A Multi-Objective Simulator for Optimal Power Dimensioning on Electric Railways using Cloud Computing

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Abstract: Power dimensioning and energy saving have been traditionally two main issues regarding the deployment of electric grids. Electric railways are also concerned about these issues, and simulators have been traditionally used to test such infrastructure deployments. The main goal of this paper is to present the Railway electric Power Consumption Simulator, a simulation model and tool for the railway energy provisioning problem. This simulator aims to propose electric railway infrastructure deployments, optimizing the quality of the electric flow supplied to train, as well as saving as much energy as possible. The paper describes the simulator structure, as well as the ontology used to translate railway infrastructure elements into an electric circuit. Because these two objectives are conflicting, a multi-objective optimization problem is formulated and solved. Finally, a standard railway scenario is used to illustrate the capabilities of the tool, trying to find the best electric substation placements in order to optimize such objectives. The evaluation shows how the tool can handle hundreds of simulated scenarios using Cloud Computing techniques.

1 INTRODUCTION

Power dimensioning and energy saving have been traditionally two main issues regarding the deployment of electrical grids. Since their conception in the Industrial Age, power grids are designed and deployed following a trade-off between supporting high quality provisioning to the consumers, and saving as much energy as possible. Railway electric lines, as a particular case of electric grids, are also concerned about these issues, trying to supply a steady flow of energy to the moving trains, but not exceeding the power required by them.

Within this context, simulators have been the main tools to design and test railway electric lines. Prior to its installation, a particular deployment can be tested on a simulator, modelling the infrastructure and the train traffic in order to check the behaviour of the system. Simulators like the ones introduced in (Pilo et al., 2000; Bobi et al., 2007) are able to analyse per instant if the power supplied to the trains is enough of not, if there are voltage drops or over-voltages, etc.

Nevertheless, as computer systems evolve, the role of simulators must become much more from merely imitators of the real-world, to expert systems with the ability of taking decisions and complement the user knowledge with metrics in order to achieve the best solutions. In previous works (García et al., 2014), we stated that modern simulators should be capable of proposing and evaluating new designs, taking into account all possible issues that may affect, or even determine, the final validity of a solution. This search across the problem domain may be driven by expert's knowledge implemented within the simulator, in the form of generation or evaluation rules that may reduce the number of simulations performed, or give those solutions a score indicating their fitness according to specific criteria.

The research community has been aware of this need for optimal planning of power distribution systems as a whole (Pilo et al., 2015). In particular, many of the relevant works in the field are focused on providing a near-optimal solution in a computationally efficient manner. To achieve this, different artificial intelligence (AI) techniques have served as a base for the implementation of the aforementioned decision making process, such as particle swarms (del Valle et al., 2008), genetic algorithms (Ramirez-Rosado and Bernal-Agustin, 1998; Carrano et al., 2005), ant colonies (Gomez et al., 2004), simulated annealing (Parada et al., 2004), artificial neural networks (Abrahamsson and Soder, 2009), multi-agent

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systems (Nguyen et al., 2011), and evolutionary algorithms (Strbac and Djapic, 1995). These methodologies provide a holistic approach in which the simulator proposes consistent, well-suited solutions to a particular problem.

Additionally, it may occur that the optimisation process depends on different conflicting criteria, leading to a Multi-objective Optimization (MOO) problem. Works like (Augugliaro et al., 2004; Mendoza et al., 2006; Carrano et al., 2006; Ramirez-Rosado and Dominguez-Navarro, 2004; Soler et al., 2015) approach the system's design from a MOO perspective, which allows the user to define several optimisation metrics such as minimization of power losses, overall deployment cost, system failure index, or maximization of energy savings, etc. This approach has been also translated to the field of railway power supply systems, especially along with the previously cited evolutionary techniques. In (Chang et al., 1995; Chang et al., 1998), a trade-off between failure recovery and load sharing is exposed and tackled as a MOO problem.

Nowadays, many scientific areas make use of the Cloud to overcome scalability issues in simulations, and increase their performance. In particular, computing frameworks like MapReduce (Dean and Ghemawat, 2008) have been increasingly used as building-blocks for distributed large scale simulators in a wide range of areas (Radenski, 2013; Decraene et al., 2011; Kim et al., 2014). Railway simulators have been also affected by this trend, integrating MapReduce and Cloud environments to existing techniques with promising results in large datasets and scenarios (Liu et al., 2010). Finally, works like (Deelman et al., 2008) and (Angeli and Masala, 2012) demonstrate the economic feasibility of migrating scientific or engineering simulations to the Cloud, even though making use of Cloud resources entails paying for such resources to the Cloud services provider.

The main goal of this paper is to present a simulation model and tool for the railway energy provisioning problem. This simulator aims to propose electric railway infrastructure deployments, optimizing the quality of the electric flow supplied to train, as well as saving as much energy as possible. Because these two objectives are conflicting, a MOO problem will be formulated and solved. In order to handle the high number of simulations performed, the simulator is suited for Cloud Computing. The evaluation will show how the tool can handle hundreds of simulated scenarios using Cloud Computing techniques.

From the related works researched by the authors, only (Abrahamsson and Soder, 2009), (Nguyen et al., 2011), (Pilo et al., 2015), and (Soler et al., 2015) stay close to the present work, in terms of usefulness and capabilities. (Abrahamsson and Soder, 2009) proposes a fast approximator based on neural networks in order to plan power supply investments. On the contrary, our approach is independent from underlying AI techniques, so different search strategies can be implemented just performing a few modifications. In (Nguyen et al., 2011), an agent-based smart power router is implemented, which can flexibly integrate network areas and optimally manage power flows. Nevertheless, this approach is outside the railway domain, so it does not take into account the particular railway domain characteristics. (Pilo et al., 2015) and (Soler et al., 2015) propose both an optimization problem of the AC railway power system, with models well-developed and consistent, but such models do not consider as many details regarding the infrastructure as our model does. Finally, neither of these proposals are based on Cloud Computing, nor they can make use of elastic computing infrastructures according to simulation sizes and deadlines.

The paper is structured as follows: Section 2 introduces the simulator developed, including its structure and the ontology used to represent the railway domain; Section 3 exposes the MOO problem, defining the search problem, optimization metrics, and objectives; Section 4 describes the evaluation conducted and the results obtained; and finally Section 5 provides key ideas as conclusions and some insight in future work.

2 RAILWAY POWER CONSUMPTION SIMULATOR

The Railway electric Power Consumption Simulator (RPCS) proposes solutions for the problem of designing and deploying electric infrastructure on railway lines, trying to optimize the trade-off between power supplied and energy saving. In this section we will describe in detail the simulated domain, the ontology implemented by simulator that represents such domain, and the main structure of the application. In the following section we will analyse in detail the MOO problem derived from the trade-off between energy supply quality and energy saving, and its implementation within the simulator.

In collaboration with ADIF [1], the Spanish railway company, we have developed during the last years the RPCS with the aim of testing and verifying different scenarios: developing new routes, increasing train traffic across the tracks, or testing failure situa-

[1] http://www.adif.es

tions where services have to be operated on degraded mode. Currently the tool considers only direct current (DC) systems, but its extension to AC systems is now work in progress. The tool translates railway infrastructure elements such as tracks, feeders, electrical substations and trains into an electric circuit, and then solves that electric circuit. Along with the tool, we have proposed the ontology that drives such translation of real infrastructure elements into elements of an electric circuit: voltage sources, branches, and consumers (current sources). We first describe the tool and its modules, and then we detail the ontology.

2.1 Application Description

The aim of this simulator is, provided a number of trains circulating across the lines, to calculate if the amount of power supplied by the electrical substations is sufficient to allow that trains to render without delays, failures, or any other contingency. Starting from a description of the railway infrastructure (i.e. tracks, catenaries deployed over the tracks, electric substations placed along the tracks, as well as additional elements like feeders and switches), the simulator reads the position of the trains and their instantaneous power demand. Then, for each instant of the simulated period, the electric circuit formed by the trains and the infrastructure is composed and solved using Modified Nodal Analysis (MNA). More details about MNA can be found on (Jahn et al.,). Useful mean voltages, voltage drops, and temperatures of the wires are examples of results provided by the tool.

The structure of the application is shown in Fig. 1. It is a modular application with consists of a preparation phase in which all the required input data is read and fragmented to be executed in a predefined number of threads. Two classes of input files are handled:

- A shared infrastructure specification file containing the initial and final time of the simulation, besides a wide range of domain-specific simulation parameters such as station and railway specifications and power supply definition.
- A set of train movement data files, structured in a time-based manner, in which each line contains the calculation of speed and distance profiles for a particular train at a specific instant regarding the infrastructure constraints, and most important, the instantaneous power demand, with a one second interval.

Once all data have been read, the ontology module translates the infrastructure and train positions on the current instant into an electric circuit, and solves that circuit. Tracks, feeders, and catenaries are branches of the electric circuit, whereas trains act as consumers, and the converter-rectifier groups are the voltage sources. The complete transformation procedure will be described along with the ontology in Section 2.2. Finally, the simulator executes the algorithm module for each instant to be simulated. With this module, electric results are calculated on every instant, using the MNA technique and an iterative process. These results will be merged in the main thread to constitute the final output files. The MNA general formulation is:

$$\begin{bmatrix} A_1 Y_1 A_1^T & A_2 \\ M_2 A_2^T & N_2 \end{bmatrix} \cdot \begin{bmatrix} u^n \\ i_2^r \end{bmatrix} = \begin{bmatrix} -As \cdot is \\ ws2 \end{bmatrix} \qquad (1)$$

In this problem, branches are considered resistors, and there are only independent voltage sources, so the previous equation can be simplified as:

$$\begin{bmatrix} G & B \\ C & 0 \end{bmatrix} \cdot \begin{bmatrix} u^n \\ i^r \end{bmatrix} = \begin{bmatrix} i \\ e \end{bmatrix} \qquad (2)$$

where G, B, and C are matrices of known values obtained from the circuit elements (connections, conductances, etc.), u^n and i^r are the unknown voltages and and currents, and finally i and e contain the sum of the currents through the passive elements, and the values of the independent voltage sources respectively. Note that, due to the fact that the trains are in movement, the system is constantly changing, so every instant the electric circuit must be composed and calculated, varying the position of the consumers. As consequence, the MNA must be performed on every simulated instant, thus requiring a significant amount of computing power to perform the whole simulation. Simulated times may vary, from one hour, to one day, to one week, implying from 3 600 circuits simulated on short scenarios, to 86 400 on average scenarios, to 604 800 on very large scenarios.

The simulator outputs electric data indicative of the state of the circuit and all its components. They include, for each simulated instant, voltages and currents in all trains, voltages and currents in the converter-rectifier groups, and currents in all branches. Additional data is post-processed calculating useful mean voltages on trains and zones of the circuit. With all these data, several conclusions can be drawn from the simulation:

- If the power supplied to the trains is enough of not. Particularly:
  - If the power stations are powerful enough.
  - If the power stations are placed properly along the tracks.
  - If the train traffic is excessive, given a particular configuration of the power stations.

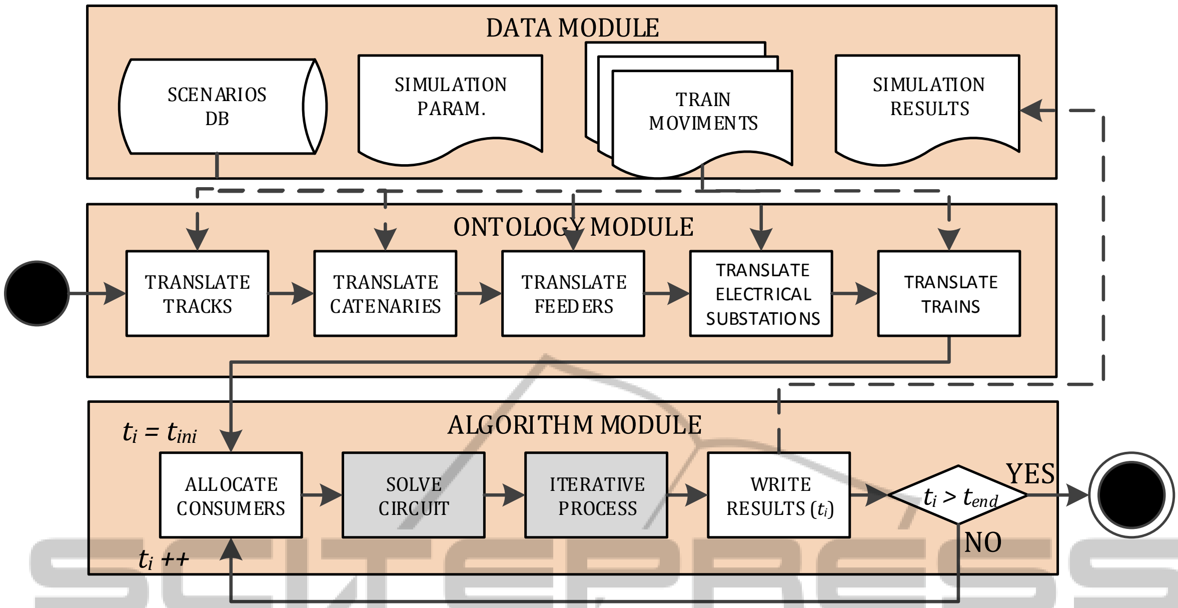


Figure 1: Application structure and its modules.

- If the current through catenaries and feeders are excessive, overheating the wires. Particularly:
  - If there is a design fault in the circuit that provokes too much current through a wire.
  - If the wires deployed are too thin.

Figure 2 illustrates an example of the graphs outputted by the simulator. Fig. 2(a) displays possible voltage drops by plotting the minimum voltage achieved at each point of the track. Fig. 2(b) represents the nominal and root mean square power of a converter-rectifier group along the simulated day. Fig. 2(c) plots the current that circulates through a feeder along the simulated day, as well as its root mean square and the maximum current that this feeder can accept before overheating. Finally, Fig. 2(d) displays a diagram of the positions of all trains circulating over a track during the day.

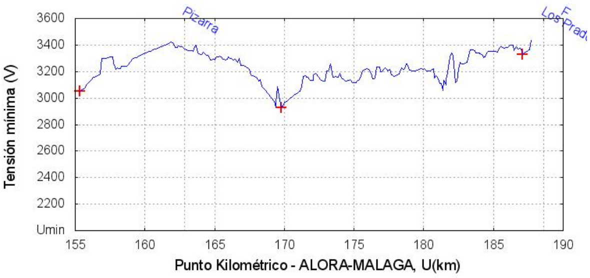
2.2 Ontology

Along with the tool, an ontology of the railway electric infrastructure domain has been developed. The main objective of this ontology is to propose a taxonomy for translating real infrastructure elements into an electric circuit. This electric circuit should reflect the real behaviour of the system (i.e. trains, tracks, electrical substations) as accurate as possible. There are several reasons for developing an ontology. The RPCS is a complete suite which includes not only the simulation algorithm, but also:

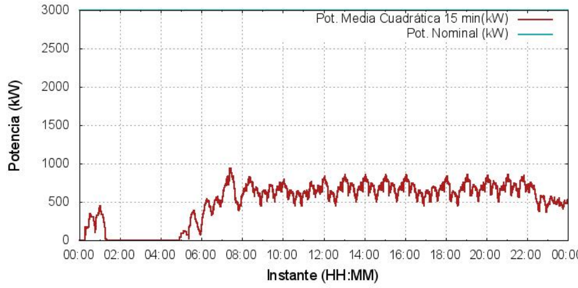
- Project Management: the user can handle different projects associated to geographical zones.
- Inventory Management: the user can handle an inventory with materials or common pieces used by the railway company. Besides, new materials or pieces with different properties can also be added by the user.
- CAD Tools. The RPCS includes several computer-aided design (CAD) tools to display the project, drawn electric or geographical schemas, etc.

All these features are easier to develop if there is a common ontology that homogenizes the problem domain. Besides, as multiple railway-related tools are in development by the authors (García et al., 2014), an ontology may ease the interaction between these tools when importing or exporting elements from one to the other. The entities and their relationships are represented in Fig. 3 through a semiformal UML model. We proceed to describe such entities:

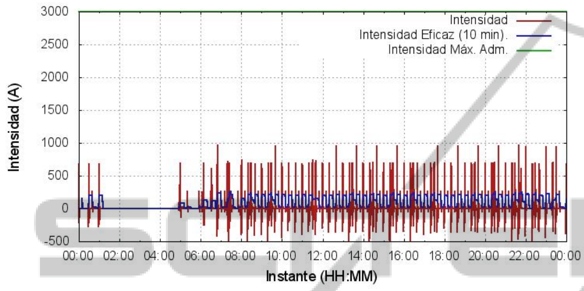
- *Material*. This entity represents a particular conductive material with specific electric properties such as resistivity or temperature coefficient. Materials compose the rails and wires of the system, thus influencing the electric behaviour of such system.
- *RailType* and *WireType*. These entities represent a particular typology of rail or wire, defined by the material that composes the rail or wire, and its section. Material and section determine the resistance per kilometre of that type of rail or wires. Examples of those types are: copper 153 mm^2 wire, or UIC-54 6934 mm^2 steel rail.



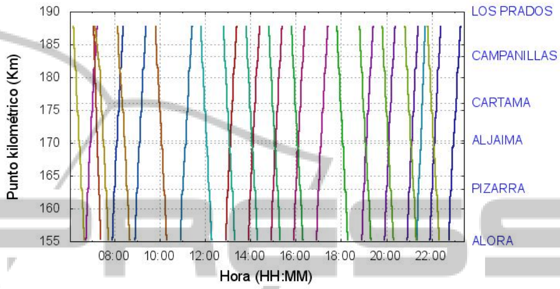
(a) Voltage drops



(b) Average electrical power



(c) Current through feeders



(d) Train traffic along the tracks

Figure 2: Different graphs outputted by RPCS.

- *FeederType.* This typology represents a group of wires. Feeders are usually deployed using several wires in order to avoid overheating. This entity represent a particular configuration of wires (e.g. 3 x Cu153, which represents a feeder configured with three cables of copper, 153 mm of section each one).
- *CatenaryType.* A typology for catenaries, which consist of supporting wire, contact wire, and optionally, a compliment feeder in order to increase the aggregated section of the catenary, avoiding excessive overheating of the supporting and contact wire because of the current.
- *RailStretch* and *CatenaryStretch*. These entities represent a section of the track, from a starting milemarker to a final milermarker, in which a particular typology of rails or catenary has been deployed. For instance, on a track, from the milemarker 20km to the milemarker 25km, the catenary is composed of a supporting wire of Cu 153 mm^2, a contact wire of Cu 150 mm^2, with no compliment feeder, whereas in other stretch of the track, a different typology of rails or catenary may be deployed.
- *Substation*, *Group*, *PositiveFeeder*, and *NegativeFeeder*. These entities represent an electrical substation and its equipment: a main building that contains one or several converter-rectifier groups (see entity *Group*). These groups transform the power from the main grid into direct current, suitable for feeding the system, thus constituting the voltage sources of the electric circuit. These sources are connected to the catenaries at some milemarker through positive feeders (see *PositiveFeeder* entity). Finally, in order to close the circuit, the substation also contains the ground reference, and the circuit is closed through negative feeders connected to the rails at some point of the track (see *NegativeFeeder* entity).
- *Train* and *TrainPosition*. These entities represent a particular train with its electric characteristics, and the collection of time/position/power records that constitute its run along the tracks. Trains demand such registered power at the particular time and point indicated by such registers.
- *Track.* This is the main entity that represents a rail track: two rails (in a common case), and an overhead catenary. The kind of catenary or rails can change along the length of the track, as stated before. Trains run across the track, stopping eventually on stations or yards at some milemarker. Otherwise connected explicitly by the user, tracks are considered electrically independent ones from the others.
- *CatenariesConnection* and *CatenarySwitch*. These entities represent particular connections and switches which allow the user to customize the electric circuit, connecting electrically two tracks, or separating electrically to ends of a track.

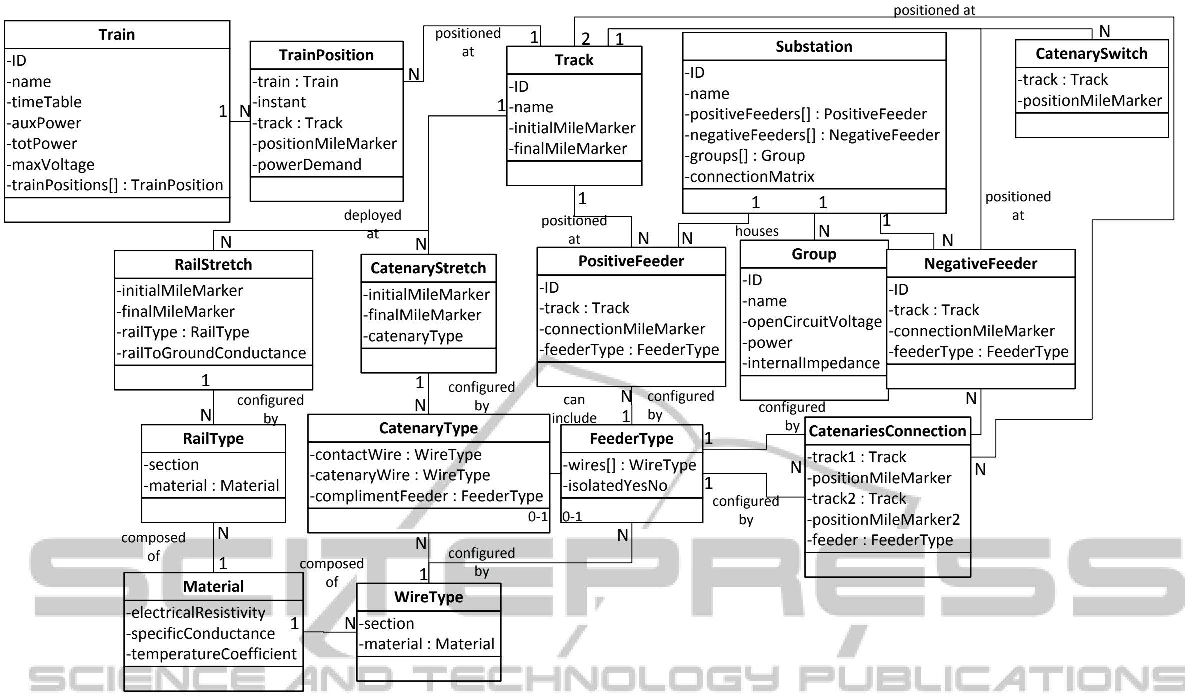


Figure 3: Semiformal modeling of the RPCS ontology using UML.

The main algorithm that composes the electric circuit proceeds as follows: starting from a set of electrically independent tracks, voltage sources (*Group*) and ground connections are connected to the track from the electric substation at some points indicated by the feeders (PositiveFeeder or NegativeFeeder). Trains run across the track demanding power at the time and point marked by their *TrainPosition* instances, thus acting as consumers in a circuit. Catenaries constitute the load branches of the circuit, whereas rails constitute the return branches of the circuit. The different typologies of catenaries and rails along the track are represented through stretchs (see *CatenaryStretch* and *RailStretch*). These stretchs will be translated to branches of some resistance depending on their configuration, through wire and rail electric properties.

Figure 4 represents how a particular infrastructure is translated into an electric circuit. In the figure, three tracks, two electrical substations, and three trains are translated into an electric circuit, where the branches are numbered. Each electric substations is translated into a set of branches and voltage sources (see branches 0 to 4 and 9 to 11). The positive feeders are translated into branches from the substation to the catenaries (5 to 8 and 12 to 13), whereas the negative ones connect the tracks to the substation (22, 23, and 24). Each catenary and track is considered a single branch (16, 17, 20, 25, 26, and 27), but the user can introduce switches in the circuit in order to divide the same track in several independent branches (18, 19, and 21). Finally, each train is represented as a branch and current source, that connects the catenary (load branch) to the track (return branch).

3 MOO APPROACH TO ENERGY SAVING ON RAILWAY LINES

In the previous section we have described the RPCS application, detailing how it can be used in order to simulate a scenario with several tracks, trains, electric substations, etc. Nevertheless, as we stated before, modern simulators should be capable of proposing and evaluating new designs taking into account possible issues that may affect the final validity of a solution. In order to do so, we have implemented an enhancement to the RPCS basic structure, turning towards a MOO problem.

In this MOO problem, not one, but many simulations will be executed. Each one of these simulations constitutes a variation of the input data –either the infrastructure or the trains–, and the results are evaluated according to a set of optimisation metrics in order to find the optimum initial configuration, with regard to a specific optimisation criteria. The way we vary the input data defines the problem's search space, which constitutes the set of solutions obtained from the simulations, and the optimisation metrics and functions define the goal we pursue in our search.

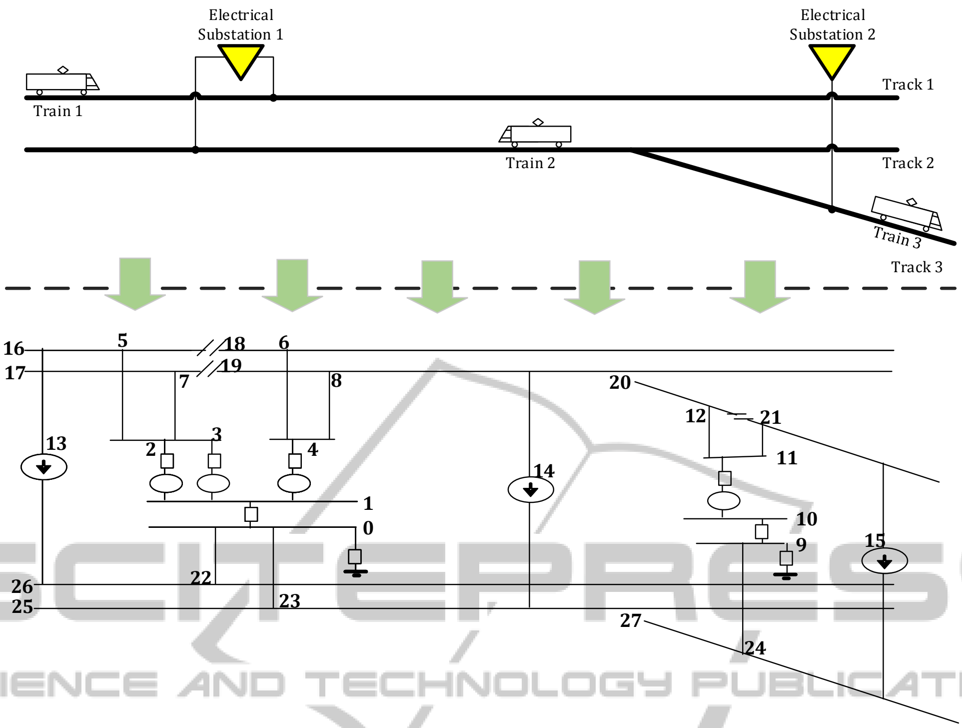


Figure 4: Railway infrastructure and its translation into an electric circuit.

In this particular case, we focus on the trade-off between energy saving and quality of energy provisioning. The quality of the power supply refers to the concept of maintaining the system as near to the nominal voltage, $U_{nom} = 3000V$, as possible. As trains circulate along the tracks demanding power, voltage oscillations may arise all across the electric circuit, leading to voltage drops or over-voltages. Note that trains do not always consume the same amount of power, and even more, they can return power to the circuit due to regenerative braking technologies. These situations should be avoided, maintaining a constant flow of electric power to the trains. While voltage drops can be avoided by adding more electric substations on the tracks, this may lead to over-voltages due to excessive power. Besides, the more substations to be placed, the more expensive the deployment is, and the more aggregated energy is consumed by the electric substations. This leads to conflicting objectives, thus to a MOO problem: the goal of maintaining a constant power flow, in favour of providing more energy, against the target benefit of saving energy.

The problem search space to be studied will be the placement of the electrical substations along the tracks –i.e. the connection milemarker of the substation to the track–. By modifying the substations' locations, we vary the electric circuit, thus we obtain different measures of instantaneous and mean voltages, as well as consumed potency. Therefore, substation placement has a direct impact on the power supply quality and energy savings.

We aim to find the corresponding Pareto frontier of the MOO problem, thus giving the user the set of optimal solutions and letting him or her chose the preferred option. We propose a set of restriction rules that must be fulfilled by the design in order to be considered as acceptable, and set of optimisation metrics in order to score those accepted solutions. Both sets are obtained analysing the European regulations (AENOR, 2004), (CENELEC, 2012), and (CENELEC, 2015)[2]. A formalisation of the resulting MOO problem is described next.

3.1 Problem Formalisation

As previously described, there are two objectives that guide the optimisation process:

- Improve the quality of the power supply.
- Reduce the amount of power consumed by the groups.

We define from these goals the following criteria:

- Maximise the mean useful voltage per train, O_1.
- Minimise total amount of energy consumed by the groups, O_2.

[2]This normative is still under vote by the CENELEC committee until 15th of July, 2015

The mean useful voltage, described in European normative *UNE-EN-50388* (CENELEC, 2012), is defined as the mean of all voltages at the pantograph of each train in the geographic zone, along all simulation steps. This measure indicates the quality of the power supply. The lower the mean useful voltage is, the less energy is transferred from the supply stations to the trains, on average.

For the formalisation of this problem, let T be the set of trains in the whole system, and G be the set of groups in the network. The first objective is defined in Eq. 3, where U^t_{mu} is the mean useful voltage per train, and U_{max_1} constitutes the maximum permanent voltage.

$$\textbf{max} \quad O_1 = \frac{U^t_{mu} - 2800}{U_{max_1} - 2800} \quad \forall t \in T \tag{3}$$

The second objective is formulated in Eq. 4, where E^i_g is the energy consumed per group, in kW/h.

$$\textbf{min} \quad O_2 = \sum_{i=1}^{G} E^i_g \quad i \neq g, \forall g \in G \tag{4}$$

The problem is subject to the following constraints:

- According to the normative (CENELEC, 2012), the mean useful voltage per train, U^t_{mu}, must never be lower than $2800V$, and it shall not surpass the maximum permanent voltage, U_{max_1}.

$$2800 \leq U^t_{mu} \leq U_{max_1} \tag{5}$$

- No sharp voltage drops or over-voltages shall exist on normal (non failure) operating conditions (AENOR, 2004). Therefore, instantaneous voltages should be in the range of non-permanent conditions on every instant of the simulation. This derives Eq. 6a and Eq. 6b.

$$U_{min_1} \leq U_t \leq U_{max_2} \quad \forall t \in T \tag{6a}$$

$$U_{min_1} \leq U_g \leq U_{max_2} \quad \forall g \in G \tag{6b}$$

- The mean voltages on trains and the simulated zone, shall be within the limits of permanent operating conditions, even if voltages fall beyond that limits for a moment during the simulation (AENOR, 2004; CENELEC, 2012). This yields Eq. 7a and Eq. 7b.

$$U_{min_1} \leq U^t_{mu} \leq U_{max_1} \quad \forall t \in T \tag{7a}$$

$$U_{min_1} \leq U_{muz} \leq U_{max_1} \tag{7b}$$

4 EVALUATION

We selected as benchmark a standard railway scenario described in the proposed draft of the European normative *prEN-50641* (CENELEC, 2015). This proposal of normative establishes the requirements for the validation of simulation tools used for the design of traction power supply systems. Therefore, it is meaningful to apply such normative to conduct the optimisations. Key parameters of this test case are indicated in Tab. 1, and a general overview of the elements of the experiment are shown in Fig. 5.

The search space was generated by conducting the simulation with a different positioning of several substations. For each substation E_k, the initial and final points of the interval in which they can be placed must be defined –$E_{k_{ini}}$ and $E_{k_{fin}}$, respectively–, along with the distance between each planned position for the generation of the experiment set, Δ_k.

As each substation can be assigned to any of the points within the former interval, and all of the substations have to be combined with the others to generate the experiment set, we would get as many different experiments as indicated by Eq. 8, where M is the number of substations to be manipulated. The equation indicates that, the finer the grain of the planned experiments, the more simulations have to be executed in order to generate the solution space.

$$N = \prod_{k=1}^{M} \left(\frac{E_{k_{fin}} - E_{k_{ini}}}{\Delta_k} \right) \tag{8}$$

For this evaluation, we generated a set of 4 000 solutions using the variations of the positions indicated in Tab. 2, displacing each substation from one kilometre to the next, without overlapping their ranges. From this set, we sampled for this evaluation only 1 000 random experiments, aiming to increase this number for future works.

Since each experiment is composed of 4 800 simulation steps –one per simulated instant, corresponding to $1h$ and $20m$ of simulated time–, it would be required to solve 4 800 equation systems per experiment. Considering that the number of experiments to be simulated grows exponentially, as indicated by Eq. 8, the overall computing resources required to generate the solution space of the MOO would outscale those typically available in current desktop computers.

To palliate this issue, we developed a version of the power simulator suitable for the Cloud, which was based on MapReduce. The complete process of adapting and implementing the Cloud version is described in (Caíno-Lores et al., 2015), as well as all the evaluation performed in order to assure scalability when

Table 1: CENELEC test case definition.

Trains	Tracks	Electrical substations	Circuit branches (mean)	Simulated time	Input size (MB)
6	2	3	150	1 h 20 min.	4.2

Table 2: Variations of electrical substations placement on MOO optimization.

Electrical substation	E1	E2	E3
Milemarkers(km) (initial, final, Δ)	(0, 20, 1)	(20, 40, 1)	(40, 50, 1)

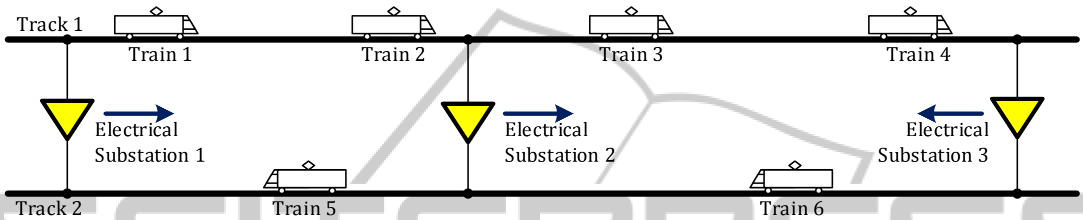


Figure 5: Schema of the main railway elements in the CENELEC test case. Parallel connections between catenaries or tracks are not shown.

tackling with a high number of experiments. This platform allowed us to disseminate the experiments across a large cluster, resulting in an efficient and scalable deployment that accelerated the overall solution space generation process. Besides, Cloud Computing paradigm brings us several features that can be useful in the context of MOO:

- Virtual unlimited scalability of hardware resources. The user is not tight on its local infrastructure, and more computing power may be allocate on-demand.
- Flexibility according to instantaneous user needs (through adapting computing resources). The user may allocate more or less computing power depending on the size of the simulation, and the deadline for obtaining the results.

The selected cloud infrastructure consisted of a general purpose *m2.4xlarge* node as dedicated master and one hundred *m2.xlarge* machines as slaves. Table **??** shows the main aspects of the selected instances. The results we obtained were parsed and evaluated according to the metrics defined in Sec. 3. The Pareto-optimal frontier for the former data is shown in Fig. 6, along with the other solutions that resulted from the subsequent simulations. The solutions that belong to the Pareto-optimal frontier highlighted in Fig. 6 are the ones that meet the optimisation criteria developed in Sec. 3, yet the preferred solution still has to be chosen by the end user. The final selection could balance the supply quality (O_1) and the wasted energy (O_2), or be directed towards emphasising one of the optimisation objectives. Table **??** gives the substation configuration for the limit solutions in the Pareto-optimal frontier, the positions are indicated with respect to the beginning of the rail track.

5 CONCLUSIONS

In this paper, we have presented the RPCS, a simulation model and tool, with the aim of proposing electric railway infrastructure deployments. The tool intends to provide optimal solutions with regard to the quality of the electric flow and the energy consumed. Because these two objectives are conflicting, a MOO problem is formulated and solved. In this MOO problem, not one, but many simulations will be executed. Each one of these simulations constitutes a variation of the electric substation placement, trying to find the best positions according to the optimization objectives.

In order to solve a single scenario, the tool translates railway infrastructure elements such as tracks, catenaries, feeders, and electrical substations, as well as the trains, which act as consumers, into an electric circuit. Then, for each simulated instant, the tool solves the circuit using the MNA technique, obtaining the resulting values of train voltages and currents. Along with the tool, an ontology to translate railway infrastructure elements into an electric circuit is proposed, as well as the algorithm to perform such translation.

In order to illustrate the capabilities of the tool, we perform an evaluation using a standard railway scenario defined in an European normative. The aim is to find the best electric substations' placement in or-

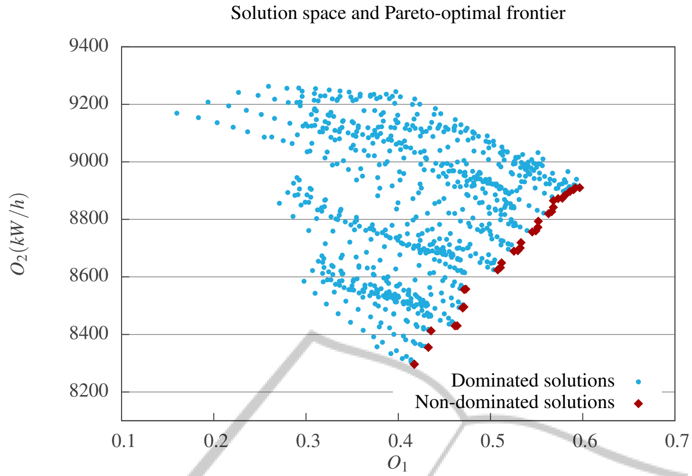


Figure 6: Resulting solution space and Pareto-optimal frontier for the CENELEC experiment set.

der to maximize the two aforementioned objectives. The number of explored solutions reaches one thousand. Besides, for each simulation, the MNA technique must be performed on every simulated instant, leading to 4 800 000 equation systems solved. In order to tackle this amount of computing power required, the application is built for Cloud Computing, using instances allocated on demand to solve all of the simulations derived from the MOO problem.

As future work, we intend to enhance the MOO problem focusing on different optimization objectives. Currently, we only vary the electric substation placement, but other infrastructure elements can be modified in order to improve the overall system performance: feeder typologies, electric substation configurations, etc. Besides, a different MOO problem can be proposed, focusing on fault-tolerance and system resilience, as some other works do on general electric grids, but particularizing the specific railway domain characteristics. Furthermore, a different approach may be proposed, trying to optimize the train traffic instead of the infrastructure. Thus, the number, type or even train drivers signature can be explored in order to improve system efficiency. A main guideline is to transform the tool into a a complete integrated IDE, so that the user could set its own search variables, optimization metrics and restrictions, proposing her/his own MOO problems using the tool. Finally, through this Cloud implementation, we aim to develop several heuristics, in order to propose sizes of the Cloud infrastructure (virtual instances, processors, memory, etc.) according to each particular MOO problem's characteristics (problem domain, restrictions, solution space, etc.).

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