A Holistic Approach to Railway Engineering Design using a Simulation Framework

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Abstract: Simulators have become frequently used tools in railway infrastructure design. However, most of them could be improved by adding capabilities to increase their productivity. In this paper, we propose a simulation framework in the field of railway infrastructure design, which allows to increase the productivity of simulators by integrating as many aspects of the design process as possible. Also, we state that new generation simulators should be capable of generating and evaluating new solutions by themselves. The framework follows a holistic approach, focusing on four main issues: a) trade-off between accuracy and complexity; b) automatic generation and simulation of solutions; c) taking into account all parts in the design process (e.g. normative); and d) integrating expert's knowledge and optimization metrics. A case study is provided through a real-world simulator of railway overhead air switches. The simulator is analyzed from the point of view of the proposed framework, indicating how the different layers are fulfilled. Finally, the usability and productivity of the simulator is demonstrated performing an evaluation using different study cases. The evaluation shows how a high number of scenarios are simulated, evaluated, and rated using optimization metrics, in order to find the best solution of the problem's search space.

1 INTRODUCTION

Simulators are excellent tools to face new engineering problems, testing different prototypes to develop optimal designs in an easy and economic manner. Simulators have been widely used in railways since the past century (Brunner et al., 1998; Goodman et al., 1998), but they have traditionally adopted the role of solvers, calculating the physical, chemical or mathematical equations associated to a particular engineering problem (e.g. FEM, CFD, etc.), which usually are set by the user.

We state that new generation simulators should be capable of, starting from a range of possible parameters, proposing and evaluating new designs, and that they should consider all issues that can affect to the final solution as part of its scope. Examples of such aspects are physical optimizations, normative, cost analysis, etc. We can resume this approach in four main issues:

1. Trade-off between accuracy and complexity. The simulator must evaluate a possible solution in the lowest possible time. The results obtained must be applicable to real world.
2. Automatic generation and simulation of possible solutions. A simulator must be capable of proposing and evaluating new solutions, exploring the search space.
3. Other actors taking part in the design process (e.g. legislation and normative) must be taken into account, to incorporate them into the simulator insofar as they influence the validity of the solutions.
4. Expert's domain knowledge, useful to find the best solutions, must be also integrated into the simulator, as well as optimization metrics.

These issues have a great impact on the complexity and usability of the simulators, and should be considered carefully.

In this paper we introduce a simulation framework which takes into account all the aspects that can influence in the design process of engineering solutions. This framework proposes an holistic approach, in which simulators can propose and evaluate solutions, needing little or no interaction by the user. Since those aspects (apart from the simulator's physical domain) which can influence the final design have been also taken into account, outcomes proceed-

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ing from this framework are more suitable to be implemented in the real world.

In order to provide a study case, we illustrate the proposed framework through a real-world simulator in the field of electric railways. We will analyze the simulators characteristics, establishing a correspondence to the different issues of the framework. The aim of that simulator, presented in (Gomez et al., 2012), is to design optimal configurations of overhead line deployments on railway switches. Starting from a set of parameters with regard to both infrastructure and train, the simulator generates different deployments of the overhead infrastructure. For each deployment, the simulator reproduces the pantograph behaviour of the train running across the switch, taking into account pantograph and wire positions, catenary geometry, tension of the wires, angles of attack, and more. All these factors can influence the viability of a solution, and thereby they must be considered. Finally, the best deployment is selected, on the basis of several optimization metrics adopted from legal normative and experts of the field. Therefore, more than solving a particular set of equations, the simulator takes into account the whole design process.

The paper is structured as follows: Section 2 describes the simulation framework proposed. Section 3 analyses in detail the railway overhead air switch problem. Section 4 describes the architecture of the simulator, and how it corresponds to the proposed framework. Section 5 evaluates the simulator, indicating times spent on each one of the framework issues. Finally, conclusions, final remarks, and future work are presented in Section 6.

2 SIMULATION FRAMEWORK

Railway infrastructures are considered critical systems, with requirements of efficiency, security and safety, and hence they should be optimized. Nevertheless, performing a high number of experiments with real systems (tracks, locomotives, electric installations, etc.) is impracticable in terms of time and money. The main goal of a simulator, in the field of railway infrastructure design, is to simulate experimental designs or prototypes to evaluate if they are acceptable or not, or to provide a degree of fitness. This procedure is composed of several tasks: first, a candidate solution must be selected, either being provided by the user, or being generated by the simulator itself. Then, the simulation is performed and the results are analysed. The candidate solution is scored, and a decision to accept it or reject it is taken. This procedure is repeated across multiple fields in this area. In railway dynamics, rail-vehicle interaction is analysed, aiming to get new designs of rails and bogies which may reduce wear and breakdowns. In overhead contact line designs, structural behaviour (Nejlaoui et al., 2013) of poles and portal frames are evaluated, checking their feasibility (Saa et al., 2012). In the field of energy provisioning, a proposal of electric installation locations may be simulated checking whether energy is available to all planned trains (Abrahamsson et al., 2013). (Hani et al., 2006) provides a simulation-based optimization in order to provide the best building positions in a railway maintenance facility.

Although this general structure is present in most railway infrastructure simulators, it may not be sufficient to grant an acceptable degree of productivity, and should be enhanced. A simulator in railway infrastructure design must not be restricted to evaluate solutions provided by the user, but also it should find acceptable solutions by itself, with a high degree of fitness, and in a reasonable amount of time. To achieve these targets we present a simulation framework, which allows to increase the output of simulators by covering more capabilities than the main procedure described before. Our enhancements are focused on four main issues below addressed. The sources of this approach are: railway company experts, railway infrastructure design and planning processes described in (Kiessling et al., 2009), and previous works in this area made by the authors (Carretero et al., 2003) (Saa et al., 2012).

First of all, a trade-off between accuracy and complexity is required when designing a simulator. Productivity issues in railway industry require not to waste so much time when evaluating a single solution, as the design process may require to evaluate a lot of candidate solutions. There is a relationship between the accuracy of the model and the complexity of the simulation. On the one hand, accurate models are usually hard to simulate, and require more and more operations, so the more accurate is the model, the more complex it is, and the more time is needed to reach the solution. On the other hand, accurate models are likely to reproduce real results. Optimal balance between accuracy and simulation may be different in different design processes, but we state that an efficient simulator should simulate and evaluate a single candidate solution in the lowest possible time. We state that an acceptable threshold to be productive is to simulate and evaluate a candidate solution in less than one hour.

In the second place, automatic generation and simulation of solutions falls outside the scope of most simulators. Therefore, the user must feed the simulator providing new possible solutions, which leads to

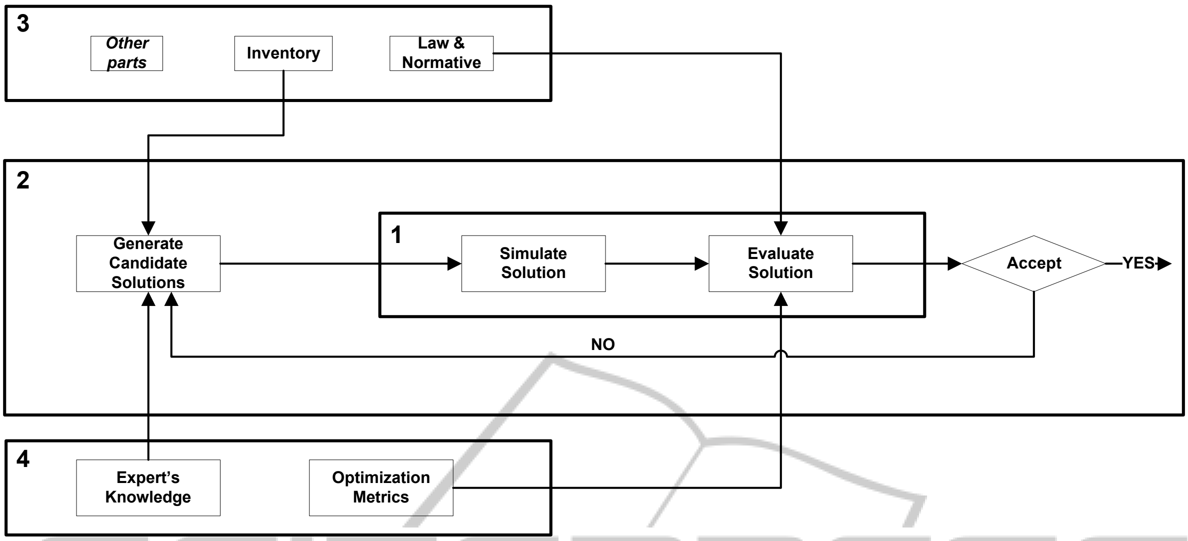

Figure 1: Simulation framework presented by the authors.

productivity losses. Moreover, the capacity of finding good (maybe optimal) solutions is tied to the user and her own ability to explore the problem's search space. We state that an efficient simulator should evaluate and simulate a set of solution with a minimal user involvement. To achieve that: a) the user should provide the simulation parameters as a set of possible values (e.g. [minimum, maximum, increment]), and the simulator uses them to generate candidate solutions; b) the simulator should be able to generate new solutions starting from an initial database (e.g. an inventory or catalogue).

Thirdly, there are many stakeholders taking part in the design process which usually fall out of the scope of the simulation models. These parts can influence, or even determine, the final acceptance of the candidate solutions (Naweed et al., 2013). For instance, the set of possible solutions when looking for a valid design of a railway portal frame, can be limited by the availability of constructive pieces in the company's inventory, and once found, a portal frame that stands could not be in compliance with legal normative in certain countries (BS-EN-50119, 2009). All issues that have to be considered throughout the design process, but fall out the scope of the simulation model, should be also taken into account when simulators generate and evaluate candidate solutions. This category includes provider specifications, client requirements, technical security, and legal normative. Different ways to include such restrictions out of the simulation model are: a) restrictions to generate candidate solutions: the simulator only generates candidate solutions that fulfill with these initial restrictions; b) restrictions to evaluate a candidate solution, so that the simulator evaluates these restrictions as well as any others conditioned by the simulation model.

Finally, expert's domain knowledge is a fundamental part in the engineering design process (Adeli, 2003). Expert's knowledge defines as heuristics that allow to speed up the search process and achieve the best solutions in the problem's search space. Therefore it should be included as a part of the simulation, particularly in those simulators that include automatic generation of candidate solutions (described as the second issue). In a similar way to other participants in the design process, expert's knowledge can be included when generating candidate solutions in the form of decision rules. Those rules guide the search process to generate better candidate solutions. They can also be included to evaluate a candidate solution in the form of optimization metrics, that can be used to score the solution and to compare it with others, thus choosing the best one.

The proposed framework is showed in Figure 1. This figure is layered following the four issues previously mentioned. The core procedure of simulating and evaluating candidate solutions composes layer 1. Time invested in performing these two tasks must be the lowest possible. Issue 2 is covered by the layer 2, which contains the task of generating automatically new solutions to be evaluated. This task could be fed from other elements in layers 3 and 4 (e.g. requirements related to an inventory of constructive pieces, or expert's domain knowledge, applied to generate better candidate solutions). Layer 3 is composed by those restrictions that are not included in the simulation procedure (layer 1), but that have an impact on the solution. Those restrictions can be applied either when generating or when evaluating a candidate solution. Examples of such restrictions are availability of constructive pieces in company's inventory when proposing a design, or compliance with legal normative when evaluating the proposed design. Finally, layer 4 represents the expert's domain knowledge that allows to obtain better solutions. Decision rules used to generate better candidate solutions, or optimization metrics used to choose the best one, are included in this layer. This approach improves the efficiency of the simulators by giving them the ability of searching for the best solutions in the problem space. Obtained solutions will be fully-integrated with the different actors of the design process, and therefore they are more suitable to be implemented in the real world.

3 CASE STUDY: OVERHEAD LINE AIR SWITCHES

Overhead lines have become the way to provide energy to high speed trains. Apart from the significant advantages over other mechanisms such as a third rail, overhead lines are the only alternative when dealing with high voltages (25.000 V) like those used in high speed railways. Nevertheless, overhead lines require to maintain the contact between pantograph and the wire, in order not to break energy supply to the train. This suppose an engineering challenge when the train is moving along the main tracks (geometry, catenary dynamics, wearing down, etc.).

When a train takes a switch in order to change to other track, even more difficulties arise. The pantograph has to lose contact with the outgoing catenary of the straight track, and make contact with the incoming catenary of the diverging track. On the one hand, transition between overhead lines must be conducted without losing contact with at least one of the wires, in order not to interrupt power supply to the train. On the other hand, the change must be performed gently, in order to avoid excessive wearing or breakdowns.

The task of designing an overhead line air switches is a complex problem since several elements with different parameters must be considered. (Kitchin and Holland, 1950) discusses the problems to be faced by the designers of overhead equipment for the electrification of railways. Some research about the integration of catenaries and switches is presented in (Kiessling et al., 2009).

A standard catenary is composed of a messenger wire holding a contact wire that supplies the electric power to the pantograph of the train. Both wires are hung at a specific tension and are attached to each other at regular intervals by drop wires. These droppers are responsible for maintaining the contact wire hung at a constant height with a slight deflection. Hence an uniform contact between the pantograph and the wire as the train travels along the track is possible, thus avoiding any notches due to the pantograph thrust force. In addition, contact wires must be zigzagged slightly to the left and to the right of track axis so that the pantograph wears evenly its friction surface. This stagger is a critical issue to be analyzed in the problem presented.

We focus on the critical study case of railway switches, where a train travelling along the straight track has to change to the diverging track. In this kind of problem, two different catenaries are needed to guarantee the electricity supply to both tracks, the left side of the Figure 2 shows a real example of tangential overhead line air switches. Therefore, there will be overlapped spans along the switch stretch length. The right side of Figure 2 shows the configuration of a overhead line air switch. As may be seen, the diverging track elevation span allows to lower the contact wire height, so that the pantograph can progressively change the rubbing wire while moving forward. The beginning of this change takes place at a characteristic point Cp where the heights of both elevation spans match (see the right-up side of Figure 2). From this point on, the pantograph will interact with the contact wires of two different catenaries. Next, in the switching span, both catenaries are gradually separating. This allows the pantograph to lose the contact with the outgoing catenary and to get contact with the incoming catenary.

The configuration of an overhead air switch poses a set of restrictions to be ensured along the train trajectory on the railway switch:

- When the train travels over the straight track, the pantograph should only rub the contact wire of this track. This avoids an excessive wear and tear of the diverging track contact wire, that may result in breakdowns and economical costs.
- Other possible flaw points to be analyzed, may occur when the train is travelling along the diverging track. Firstly, as the entire pantograph surface is not suitable for making contact with the contact wire, the pantograph should start rubbing it over its central part, called friction surface. Secondly, the beginning of the rub should be smooth and progressive. A hazardous breakdown of the catenary or the pantograph may occur otherwise.
- Regardless of the track to be simulated, it is essential that the pantograph is always rubbing one of the contact wires, so that there is no electricity notches affecting the train movement.

The number of combinations of catenary infras-

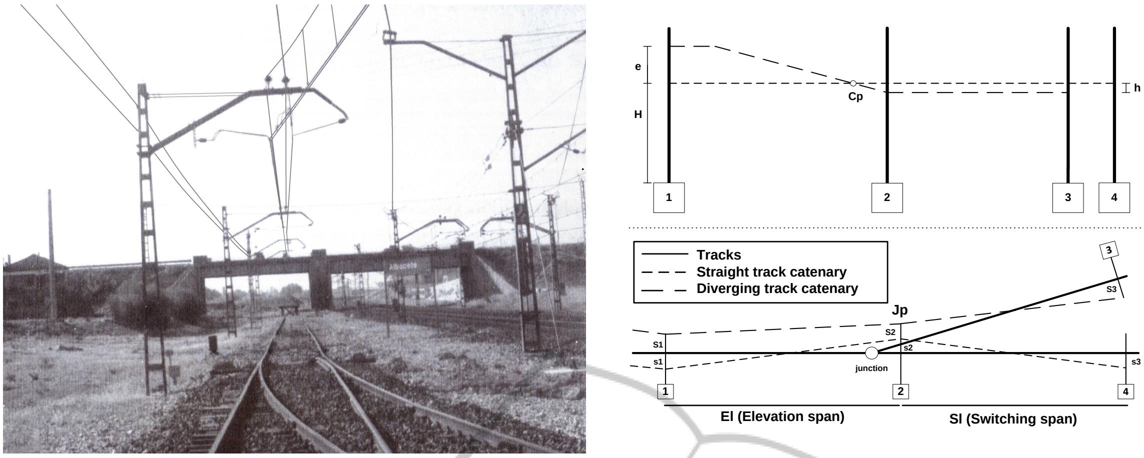

Figure 2: Photography of a real air switch and schemes (ground and elevation views).

tructure geometry for a single air switch may vary between a few thousand and more than one million. Each one of these combinations is a possible solution of the design problem.

4 SIMULATOR ARCHITECTURE

This section describes the air switch simulator in terms of the proposed framework described before. The aim is to illustrate how a real-world simulator can be adapted to the framework and the enhancement in usability and productivity obtained through the adaptation. We start by describing the simulation model, the core of the simulator in which one single scenario is simulated and evaluated. Next, we analyse all layers of the framework and how they are reflected in the simulator.

4.1 Simulation Model

The complete simulation model is described in (Gomez et al., 2012), including all the equations which determine output data. The model starts from three main sets of input data which correspond to the two key factors in an overhead line air switch: the switch scheme and a candidate overhead line deployment, and the environmental conditions in which the simulation is carried on:

- The switch scheme determines the trajectory of the train across the rails, and therefore the position of the pantograph on each instant. Based on these data and trigonometry equations, the angle at any point of the switch axis can be obtained, thus allowing to simulate the pantograph position when travelling along the switch.
- Overhead line deployment configuration determines characteristics of the contact wires across the switch. It can be divided in two groups: catenary geometry, which indicates the position of the wires, and catenary installation features, which defines catenary behaviour when the pantograph makes contact with it.
  - Catenary geometry contains the parameters related to the modelling of the ground plan and elevation of the catenary, i.e., its geometry. However, catenary geometry can support multiple configurations that are allowed for the given design problem. For example, one solution may be feasible whether the junction point is 90 or 120. These different configurations define the multiple solutions for the design problem.
  - Catenary installation features defines physical characteristics of the catenary (stiffness, deflection, tension), which may affect the way the pantograph makes contact with the wires. For instance: a more rigid catenary is less sensitive to displacements provoked by pantograph inertia, but it is prone to breakdowns due to wear and tear.
- Finally, a third set of input parameters is simulation conditions data, which contains those environmental conditions apart from the rail switch and catenary data (i.e. wind speed and direction, trains speed, etc.).

With these data, the pantograph-catenary interaction along the switch is simulated. Pantograph trajectory across the switch is divided in simulation steps. The simulator calculates the position of the pantograph referring to the contact wires on each step for each simulation step of the scenario. Figure 3 illustrates all the stages followed by the simulator, that are

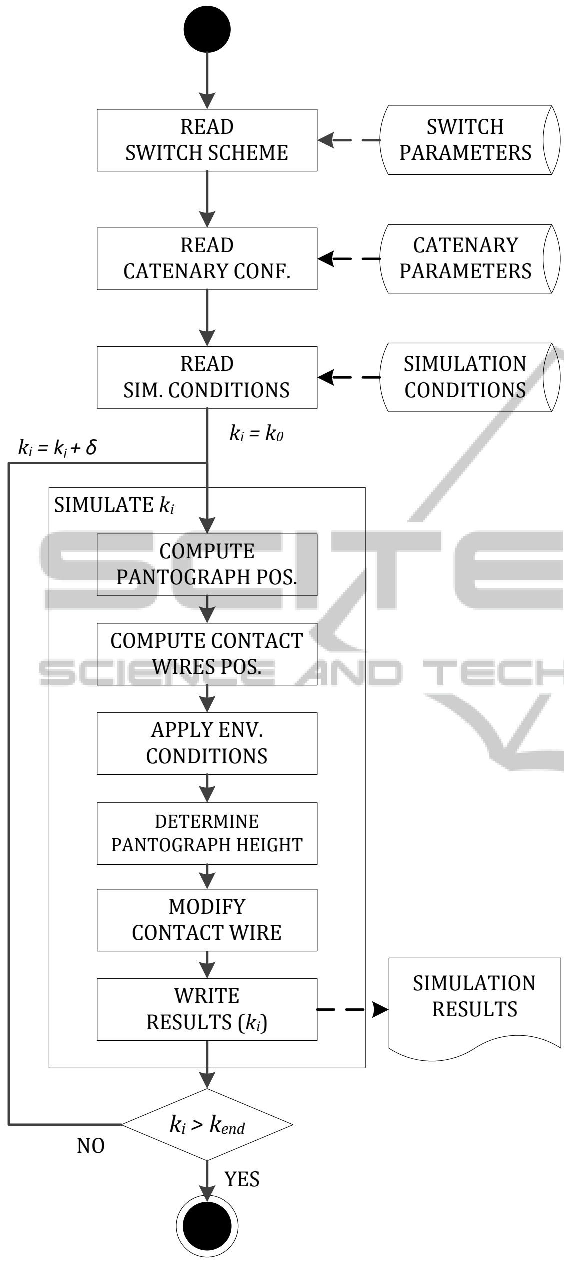

Figure 3: Simulation model and its stages.

stated below.

1. *Compute pantograph position*. First, pantograph position k_i is computed for each simulation step i by increasing the former pantograph position in the track with the pantograph displacement defined (see Equation 1). For the first step, the initial position is set to the position of the first pole of the switch infrastructure k_0.

$$k_i = k_{i-1} + \delta_j \tag{1}$$

2. *Compute contact wires position*. Second step is computing contact wires position. This step is in charge of calculating the position of the contact wires accurately for the pantograph position at this simulation step. Equation 2 is applied along the span to compute the base wire height for that point.

$$y_i(k_i) = \begin{cases} H & k_i < d \\ H - deflection(k_i) & d \le k_i < l - d \\ H & k_i \ge l - d \end{cases} \tag{2}$$

where d is the distance from the beginning of the span to the first dropper, and l is El or Sl, depending on whether the current span is the elevation span or the switching span. Equation 3 is used to compute wire deflection at each point, being D_{max} the maximum deflection defined as an input parameter.

$$deflection(k_i) = \left((l-d)\cdot(k_i-d) - (k_i-d)^2\right) \cdot \left(4 \cdot \frac{D_{max}}{(l-d)^2}\right) \tag{3}$$

3. *Apply environmental conditions*. Depending on the simulation conditions defined by the input parameters, wire stagger could be modified due to several environmental aspects. Equation 4 is used in our simulator to include the transversal wind force. The equation computes the horizontal displacement of the contact wire due to wind effects in standard conditions (15 degrees and 600 meters over the sea).

$$W_c = Pv_{ContWire} + Pv_{MesWire} \tag{4}$$

where

$$Pv = q_k \cdot G_c \cdot dWire \quad being \quad q_k = \frac{1}{2} G_q \cdot G_t \cdot \rho Ws^2$$

G_q reflects the wind burst, with a value of 2.05, as defined by the standard ENV 1991-2-4:1995 (see page 42 in (BS-EN-50119, 2009)), G_t is a terrain factor, Ws is the wind speed, ρ is a factor equal to $1.225 \frac{kg}{m^3}$, and $dWire$ is the diameter of the wire, obtained from its section area A. Equation 5 is applied to calculate wire contact horizontal displacement:

$$w_i(k_i) = \left(\frac{W_c}{T}\right) \cdot \left(\frac{k_i^2}{2}\right) \tag{5}$$

where W_c is the resulting wind force and T is the tension due to the catenary. The result is a quadratic curve, similar to the wire deflection.

4. *Determine pantograph height*. Once calculated the contact wire positions, the pantograph height must be computed for this simulation step as follows. Since there are two catenaries, for the main and the diverging tracks, the pantograph height will be the minimum height of the wires that are within the projection of its friction surface, i.e., the rubbing contact wire will be the lower one. If both wires are out of the friction surface projection, then the pantograph height will be considered as ∞ to indicate an error.

5. *Modify contact wire elevation and angle*. The fifth step is modifying contact wire elevation and angle due to the pantograph interaction. Some parameters needed, such as elasticity in the center of the catenary spans and in the cantilevers, are received as input parameters in the catenary installation features. Train speed Ts, must also be considered. In order to know the elevation, the pantograph pressure over the wires must be computed, as shown in Equation 6 that follows ETI regulation (ETI, 2008).

$$F_m = \begin{cases} 0.00097 \cdot Ts^2 + 70 & \text{Ccs is A.C.} \\ 0.00097 \cdot Ts^2 + 110 & \text{Ccs is D.C. 3.0 kv} \\ 0.00228 \cdot Ts^2 + 90 & \text{Ccs is D.C. 1.5 kv} \end{cases} \quad (6)$$

Next, the elasticity is computed for the catenary point using Equation 7, where the denominator is the stiffness at that point.

$$E(k_i) = \frac{1}{K_0\left(1 - \alpha \cos\left(\frac{2\pi k_i}{l}\right)\right)} \quad (7)$$

where

$$K_0 = \frac{K_{max} + K_{min}}{2} \quad \textit{and} \quad \alpha = \frac{K_{max} - K_{min}}{K_{max} + K_{min}}$$

The elevation of the contact wire due to the pantograph is obtained using Equation 8.

$$e(k_i) = E(k_i) \cdot F_m \quad (8)$$

After determining the elevation produced by the pantograph, the definitive contact wire height must be computed as expressed in Equation 9.

$$y_i(k_i) = y_i(k_i) + e(k_i) \quad (9)$$

Thus, the contact wire position at a kilometric point k_i can be defined as the following tuple:

$$Wp_i(k_i) = (st_i(k_i) + w_i(k_i), y_i(k_i)) \quad (10)$$

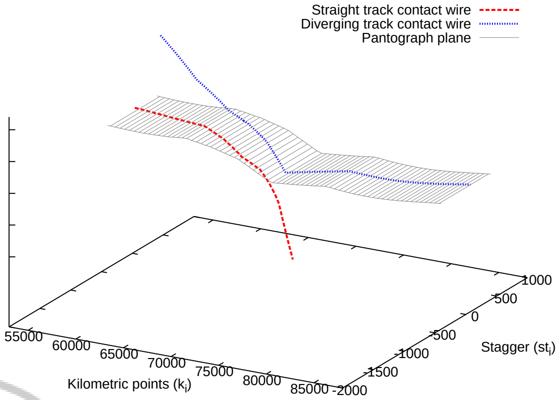

Figure 4: Simulation graphic representation.

6. *Write results*. Last step is logging results to file. Once computed all the significant parameters, the target output data of the simulation step are written to the simulation scenario log file.

The simulator provides the following output data:

- Kilometric point where an iteration of the simulation algorithm has been executed.
- Output data of the catenaries belonging to the straight track and the diverging track respectively, including elevation, stagger, height, angle, etc.
- Switching distance at this simulation kilometric point. It increases as moving forward along the switch.
- Identification of what catenaries (straight, diverging, or both) are rubbed by the pantograph.

Having all these output data will allow to reproduce the simulation results a posteriori using a graphical representation of the simulation. This representation shows relevant data displaying the pantograph run, wire positions, alarms, etc., and can help to provide users relevant information. An example of this representation is shown on Figure 4.

4.2 Evaluation Rules

Once simulated, a solution have to be evaluated in order to decide a) if that solution is feasible, and b) if that solution is a ”good” (maybe optimal) solution. Evaluating a solution is carried out by a rules engine, which applies a certain number of rules over the output results obtained from the simulation. These rules can be catalogued in different categories.

From domain specific restrictions (*sine qua non* conditions), to different aspects involved in the design process beyond the simulation model scope, the rules engine allows us either to mark a solution as valid or not, or to score the solution indicating a degree of goodness. Domain specific restrictions, as part of the simulation model, will be described now, while additional rules coming from other actors in the design process will be discussed on sections 4.5 and 4.6.

The following are domain restrictions inherent in the simulation model. More than to normative, economic aspects, or other parts, they are related to the physical issues of the problem, such as maintaining the power supply, avoiding breakdowns, etc.

1. The contact wires do not interact with the pantograph, so overhead line is not supplying the train with energy.
2. The stagger of any of the wires interacting with the pantograph is larger than a half of the pantograph friction surface. Usually pantographs are designed to rub against the wire in a specific strengthened zone, located at the middle of the pantograph. In order to avoid breakdowns, contact wires cannot make contact with the pantograph outside this zone.
3. Contact wires of straight and diverging tracks intersect. Since different centenaries can be fed by different power stations, accidental contacts between contact wires can produce short-circuits.

4.3 Layer 1: Trade-off between Accuracy and Complexity

Time spent on simulating one single scenario is a critical issue with regard to simulator's usability and productivity. Furthermore, the more accurate a simulation is, the longer the time required to carry on with it will be. When simulating overhead air switches, step size determines the detail level of the simulation. In order to obtain results as real as possible, simulations have to be carried out by millimetre-steps. By this way, pantograph and wires output data are more accurate. On the other hand, more steps imply more computing resources, performing more calculations in order to obtain a larger amount of output data.

For each simulation step, the processor has to solve the equations shown before. Modern CPU cores can perform millions of operations per seconds, which implies no more than a millisecond spent on solving simulation steps and writing output data to files. The problem is that the largest railway switches may have a length up to 1000 metres. This implies that a scenario may require about one second to be simulated (using steps of one millimetre). This amount of time is acceptable when dealing with just one single scenario, but when dealing with thousands or millions of scenarios (see further sections) high-performance techniques are necessary to run different simulations concurrently, taking advantage of multi-core or multi-processor systems.

4.4 Layer 2: Generation and Evaluation of Possible Solutions

As previously mentioned, we state that an efficient simulator should evaluate and simulate a set of solutions with a minimal user involvement. New generation simulators should be capable of, starting from a range of possible parameters, proposing and evaluating new designs. The proposed framework aims this objective through introducing a new component in the simulator.

This component is a scenario generator, which wraps the simulation model (simulation and evaluation of one single scenario) generating different solutions to be evaluated. This component generates new scenarios through variations on the input data, thus allowing experimentation with different simulation parameters, different components, or different domain restrictions. Those scenarios are provided to the simulation engine, which carries on with the simulation as described in the previous section.

Generating and evaluating multiple scenarios automatically allows the simulator to test different solutions, thus providing a faster way of exploring the solution space. Rather than obtaining one single solution, by this way a set of feasible solutions is obtained, and the user can select the best one. Moreover, as will be described in Section 4.6, enhancing the simulator with optimization metrics or some experts knowledge brings the opportunity of performing an automatic guided search of the solution space.

In order to cope with this issue, our simulator implements a new module, accountable for generating multiple scenarios. In order to do this, we change the input data definition. With regard to the simulation model, input parameters are transformed from scalar values (e.g. train speed Ts = 220 km/h) to an interval of test values defined by the user, who specifies a maximum, a minimum, and a delta variation. Let P an interval parameter, $P = \{P_j / P_{min} \leq P_j \leq P_{max}; P_j = P_{min} + j \cdot \Delta P; j \in \mathbb{N}^*\}$. By this way we define a complete set different values, and different simulations each one using a different value of this parameter have to be performed.

Of course, introducing variations in several parameters at the same time increases the number of scenarios exponentially, since we have to perform combinations with elements of the two (or more) sets. An advantage of this explosion is that the solution space is rapidly explored, evaluating a huge number of solutions from the problem space. As a drawback, a large amount of computing power is required to perform a large number of simulations, so the trade-off between accuracy and complexity previously mentioned has great significance. In this particular case, the number of combinations of catenary configuration parameters can reach over one million. Each one of these combinations is a possible solution of the design problem. In order to carry out the search efficiently, multiple scenarios can be simulated concurrently, dispatching simulation kernels performing different scenarios to different CPUs. In Section 5, an illustrative example will be shown, indicating input parameters variation, number of scenarios generated, evaluated, and time consumed in simulation.

4.5 Layer 3: Other Actors

The amount of scenarios outputted from the previous layer would be unmanageable by the user if no more filtering is applied apart from the physical domain restrictions. In order to increase the functionality and productivity of the simulator, we have to take into account the different stakeholders which take part in the design process. Different determining factors may fall into this category: legislation and normative, cost limitations, provider or client restrictions, available stock, and so on. There are two ways of considering such participants. The first is enhancing the set of evaluation rules, checking not only physical domain restrictions, but also specific restrictions from different sources. The second is restricting values of the input parameters, limiting the generation of new scenarios to only those which may comply with those restrictions.

Our simulator may take into account different normative currently in force. So additional evaluation rules have been implemented in order to check if a solution is feasible or not, counting:

- Normative EN-50119 (BS-EN-50119, 2009). This normative stipulates different restrictions with regard to overhead line deployment (minimum and maximum height, droppers configuration, etc.). Moreover, it stipulates different restrictions about the way the pantograph makes contact with the wires.

- Normative EN-15273 (BS-EN-15273, 2009). This normative stipulates maximum width and headroom in railway lines, stating that certain area around the rails have to be free of obstacles. This restriction has effect in the way the overhead lines are deployed.

4.6 Layer 4: Expert's Knowledge

Even if additional restrictions from other actors are considered to filter the number of feasible solutions, the resulting set might be too large to be useful. Besides, the user doesn't know what solutions are better than the others. Expert's knowledge can be applied in order to discriminate, from the set of feasible solutions, what are the best ones. In order to do this, first of all we have to declare what optimization metrics are going to be followed, i.e. the criteria that determines if a solution is better than other. Then, that criteria can be applied by two ways: the first is enhancing the set of evaluation rules with a new set of rules which don't check the feasibility of the solution, but score the solution following the proposed criteria; the second is modifying again the generation of new scenarios trying to seek those scenarios that best fit with the proposed criteria, in the same way as MOEAs (MultiObjective Evolutionary Algorithm) try to reach the optimal solution. The first approach may lead to an exhaustive search in the solutions space, but as drawback, all solutions must be simulated. The second approach saves time by driving a guided search, but a number of solutions can remain ”untested”.

With regard to our overhead air switch simulator, several optimization metrics have been chosen. The issue of getting such a solution for the overhead air switch design problem is not defined by any regulation, i.e., it is still an open research topic. We have closely cooperated with railway experts to define the metrics to be used, thus including that knowledge within the simulator. Some example rules are shown below:

1. Maximizing the average distance between contact wires of straight and diverging tracks. It forces the wires to be as far apart as possible. This will avoid potential problems due to high electrical voltages flowing through the wires.

2. Minimizing the variance of stagger of the diverging track contact wire. This metric is intended to avoid too many sudden changes of position of the contact wire on the pantograph.

3. Minimizing the average symmetry between contact wires of straight and diverging tracks. It measures the difference between the stagger of both contact wires, which are sought to be as symmetrical as possible to the axis of the pantograph, thus avoiding a pantograph tilt towards one of the sides.

4. Minimizing the input angle of the diverging track contact wire in the pantograph along the transitions STI-BTI. This angle is intended to be as low

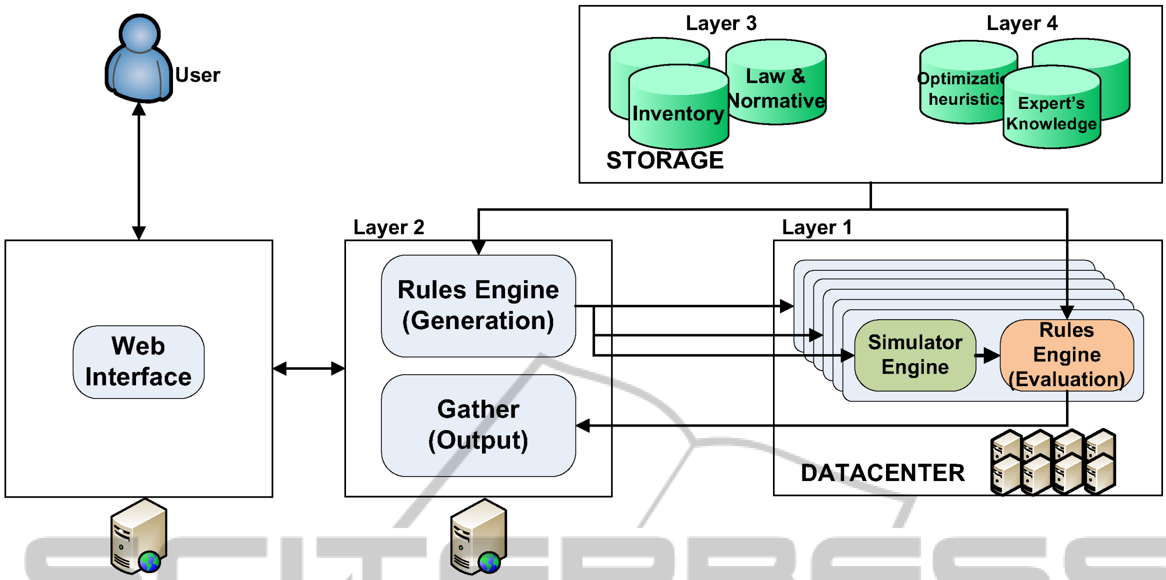

Figure 5: Simulation architecture following the proposed framework.

as possible, thus avoiding a sharp blow on the pantograph. By smoothing the entry of the contact wire in the pantograph, damages and premature wear of the wire can be decreased.

5. Minimizing the output angle of the straight track contact wire out of the pantograph along the transitions BTI-DTI. This angle is desired to be as low as possible, thus avoiding a sharp blow on the pantograph. This metric is particularly important when simulating a train the other way around, i.e., from the diverging track to the straight track.
6. Minimizing the average of stagger of the diverging track contact wire. This metric ensures that the diverging track contact wire is as focused as possible to the axis of the pantograph, thus avoiding the approximation of the thread to the edges of the pantograph and ensures that the contact wire is always going to enter a valid area.

The first metric is maximized, but the overall function, that includes all the metrics, must be minimized. To resolve this conflict, we change the sign of the first metric value so as to normalize the result. In order to compute the overall function, we use a specific weight to confer greater or lesser importance on each metric. At the end, the optimal scenario is the one that minimizes the overall function value. Since there are metrics inversely correlated, it is impossible to find a scenario having the best value per metric, being possible to have a scenario better in some metrics and worse in other ones. According to this fact, the framework finds best scenarios considering an overall function of all metrics, following a Pareto frontier.

Figure 5 describes the global architecture of the simulator, adapted to the proposed framework. The simulation model is composed of the simulation and evaluation components. A generation engine produces different scenarios to be tested, dispatching simulations concurrently to any CPU available. Data proceeding from other actors and expert knowledge feed both generation and evaluation engines, in order to reduce the amount of generated scenarios, filter the number of feasible scenarios, and calculate the degree of goodness in order to obtain the best ones.

Table 1: Parameters of the study cases.

Study case	Radius	Max. speed	Type
1	250 m	20 km/h	Former installations
2	500 m	60 km/h	Non high-speed
3	1500 m	100 km/h	High-speed

5 EVALUATION

In this section we perform an evaluation of the overhead air switch simulator using three different study cases. A brief description of that study cases is presented in Table 1.

We have selected three types of switches, depending on the maximum allowed speed of trains running along the switch. The first study case is a small switch with a short radius (the shorter the radius is, the slower the train has to run along the switch). These switches are used in old stations, legacy of former installation. Due to its closed curve, these switches should be crossed at low speed. The second study case is a regular switch used in modern non-high

Table 2: Computing time and number of solutions generated and simulated.

Case	Mode	Scenarios generated	Scenarios discarded	Final set	Generation time (s)	Simulation time (s)	Evaluation time (s)
1	Parallel Sequential	55440	54944	5	6	243 1067	2
2	Parallel Sequential	81900	81750	5	8	960 3548	10
3	Parallel Sequential	126000	125700	5	12	1789 6510	24

speed tracks. Finally, the third study case is a high speed switch.

Once all the study cases have been presented, we analyse the results from two different points of view: a performance analysis in terms of computational efficiency, and an analysis of the adaptation between the proposed framework and the described simulator. All the experiments have been carried out in a Linux workstation with an Intel Core i5 760 2800 MHz, 4 CPU cores, and 16GB of RAM. We have used a MPI version of the simulator dispatching one MPI process per core.

Table 2 shows the workload distribution across the different stages of the framework. It also indicates the number of scenarios generated, evaluated, and discarded. Following the proposed framework, most of the computing time is spent on simulating and to a lesser extent evaluating solutions. The remainder of the computing time is spent on generating all the scenarios. In order to analyse the performance we have calculated the speed-up, which shows the time improvement provided by concurrent simulation of scenarios when using a multi-core computer. The average speed-up calculated among all the study cases is 3.90. It can be seen that the parallel execution outperforms sequential execution. This is because, as we state on Figure 5, the simulator allows to dispatch scenarios to different cores of the CPU, carrying on simulation and evaluation stages concurrently. Provided that all study cases have been test in a four-core CPU, the calculated speed-up value is nearly the theoretical one (4). This implies the absence of bottlenecks and a high degree of scalability with regard to to the number of scenarios simulated. Only the generation stage is not carried out concurrently, which represents the remaining 0.1 between calculated and theoretical speed-ups.

After analysing the performance, we focus on the adaptation to the proposed framework. The characteristic points are marked below:

- Generation of different scenarios by combining the interval parameters is implemented as a rules engine within layer 2.
- Normative EN-50119 and EN-15273 are implemented as evaluation rules in layer 3, along with physical domain restrictions described in Section 4.2. All are applied in the evaluation step.
- A high number of solutions are generated by variation of input parameters in all study cases. Nevertheless, most of them are discarded by physical criteria or normative. The final set of feasible solutions is ordered through applying optimization metrics defined in Section 4.6, leaving the user to analyse only 5 scenarios out of the thousands that compose the problem space.

6 CONCLUSIONS

In this paper, we have presented a simulation framework with the aim of enhancing functionality and productivity of simulators in the field of railway infrastructure design. This approach is focused on four main issues: trade-off between accuracy and complexity, automatic generation and simulation of possible solutions, taking into account other participants in the design process, and integrate expert's domain knowledge and optimization metrics. This structure improves the efficiency of the simulators by giving them the ability of searching for the best solutions in the problem space. Also, obtained solutions will be fully-integrated with the different actors of the design process.

A case study is provided in the form of a railway overhead air switch simulator. We describe the problem and the current simulation model which reproduces the pantograph run across the air switch. Starting from this simulation model, more layers have been added following the proposals of the simulation framework. As a result, the simulator provides a set of feasible solutions, in accordance with current normative, and sorted by a degree of goodness provided by expert in the field. Evaluation results show how a huge amount (tens of thousands) of scenarios can be tested, obtaining a reduced set of feasible solutions, and grading these solutions using optimization metrics. Time to simulate and evaluate all scenarios has been less than two hours in the works case.

As future work, we will analyse in more detail the simulation framework. A main guideline is to propose a complete IDE, in which the user can customize all elements described in this paper (simulation model, evaluation rules, experts knowledge, etc.). Besides, several efforts are currently in progress in order to adapt the framework to modern computing paradigms such as cloud computing. Finally, other future work will be to extend the framework, from the limited domain of railway infrastructure design to a broad domain of simulation in engineering. Concepts in railway infrastructure design are quite similar to other engineering domains, (civil engineering, chemistry) so the proposed framework could fit with these other domains.

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