ in PROMETHEE need furthermore to respect the following features: they should be non-negative numbers, independent from the measurement units of the criteria and the higher the weight, the more important is the criterion. Normed weights can be considered (formula 2). Several PROMETHEE software allows performing this normalization routinely adding arbitrary numbers that are then divided by their sum (Brans and Mareschal, 2005).

$$\sum_{j=1}^{k} w_j = 1 \quad (2)$$

With regard to the representation of the latters, several variations of the PROMETHEE method exist: (1) PROMETHEE I partial ranking, where both the positive and negative outranking flows are presented. The positive preference flow $\phi+(a)$ measures how much an action a is outranking the other n-1 ones. It is a global measurement of the strengths of action a. The larger ϕ+(a) the better the action. It is its power, its outranking character. The higher the flow is the better the alternative. The negative preference flow $\phi-(a)$ measures how much the other n-1 actions are preferred to action a (how alternative a is outranked). It is a global measurement of the weaknesses of action a. Its outranking character. The smaller ϕ-(a) the better the action. In PORMETHEE I all the actions are not necessarily compared and that the ranking can include incomparability's (Mareschal, 2013). In PROMETHEE II complete ranking, where a net outranking flow is presented based on the balance between the positive and negative outranking flows, the net preference flow $\phi(a)$ is the balance between the positive and negative preference flows:

$$\phi(a) = \phi+(a) - \phi-(a) \quad (3)$$

It thus takes into account and aggregates both the strengths and the weaknesses of the action into a single score. $\phi(a)$ can be positive or negative. The larger $\phi(a)$ the better the action (Mareschal, 2013). The global net flow of an alternative is the scalar product between the vector of the weights and the profile vector of this alternative. This property is furthermore extended in the GAIA (Geometrical Analysis for Interactive Aid) plane, which provides a graphical representation of the position of the alternatives relative to the various criteria.

A disadvantage of using PROMETHEE is that it does not provide a specific method according to which the weights are to be determined (Macharis *et al.*, 2004). But in this case this can be solved by the direct involvement of the decision-makers (as for the MCA) and their assignment of the weights.

The PROMETHEE method is one of the most intuitive and user-friendly MCA methods. This approach allowed an improved and clear gathering of the Brussels public transportation company experts pro/cons experts about the different braking energy recovery technologies (alternatives). A first step was to evaluate the effectiveness of those

alternatives on each criterion. The criteria were grouped into the following main groups: performance, implementation, reliability/maintenance and the environmental aspects.
The out coming categorisation was noticeably influenced by the established weights attributed to each criterion. Thanks to the flexibility of the MCA it is possible to measure the stability of this ranking through a sensitivity analysis for each field to see if the result significantly changes when the weights are changed, which is useful when the decision-maker has not established too rigidly weights. Furthermore preference scales and/or other characteristics were defined in straight collaboration between the decision-makers and the MCA analysts.

4. MCA software: D-Sight

D-Sight is a decision support software that helps decision-makers find the best solution to their Multi-Criteria Analysis problems. It allows them to conduct a deep but simple evaluation process. The software offers a pre-defined framework in order to structure the decision problem. The alternatives and the criteria can be simply defined. Those criteria can be gathered in different groups organized in a hierarchy tree reflecting the importance of its elements. D-Sight relies on two methodologies. The first one is PROMETHEE that is based on pairwise comparisons in order to process the alternatives evaluations. It is enhanced by its GAIA extension that offers a visual representation of the results. The second methodology is based on the Multi-Attribute Utility Theory (MAUT) that allows the decision-makers to define so-called utility functions which are used to score the alternatives on a specific basis.
Different visual tools are proposed to the decision-makers and present various aspects of the problem such as the ranking, the profiles of the alternatives (the way it is scored on all the criteria), the possible links existing among the criteria, etc. All those tools are meant to provide the decision-makers with an easy way to understand the nature of the results. It consents improving possible interactive discussion(s) of the involved stakeholders in the decision process.
D-Sight allows performing sensitivity analysis on the final results. Indeed, the software does not only provide the decision-makers with a ranking of their options, but it also offers the possibility to assess the robustness of the solution. For instance, D-Sight enables users to know in which intervals each (criterion) weight could be modified without affecting the final choice. This gives an indicator of the reliability of the solution.

5. MCA process

Step 1: Defining the problem and the alternatives

Rail vehicles have the ability to regenerate their kinetic energy into electrical energy during braking. A small portion of this regenerated energy can be reused to power vehicles auxiliaries, the remaining energy being sent back on the network to another vehicle accelerating nearby. In conventional networks, if no vehicle is located nearby, the network voltage increases due to the energy surplus and this extra energy has to be dissipated in braking resistors (Fig. 1 and Fig. 2). To avoid such energy losses, manufacturers are putting energy recovery solutions on the market, both on-board and stationary, and this for various goals: to reduce the overall energy consumption; to decrease the emissions associated to the energy generation; to stabilize the network voltage by limiting the voltage drops; to benefit from better electricity tariffs derived from lower power levels; to allow catenary-free operations on short distances (only for on board options). The arrows in Fig. 1 point the direction of the energy flow. When the vehicle is in traction mode, the energy comes from the catenary, passes through the drivetrain to yield a torque at the wheels. This torque is used to overcome the forces acting on the vehicle and produce movement. The same energy flow direction is indicated on Fig. 2 with the arrows. The kinetic energy of the vehicle is transformed in electrical energy thanks to the electric motor acting as a generator. The energy goes from the wheels to the catenary or the braking resistors. If the network is receptive, this energy will go to the other vehicle, to an energy storage technology or will be fed back to the AC supply thanks to the reversible substation. If the network is not receptive, the energy will be dissipated in the braking resistors.

Fig. 1 – Schematic of conventional train in traction mode

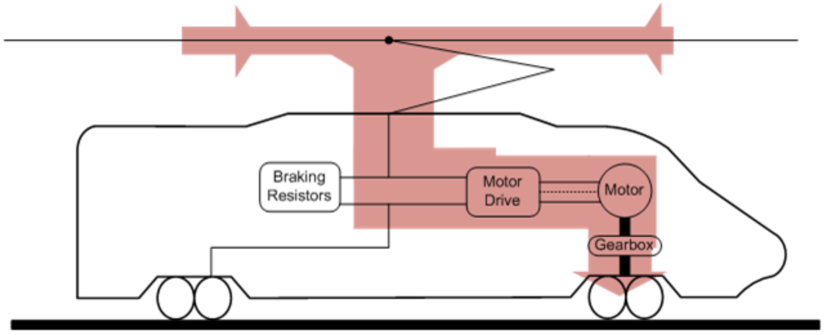
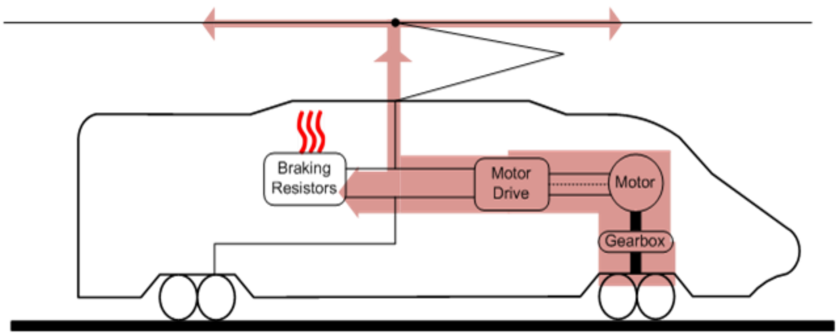


Fig. 2 – Schematic of conventional train in braking mode



In this study we focused on three energy saving methods. These three alternatives will be explained briefly in the following section.

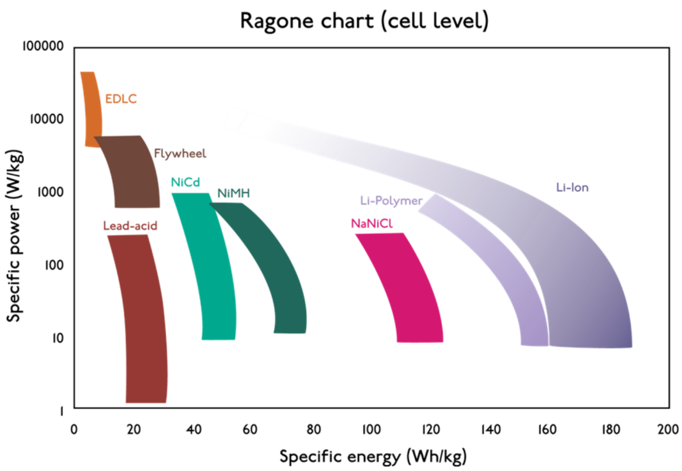
Braking energy recovery
When vehicles decelerate, usually an important amount of kinetic energy is lost in heat and dissipated in braking resistors. Power recovery techniques can be exploited to temporarily

store this energy and use it for future accelerations or send it back to the electricity grid.
During the research context the public transport operator in Brussels invested in pilot installations to be put on the metro networks, on board or alongside the tracks. If the results turn out to be positive, these energy storage/recovery systems will be implemented on a broader scale, larger than the project itself.
The energy recovery technologies in DC fed rail networks can be divided in two groups:

- the first group uses Rechargeable Energy Storage Systems (RESS) to store the braking energy that will be used later. The RESS can be installed on the vehicle itself, forming a hybrid train or it can be placed out of the train, connected to some part of the supply line. In this latter case, the RESS is known as wayside or stationary RESS. In both cases, several technologies could be used: batteries, EDLCs, flywheels, etc.;
- the second group consists in sending the braking energy back to the mains electricity supply so that it can be used by any other consumer (if the transport operator owns the high voltage network, this energy could go to lighting, computers, escalators, air conditioning, other traction substations, etc.). This is a good solution if the transport operator is the owner of the high voltage network or if the electricity distributor is willing to buy this energy from the transport authority. To achieve this, reversible substations are needed.

One way to classify the different RESS technologies, and particularly interesting for portable applications, is to compare their power and energy densities, as shown by the Ragone plot in Fig. 3, where EDLCs (supercapacitors) are positioned against batteries and flywheels.

Fig. 3 – Ragone diagram (cell level). Adapted from Van Den Bossche (2009)



It is observed that EDLCs have a high power and low energy densities density in comparison to that of batteries. Flywheels have similar power density to EDLCs and are reported to benefit from higher energy densities (Vazquez *et al.*, 2010; Lukic *et al.*, 2008).

In the context of this MCA study, the following three main braking energy recovery technologies have been evaluated:

- supercapacitor based stationary RESS;
- flywheel based stationary RESS;
- reversible Substations.

These three solutions will be described more in detail in the following section.

Electric Double Layer Capacitors (Supercapacitors)

EDLCs are electrostatic storage devices that operate like large versions of common electrical capacitors where energy is stored in an electrostatic field by means of charge separation. In contrast to batteries that are charged and discharged through an internal chemical reaction, in a supercapacitor, the energy is stored as a charge or concentration of electrons on the surface of a material (NREL, 2008) and no chemical reaction occurs.

Supercapacitors bridge the gap between conventional capacitors and batteries. They have an energy density 10 to 100 times higher than conventional capacitors and a power density around 10 times higher power than most batteries of equivalent size. The main benefits of supercapacitors based ESS are a high efficiency, high peak powers and long lifetime (around one million cycles) when compared to batteries. The drawback is the low energy capacity. However, due to the characteristics of the power profile and power peaks that have to be handled, EDLCs are a good candidate to do the job.

Flywheels

A flywheel is a rotating disc spinning around an axis used for storing energy mechanically in the form of kinetic energy. The Flywheel works by accelerating a rotor to a very high speed and maintaining the energy in the system as rotational energy. Modern flywheels do not require much maintenance and also benefit from a high efficiency. Due to their mechanical nature, they can also cope with a large number of power peaks which is translated in a long lifetime, very important for braking energy recovery applications in rail transport. In specific power and energy terms, they have similar power density to EDLCs and are reported to benefit from higher energy densities (Vazquez *et al*., 2010; Lukic *et al*., 2008).

From an operational point of view, the difference among flywheels and EDLCS is that flywheels have higher energy density while EDLCs have slightly better efficiency and suffer from lower self-discharge (Haisheng *et al*., 2009). Other aspects that have to be considered when dealing with flywheels, especially for on-board applications, are the gyroscopic forces and safety enclosures (Haisheng *et al*., 2009; Bolund *et al*., 2007). High speed flywheels will need a robust a possibly bulky container for safety reasons in case of failure. The principle of operation, from the network point of view is the same as that of supercapacitor, it would store and release the braking energy when required.

Reversible substations

A substation consists in an electricity distribution system where voltage is transformed from high to low voltage (and vice-versa) using transformers. As it is more efficient to transmit electricity over long distances at very high voltages, the function of a substation is to reduce the voltage from transmission level to values suitable for local distribution. The substations used to power many conventional DC rail networks use diode rectifiers to

convert AC to DC and thus, they provide current only in one direction and are not able to absorb energy generated by the vehicles. A Reversible Substation uses an inverter to convert the rail network DC electrical energy to the mains AC and it allows the system to act in both ways.
Fig. 4 and Fig. 5 explain the difference between conventional substations and reversible substations when two distant vehicles are braking and accelerating respectively (Barrero, 2012).

Fig. 4 – Vehicle 1 braking and vehicle 2 accelerating with rectifier substation

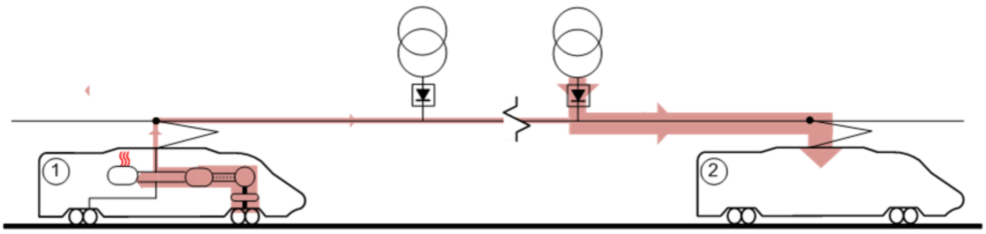
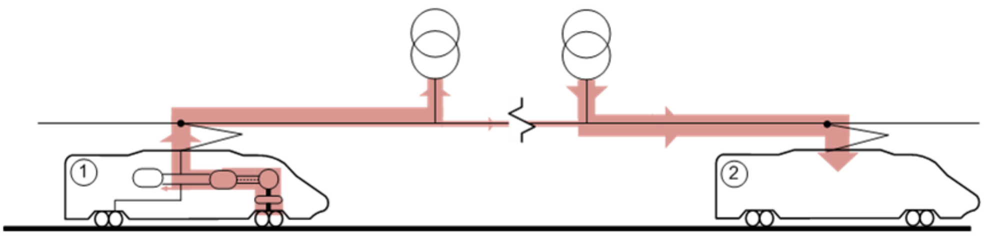


Fig. 5 – Vehicle 1 braking and vehicle 2 accelerating with reversible substation



The quantity of energy a public transport network is able to absorb is mainly conditioned by the probability of trains braking and accelerating simultaneously (UIC, 2009). This absorption phenomenon is called the receptivity of the line. The target is to improve the power line receptivity, in order to regenerate almost completely the trains braking energy. The goals are: to maximize the braking energy feedback to the upstream network, to leave priority to natural exchange of energy between trains, to reduce losses and to ensure a good quality of power supply.
From the network perspective, the operation of a reversible substation differs from that of the ESS (EDLC and flywheels) mentioned above. Reversible substations do not store the energy but they take it from the DC network, convert it to AC and send it back to the Brussels public transportation company high voltage network, where it can be consumed by other regular loads, such as lighting in buildings, computers, other substations, etc.
These systems will be less bulky than ESS and do not have the energy content limitation of

ESS, provided that all the recovered energy will be consumed. The disadvantage is that eventually they do not have the side benefits of ESS (i.e. voltage drops reduction and traffic density increase.) and that it requires the public transport operator either to own the high voltage network or to reach an agreement with the energy distributor to buy the energy sent back.

This MCA focused on two alternatives for each type of technology:

- Supercapacitors: SUPERCAP_01; SUPERCAP_02;
- Flywheels: FLYW_01; FLYW_02;
- Reversible substations: REVSUB_01; REVSUB_02.

Step 2: Defining the criteria

The choice of the criteria (and sub-criteria) was mainly defined during common meetings with the Brussels public transportation company experts and the MCA analysts. The choice of an optimal technological solution aiming at recovering the metro braking energy is interrelated to several aspects. Overall, the technologies were evaluated based on: performance, implementation, maintenance/reliability and their environmental impact.

Each criteria group has furthermore own subcriteria:

A. Performance (Technical performance of the technology).

A.1 Investment cost/Peak Power: Price per power installed.

A.2 Investment cost/Maximum energy recovery: Price per expected energy recovery.

A.3 Voltage balancing function: Is the system able to balance the voltage by avoiding voltage drops and sags?

A.4 Auxiliaries consumption/Maximum energy recovery per hour: Auxiliaries Consumption (Power) [kW] / Maximum Energy Recovery per hour (energy/time=power) [kWh/h=kW]. The energy needed to keep the system running. Used for the electronics that control the system. In voltage balancing in some cases (batteries and supercapacitors).

B. Implementation (The material and implementation characteristics of the assessed technologies).

B.1 Volume: The total space occupied by the three-dimensional technology, expressed in cubic units.

B. Mass: Mass on the ground per expected energy recovery.

B.3 Stage of development: Current status of the technology for railway applications.

B.4 Systems in service worldwide: Systems operated in railway applications.

C. Maintenance and reliability (all supply and repair actions taken to keep the technology in condition to carry out its work and the probability that the technology will perform a required function under stated conditions for a stated period of time).

C.1 Mean time between maintenance (MTBM): Systems in service worldwide: Number of times per year that maintenance events, both preventative and corrective, are needed.

C.2 Mean time to maintain (MTTM): Average downtime for preventive maintenance. This includes any logistics delay time.

C.3 Mean time between failure (MTBF): Mean exposure time between consecutive failures of a component.

C.4 Mean time to repair (MTTR): Mean time to replace or repair a failed component.

C.5 Lifecycle: The duration in years of the technology existence from its primary development through the time of dynamic usage to ultimate end-of-life (EoL) treatment.

D. Environment (environmental effects of the technology on the environment).

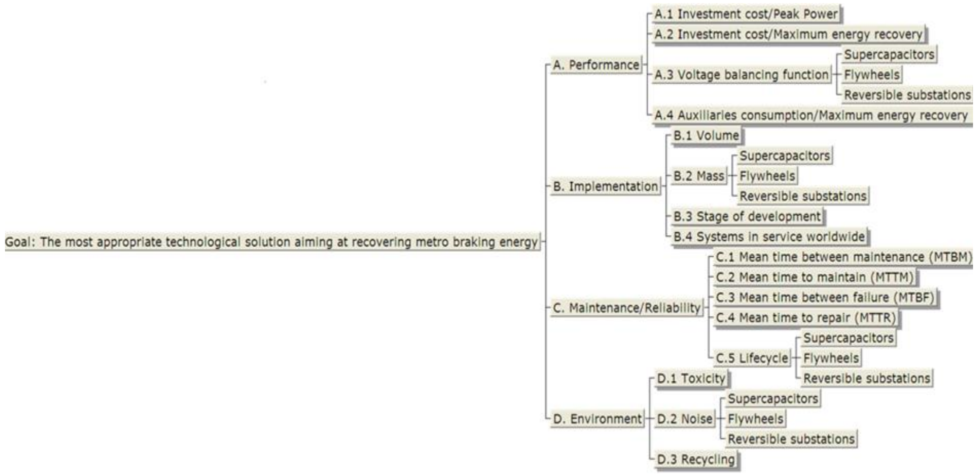
D.1 Toxicity: Systems components of harmful material.

D.2 Noise: Noise measurements out of the container.

D.3 Recycling: % of material that can be recycled.

With this information, a hierarchical decision tree can be set up (Fig. 6) in which the multiple criteria and subcriteria are highlighted on which the identified technologies will be evaluated.

Fig. 6 – Hierarchy criteria tree for the Brussels public transportation company assessment



Step 3: Allocation of weights to the criteria

Table 2 gives the overall results of the weight distribution for the different criteria. For all the criteria and subcriteria the weights are determined by the importance the experts attach to each of his or her objectives. The recognition of those weights was established by the Brussels public transportation company experts during the common meetings. The sum of the weights must equal 100% at each level of the hierarchy tree. The weight of the criteria gives the importance of the sub-criteria.

This table gives also an overview of the different parameters of each criterion:

a) if the criterion has to be minimised (i.e. investment cost/peak power) or maximised (i.e. Lifecycle);
b) the used unit;
c) for some criterion also the preferences (indicates the preference threshold of the preference function, and d) if the criterion is based on a numerical scale (means that the scale is quantitative (i.e. volume) or a qualitative scale (i.e. toxicity: low/middle/high).

Table 2 – Criteria and sub-criteria weights and parameters

Code	Criteria	Weight	Min/Max	Unit	Scale numerical/ qualitative
A.1	Investment cost/Peak Power	33%	Minimize	€/MW	Numerical
A.2	Investment cost/Maximum energy recovery	40%	Minimize	€/kWh/h	Numerical
A.3	Voltage balancing function	13,3%	Maximize	Yes/No	Voltage balancing function
A.4	Auxiliaries consumption/Maximum energy recovery per hour	13,3%	Minimize	%	Numerical
		Tot. 100%			
B.1	Volume	30%	Minimize	m3	Numerical
B.2	Mass	20%	Minimize	kg	Numerical
B.3	Stage of development	30%	Maximize	Product/ Prototype	Stage of Development
B.4	Systems in service worldwide	20%	Maximize	Number	Numerical
		Tot. 100%			
C.1	Mean time between maintenance (MTBM)	20%	Minimize	Times/yea	Numerical
C.2	Mean time to maintain (MTTM)	10%	Minimize	Hours	Numerical
C.3	Mean time between failure (MTBF)	40%	Maximize	Years	Numerical
C.4	Mean time to repair (MTTR)	10%	Minimize	Hours	Numerical
C.5	Lifecycle	20%	Maximize	Years	Numerical
		Tot. 100%			
D.1	Toxicity	50%	Minimize	Low/ Middle/ High	Toxicity
D.2	Noise	25%	Minimize	dB	Numerical
D.3	Recycling	25%	Maximize	%	Numerical
		Tot. 100%			
A	Performance	40%			
B	Implementation	20%			
C	Maintenance and reliability	30%			
D	Environment	10%			
		Tot. 100%			

Step 4: Assessment of the alternatives and categorisation

Below, the functions of the different criteria that are used to evaluate the alternatives are presented; then we describe the results obtained as well as an analysis of those results.

Input parameters

The input parameters represent the way the different alternatives have been evaluated for each criterion. In this case, two methods have been considered:

– Pairwise comparisons (based on the PROMETHEE method): the alternatives are pairwise compared in order to calculate a score for a criterion.
– Utility (based on the Multi-Attribute Utility Theory): the alternatives are directly scored for a criterion using a so-called utility function.

Table 3 – Sub-criteria assessment parameters

Criteria	Min/Max	Type	Function	Pair wise only	
				Indifference	Preference
Investment cost/Peak Power	Minimize	Pairwise	Linear	0	50.000
Investment cost/Max energy rec	Minimize	Pairwise	Linear	0	250
Voltage balancing function	Maximize	Utility	See below	-	-
Aux cons/Max energy rec per hour	Minimize	Pairwise	Linear	0	50
Volume	Minimize	Utility	See below	-	-
Mass	Minimize	Pairwise	Linear	0	10
Stage of development	Maximize	Utility	See below	-	-
Systems in service worldwide	Maximize	Utility	See below	-	-
MTBM	Minimize	Pairwise	Usual	0	1
MTTM	Minimize	Pairwise	Usual	0	1
MTBF	Maximize	Pairwise	Usual	0	1
MTTR	Minimize	Pairwise	Usual	0	1
Lifecycle	Maximize	Utility	See below	-	-
Toxicity	Minimize	Utility	See below	-	-
Noise	Minimize	Utility	See below	-	-
Recycling	Maximize	Pairwise	Linear	0	10

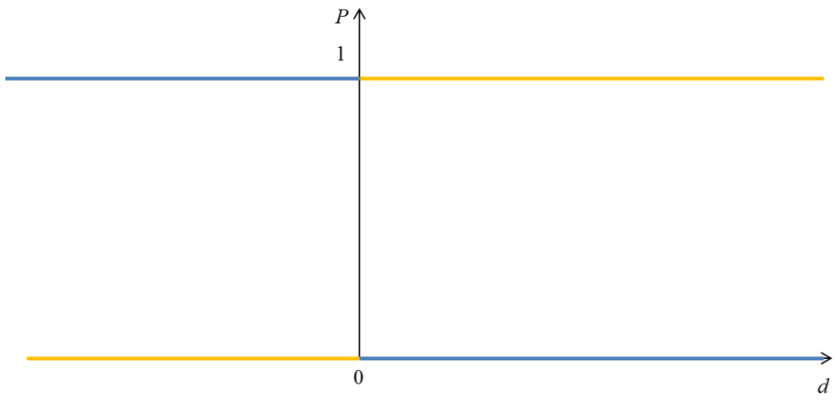
Table 3 gathers the different sub-criteria and the way they have been evaluated. The Min/Max column indicates if the criterion is to be maximized or minimized (as it was indicated in table 2). The Type column indicates whether pairwise comparisons were made or if a utility function was used. When Pairwise was chosen, the three following columns respectively indicate the PROMETHEE preference function, the indifference threshold and the preference threshold. According to Mareschal (2011) the following recommendations are to be taken into account while selecting the accurate preference function (in this case study the Usual and the Linear function). The Usual (type I) preference function is best suited for qualitative criteria. In case of a small number of levels on the criteria scale (e.g. yes/no criteria or up to 5-point scale) and if the different levels are considered quite different from each other, the Usual preference function is the good choice. While the linear (type V) preference function is best suited for quantitative criteria (i.e. prices, costs, power, etc.). All utility functions are explained afterwards. The thresholds are expressed in the unit

of the criterion as indicated in Table 3.
The so-called preference functions are used to make the pairwise comparisons. When comparing two alternatives *a* and *b* for a criterion *j*, they transform a difference of performance $d_j(a,b) = f_j(a)-f_j(b)$, into a preference degree of *a* over *b*, $P_j(a,b)$, for the related criterion such that $0 \leq P_j(a,b) \leq 1$. Making the comparisons for all the pairs of alternatives allows computing a score for each alternative, for the considered criterion. Six different functions are present in the PROMETHEE method. As indicated in table 3, only two of them are used in the present analysis: the linear and the usual function.
The usual function (Fig. 7) provides only two possible values of preference degrees:

- 0 when $d_j(a,b) \leq 0$;
- 1 otherwise.

There are no parameters to fix. Usual functions where used when comparing the different mean times (MTBM, MTTM, MTBF, MTTR). This typically means that if there was the slightest difference between two of the alternatives on those criteria, the alternative having the lowest (resp. highest) mean time would get a preference degree of 1 if the criteria was to be minimized (resp. maximized).

Fig. 7 – The usual function



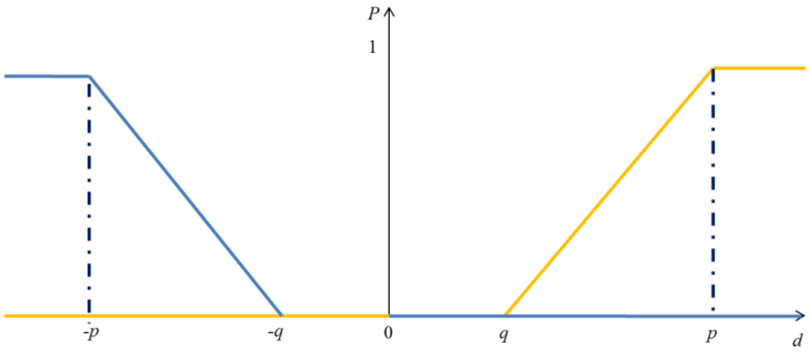
The linear function (Fig. 8) allows more granularity by allowing having values of the preference degrees in the whole range between 0 and 1. Furthermore, two thresholds are considered when making the pairwise comparisons:

- the indifference threshold (noted *q*) below which two alternatives are considered to be indifferent;
- the preference threshold (noted p) beyond which, the preference is considered as “strong”.

The preference degree is then calculated as follow:

- 0 when $d_j(a,b) \leq q$;
- $(d_j(a,b) - q) / (p - q)$ when $q < d_j(a,b) \leq p$;
- 1 when $d_j(a,b) > p$.

Fig. 8 – The linear function



A linear function was for instance used to compare the mass of the different alternatives. The indifference threshold was set to 0 (kg/kWh/h) meaning that a preference degree will be computed as soon as there is a difference between two alternatives while the preference threshold was set to 10 (kg/kWh/h) meaning that above a difference of 10 (kg/kWh/h) between two alternatives, the one with the lowest mass would be strongly preferred.
In order to illustrate this further, let's consider for instance two systems X and Y with a mass of 25 kg/kWh/h and 30 kg/kWh/h. The preference degree of *X* over *Y* is 0,5 as there is a difference of 5 kg/kWh/h and the criterion is to be minimized. For the Voltage Balancing Function, it has been decided that if the system had the functionality, it was scored to +1 for this criterion and to -1 if not. Two stages of development were here considered: prototype and product. The first one was scored to –1 and the second to +1.
Considering the Volume the alternatives were directly scored via a utility function. Having a volume under 9 m^3 is considered as "very good" and a maximal score (+1) is assigned in such cases. The score slowly decreases when the volume is over 9 m^3. Over 12 m^3 the score then goes down at a faster rate until it reaches the lowest score corresponding to a volume of 18 m^3. The Systems in service worldwide criterion has been evaluated with an increasing linear function going from 0 to 14 systems in service with respective scores of –1 and +1. For the Lifecycle the central threshold is a lifecycle of 20 years with a score of 0,7. An increase of the lifecycle brings a small increase of the score (maximum score of +1 is achieved with a lifecycle expectancy of 30 years).
On the other hand, when the lifecycle goes under 20 years, the score is strongly penalized. It decreases linearly to reach the –1 score for a lifecycle of 10 years. Regarding Noise it has been decided that the noise would be scored to +1 below 70dB and to –1 above 80dB.

Global Visual Analysis

Based on the input parameters explained above, we can now move forward and analyze the results obtained. In the following illustrations, the Reversible Substations, the Flywheels and the supercapacitor are respectively represented by green, purple and blue points. The criteria are represented by the axes. In Fig. 9, the four main categories are displayed. An axis indicates the direction of the most preferred alternatives for the related criterion. If the projection of an alternative goes far on the axis, it means that it is well scored for the criterion. One can observe that the Environment and the Performance axes are close to each other.

Fig. 9 – Global Visual Analysis of the assessed braking technologies

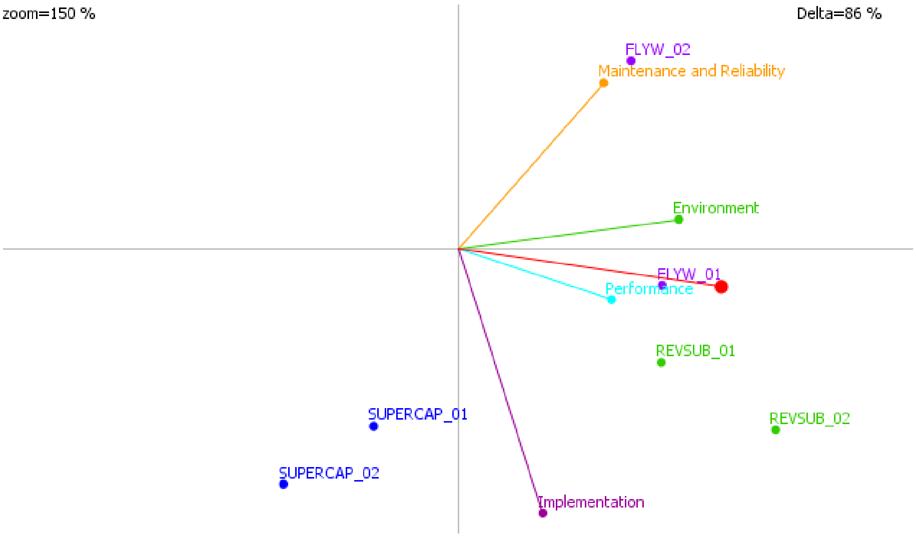
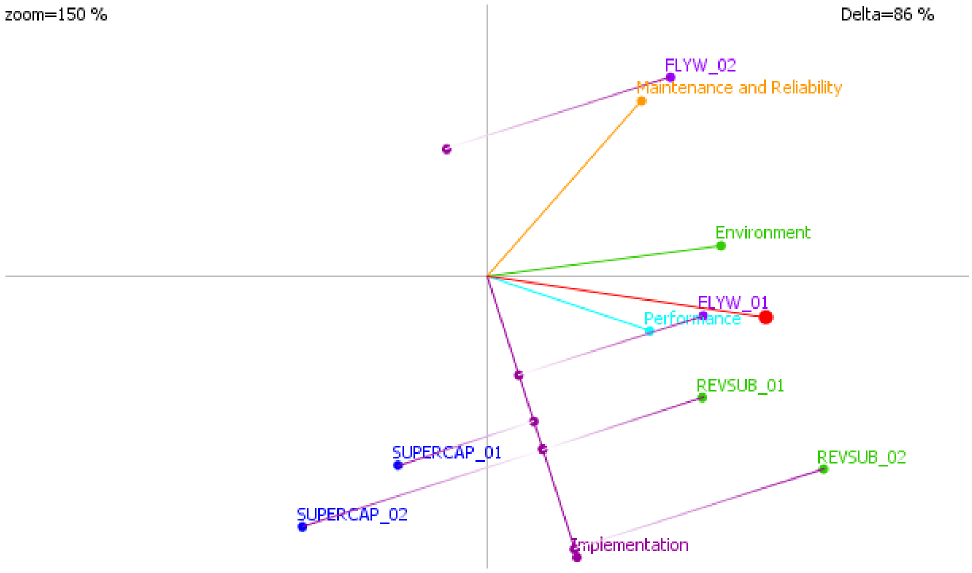
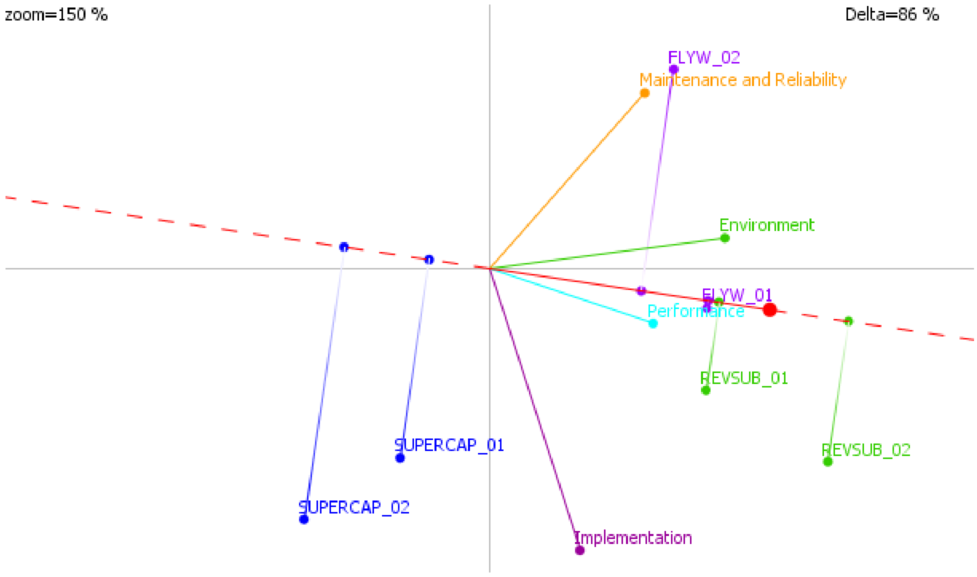


Fig. 10 – Projections of the assessed braking technologies on the Implementation axis



This means that, on average, the systems having good Performance scores also have good Environment scores. They are correlated. On the other hand, the Implementation axis goes in a quite opposite direction of the Maintenance and Reliability. As we can observe on Fig. 10 (which is similar to Fig. 9 with additional projections on the Implementation axis), the two Supercapacitors are very attractive for the Implementation but not at all for the Maintenance and Reliability while it is the opposite for the Flywheel 2. There are three interesting alternatives. Those are the two Reversible Substations and the Flywheel 1. Indeed, none of them has negative aspects (e.g. have negative projections on the axes). They are especially well scored for the Environment and the Performances.

Fig. 11 – Complete ranking of the assessed alternatives



Ranking

The red axis is called the decision stick. It is computed with the weights given to each criterion. In Fig. 11, it is computed with the weights of the categories. As the main four axes go in the right direction of this plane, it is then logical to find a long red axis pointing to the right part of the plane as well. Projecting the alternatives on it allows us to have a visual representation of the most globally preferred alternatives. Those are the Reversible Substations, followed by the Flywheels, followed by the Supercapacitors. The global scores of the alternatives are also included between +1 and -1, +1 being the best. The ranking is represented in Fig. 12. As observed in the previous figures, the two best systems are the green ones (the reversible substations) with a score of 0,48 for Reversible Substation 02 and 0,33 for Reversible Substation 01. They are followed by the Flywheels systems with a score of 0,33 for Flywheel 01 and 0,08 for Flywheel 02. Table 4, indicates the scores of the alternatives. We can then see that Reversible Substations 01 has a score of 0,332 while Flywheel 01 has a score of 0,326. They stay very close to each other though.

Fig. 12 – Complete ranking of the assessed alternatives

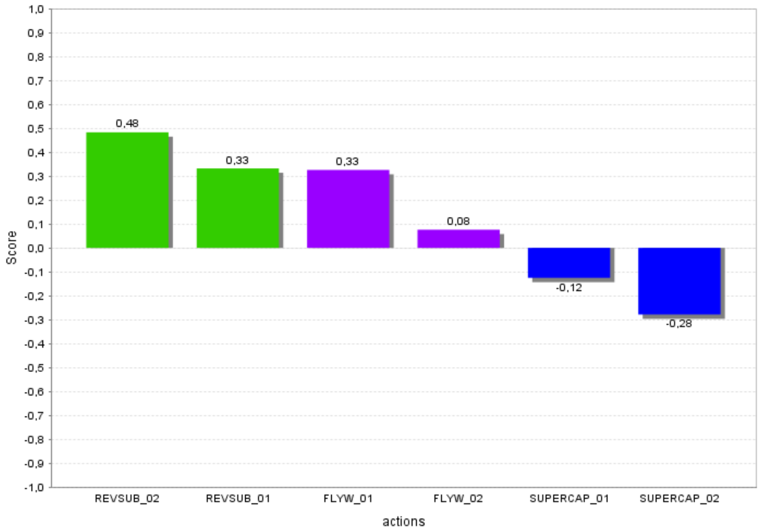


Table 4 – Scores of the assessed alternatives

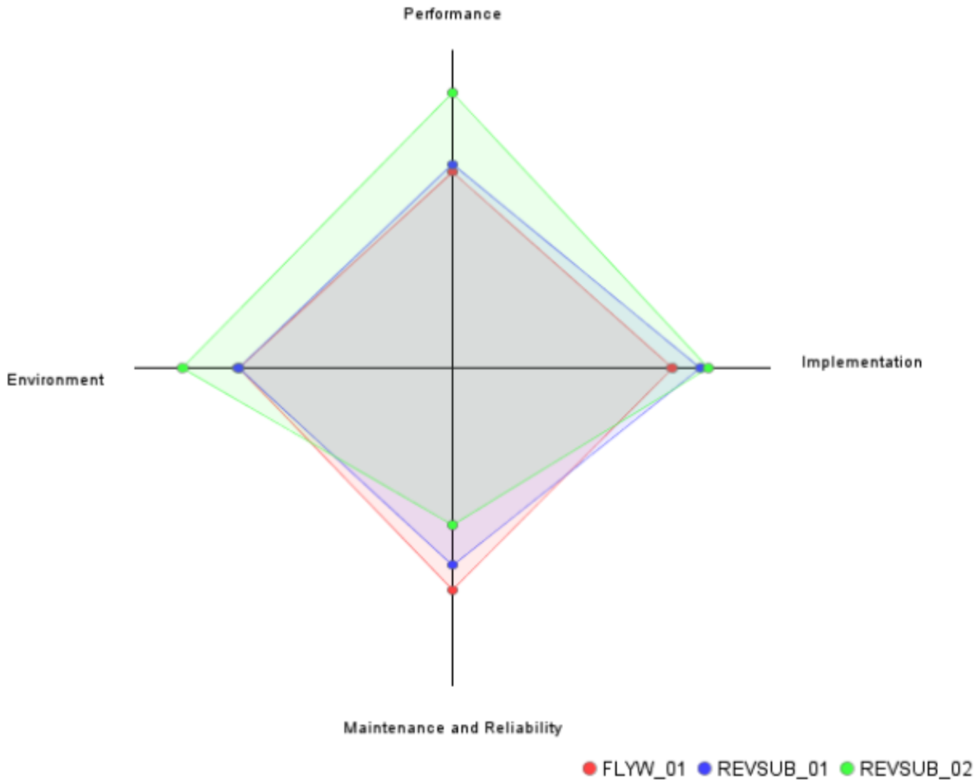
Alternative	Rank	Score
Reversible Substation REVSUB_02	1	0,483
Reversible Substation REVSUB_01	2	0,332
Flywheel FLYW_01	3	0,326
Flywheel FLYW_02	4	0,076
Supercapacitor SUPERCAP_01	5	-0,125
Supercapacitor SUPERCAP_02	6	-0,278

Profiles

It is interesting to compare the profiles of the three best alternatives. In Fig. 13, their scores are represented for the four main categories. Having a point on the extremity on the axis means a score of +1 while having the point on the crossing axes means a score of -1. We can observe that Reversible Substation 02 is the best on Environment, Performance and Implementation with a strong differentiation on the first two. As we have observed in the global visual analysis, it is in between of for the Maintenance and Reliability category.

Looking into this category (Fig. 14), allows us to notice that Reversible Substation 02 is average on all the sub-criteria of this category. For this alternative, there are no extreme scores for any of the sub-criteria: they are all close to 0. This means that the Maintenance and Reliability score of Reversible Substation 02 is almost not sensitive at all to the weights of the sub-criteria from this category. We can also see that Reversible Substation 01 is very good on the Lifecycle, the MTBM and the MTTR but is not so good on the MTTM and not good at all on the MTBF.

Fig. 13 – Profiles of the three best scoring alternatives for each main category



Step 5: Sensitivity analysis

After obtaining a global ranking, it is important to perform a sensitivity analysis in order to know if Reversible Substation 02 is a robust solution or not. Indeed, as the weights of the criteria have a strong impact in the ranking of the alternatives and therefore, in the decision, we need to know if the same solution would also have been chosen for a slightly different set of weights.

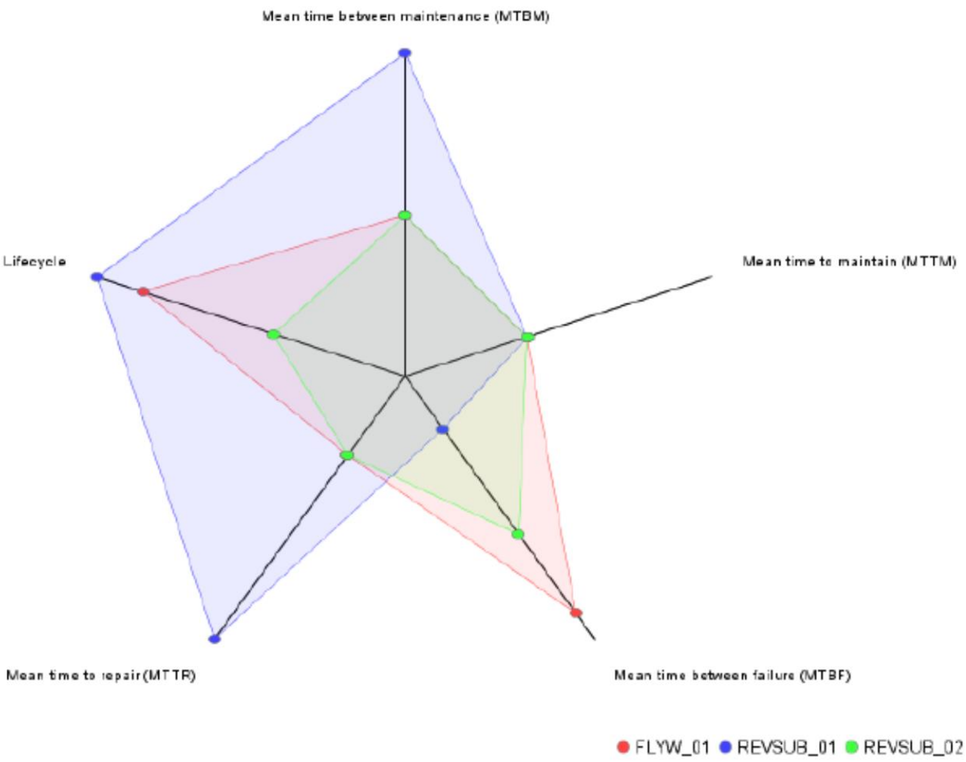
The so-called stability intervals are represented in table 5. They indicate for each criterion or category, in which interval the weight can be changed without affecting the ranking. Two important hypotheses are made here:

1. the results are here presented for the "first level". This means that the interval is computed for the stability of the first rank without taking into account rank reversal between the other ranks. This is of interest if the first alternative loses its top position,

regardless if the second, third, etc. alternatives are shifted around. Let us note that higher levels (e.g. the three first keep they rank) can also be computed;

2. when a weight is changed, the other weights change proportionally to the initial distribution.

Fig. 14 – Profiles of the three best scoring alternatives for Maintenance and Reliability



Tab. 5 – Stability intervals of the main categories

Criteria group	Min weight	Chosen weight	Max weight
Performance	12,3%	40,0%	100,0%
Implementation	0,0%	20,0%	100,0%
Maintenance and Reliability	0,0%	30,0%	49,4%
Environment	0,0%	10,0%	100,0%

We can then observe in table 5, that the result is very robust. Indeed, all the intervals are very large. The larger is the interval, the slighter is the effect on the PROMETHEE complete classification. The weights on the Implementation and Environment criteria can even be changed from 0% to 100% without affecting the first rank of Reversible Substation 02. Let us emphasize that a complete interval (from 0% to 100%) does not mean that the related criterion does not have a role to play in the analysis.

4. Conclusion

Braking energy recovery technologies have recently become a priority for the industry and most suppliers are investing in R&D in this field. Different technologies are competing on the same segment with no clear leading technology. Each technology has advantages and drawbacks that will depend on each situation and context (Devaux and Tackoen, 2011). The Multi-Criteria Analysis turned out to be an efficient way to compare the different technologies. The MCA method PROMETHEE demonstrated the operationalization side of this assessment tool to aid the public transportation company in analysing the appropriate best compromise technology. Indeed, it allowed evaluating the different options while considering the different aspects that were important to the decision-maker. During this Multi-Criteria Analysis decision support application the following technologies: Supercapacitors, Flywheels and Reversible Substations were assessed according to the four criteria groups: Performance, Implementation, Maintenance and Reliability and Environment.

The Reversible Substation 02 was very attractive regarding the Performance, the Environment and the Implementation. On the other hand, Reversible Substation 01 and Flywheels 01 have obtained better scores for the Maintenance and Reliability. Furthermore, it gave a decisive support to take into account the various points of view of the stakeholders involved in the decision. The aim of this study was to determine which technology would fit best in the Brussels public transportation company network. As we have seen previously, all the solutions have their own strengths and weaknesses. The analysis showed that, the reversible substations were good solutions for the Brussels public transportation company with respect to their own requirements and preferences. Furthermore, the sensitivity analysis that was made reinforces the choice of the reversible substations that have been proven to be robust solutions. This research allowed the Brussels public transportation company to choose the proposed best suiting technology that was the reversible substation.

Acknowledgments

The authors acknowledge the financial support by the Brussels public transportation company. The authors would also like to thank Quantin Hayez from D-Sight for his expedient contributions.

References

Allegre A.L., Bouscayrol A., Delarue P., Barrade P., Chattot E., El-Fassi S. (2010), "Energy Storage System With Supercapacitor for an Innovative Subway". *IEEE Transactions on Industrial Electronics*, vol. 57, n. 12, pp. 4001-4012.

Barrero R. (2012), *Energy Recovery Technologies in Public Transport. Faculty of Engineering Department of Electrical Engineering and Energy Technology*. Vrije Universiteit Bruxessel, BE.

Behzadian M., Kazemzadeh R.B., Albadvi A., Aghdasi M. (2010), "PROMETHEE: A comprehensive literature review on methodologies and applications". *European Journal of Operational Research*, vol. 200, n. 1, pp. 198-215.

Bolund B., Bernhoff H., Leijon M. (2007), "Flywheel energy and power storage systems". *Renewable and Sustainable Energy Reviews*, vol. 11, n. 2, pp. 235-258.

Brans J.P. (1982), "L'ingénierie de la décision. Elaboration d'instruments d'aide à la décision. Méthode PROMETHEE", in Nadeau R., Landry M. (eds), *L'aide à la Décision: Nature, Instruments et Perspectives D'Avenir*. Presses de l'Université Laval, Québec, CDN, pp. 183-214.

Brans J.P. (2004), "The management of the future". *European Journal of Operational Research*, vol. 153, n. 2, pp. 466-467.

Brans J.P., Mareschal B. (1994), "The PROMCALC and GAIA decision support system for MCA". *Decision Support Systems*, n. 12, pp. 297-310.

Brans J.P., Mareschal B. (2005), "Chapter 5: PROMETHEE methods", in Figueira J., Greco S., Ehrgott M. (eds), *Multiple Criteria Decision Analysis: State of the Art Surveys*. Springer, New York, NW, pp. 164-189.

Brans J.P., Vincke P. (1985), "A preference ranking organization method: the PROMETHEE method". *Management Science*, n. 31, pp. 647-656.

Brans J.P., Vincke P., Mareschal B. (1986), "How to select and how to rank projects: the PROMETHEE method". *European Journal of Operational Research*, n. 24, pp. 228-238.

Browne D., Ryan L. (2011), "Comparative analysis of evaluation techniques for transport policies". *Environmental Impact Assessment Review*, n. 31, pp. 226-233.

Chuang H.J., Chen C.S., Lin C.H., Chu S.H. (2005), "Optimization of inverter placement for mass rapid transit systems using genetic algorithm". *IEEE/PES Transmission and Distribution Conference and Exhibition: Asia and Pacific*, n.1, pp. 1-6.

Cornic D. (2010), "Efficient recovery of braking energy through a reversible dc substation", Proceedings of IEEE International Conference, *Electrical Systems for Aircraft, Railway and Ship Propulsion*. Bologna, Italy, October 19-21, 2010.

Destraz B., Barrade P., Rufer A., Klohr M. (2007), "Study and Simulation of the energy Balance of an Urban Transportation Network". *European Power Electronics and Applications*, n. 1, pp. 1-10.

Devaux F.O., Tackoen X. (2011), "Overview of braking energy recovery technologies in the public transport field". Energy Recovery Working Paper, www.tickettokyoto.eu.

Diakoulaki D., Karangelis F. (2007), "Multi-criteria decision analysis and cost–benefit analysis of alternative scenarios for the power generation sector in Greece". *Renewable and Sustainable Energy Reviews*, n. 11, pp. 716-727.

Figueira J., de Smet Y., Brans J.P. (2004), "MCDA methods for sorting and clustering problems: Promethee TRI and Promethee CLUSTER", Université Libre de Bruxelles. Service deMathématiques de la Gestion, Working Paper 2004/02.

Figueira J., Greco S., Ehrgott M. (eds) (2005), *Multi Criteria Decision Analysis: State of the Art Surveys*. Springer, New York, NW.

Foiadelli F., Roscia M., Zaninelli D. (2006), "Optimization of storage devices for regenerative braking energy in subway systems". *IEEE Power Engineering Society*, n.1, pp. 1-6.

Forman E.H., Gass S.I. (2001), "The Analytic Hierarchy Process - An Exposition". *Journal Operations Research archive*, vol. 49, n. 4, pp. 469-486.

Haisheng C., Ngoc Conga T., Yanga W., Tanb C., Li Y, Ding Y. (2009), "Progress in electrical energy storage system: A critical review". *Progress in Natural Science*, vol. 19, n. 3, pp. 291-312.

Han Bae C. (2009), "A simulation study of installation locations and capacity of regenerative absorption inverters". *Simulation Modelling Practice and Theory*, vol. 17, n. 5, pp. 829-838.

Hayez Q., De Smet Y., Bonney J. (2011), *D-Sight : A New Decision Support System to Address Multi-Criteria Problems*, www.d-sight.com.

Hillmansen S., Roberts C. (2007), "Energy storage devices in hybrid railway vehicles: a kinematic analysis". *Journal of Rail and Rapid Transit*, vol. 221, n. 1, pp. 135-143.

Lukic S.M., Cao J., Bansal R.C., Rodriguez F., Emadi A. (2008), "Energy Storage Systems for Automotive Applications". *IEEE Transactions on Industrial Electronics*, vol. 55, n. 6, pp. 2258-2267.

Macharis C., Brans J.P., Mareschal B. (1998), "The GDSS PROMETHEE procedure - a PROMETHEE–GAIA based procedure for group decision support". *Journal of Decision Systems*, n. 7, pp. 283-307.

Macharis C., Springael J., De Brucker K., Verbeke A. (2004), "PROMETHEE and AHP: The design of operational synergies in multicriteria analysis. Strengthening PROMETHEE with ideas of AHP". *European Journal of Operational Research*, n. 153, pp. 307-317.

Mareschal B. (2013), *Visual PROMETHEE 1.4 Manual*, www.promethee-gaia.net.

Meyer P. (2005), *La méthode PROMETEE-Gaia d'aide multicritère à la décision, Les midis de la science*, www.public.enst-bretagne.fr.

Munda G. (2004), "Social multi-criteria evaluation: Methodological foundations and operational consequences". *European Journal of Operational Research*, vol. 158, n. 3, pp. 662-677.

NREL (National Renewable Energy Laboratory) (2008), *Supercapacitors, National Renewable Energy Laboratory*, www.nrel.gov.

Roy B., Słowiński R. (2013), "Questions guiding the choice of a multicriteria decision aiding method". *EURO Journal on Decision Processes*, vol. 1, n. 1-2, pp. 69-97.

Rufer D. Hotelier P., Barrade A. (2004), "Supercapacitor-based energy storage substation for voltage compensation in weak transportation networks". *IEEE Transactions on Power Delivery*, vol. 19, n. 2, pp. 629-636.

Turcksin L., Bernardini A., Macharis C. (2011), "A combined AHP-PROMETHEE approach for selecting the most appropriate policy scenario to stimulate a clean vehicle fleet". *Procedia-Social and Behavioral Sciences*, n. 20, pp. 945-965.

UIC (2009), *Energy efficiency days*, www.uic.org.

Van Den Bossche P. (2009), "The Cell versus the System: Standardization challenges for electricity storage devices". *World Electric Vehicle Journal*, n. 3, pp. 1-6.

Vazquez S., Lukic S.M., Galvan E., Franquelo L.G., Carrasco J.M. (2010), "Energy Storage Systems for Transport and Grid Applications". *IEEE Transactions on Industrial Electronics*, vol. 57, n. 12, pp. 3881-3895.

Annalia Bernardini
Faculty of Economic, Social and Political Sciences and Solvay Business School
Department BUTO – Business Technology and Operations
MOBI - Mobility and Automotive Technology Research Centre
Vrije Universiteit Brussel
Pleinlaan 2 - 1050 Brussels
Tel.: +32-(0)2-6292362; fax: +32-(0)2-6292362; email: annalia.bernardini@gmail.com

Ricardo Barrero
Environmental Technology Officer
Cellule Environnement - Business Development
Transport Systems
STIB-MIVB
Rue Royale 76 - 1000 Brussels
Tel.: +32-(0)2 5152967; email: barreror@stib.irisnet.be

Cathy Macharis
Faculty of Economic, Social and Political Sciences and Solvay Business School
Department BUTO – Business Technology and Operations
MOBI - Mobility and Automotive Technology Research Centre
Vrije Universiteit Brussel
Pleinlaan 2 - 1050 Brussels
Tel.: +32-(0)2-6292286; fax: +32-(0)2-6292186; email: cathy.macharis@vub.ac.be

Joeri Van Mierlo
Faculty of Engineering
Department ETEC - Department of Electrical Engineering
MOBI - Mobility and Automotive Technology Research Centre
Vrije Universiteit Brussel
Pleinlaan 2 - 1050 Brussels
Tel.: + 32-(0)2-6292803; fax: + 32-(0)2-6293620; email: joeri.van.mierlo@vub.ac.be