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Knowledge-based minimization of railway infrastructures environmental impact

Francisco Barrientos [a,*], Alberto Moral [a], Jorge Rodríguez [b], Carlos Martínez [b], Francisco Campo [c], Roberto Carnerero [c], Manuel Parra [d], José M. Benítez [d], Gregorio Sainz [a,e]

[a]*CARTIF Centro Tecnológico, Parque Tecnológico de Boecillo 205, 47151 Boecillo (Valladolid), Spain*
[b]*VIAS Y CONSTRUCCIONES S.A., c/ Orense 11, 28020 Madrid, Spain*
[c]*INGURUMENAREN KIDEAK INGENIERIA, c/ Fandería 2,Oficina 102, 48901 Barakaldo (Bizcaia), Spain*
[d]*University of Granada, DECSAI, CITIC-UGR, IMUDS, ETSI Informática y Telecomunicación, 18071 Granada, Spain*
[e]*University of Valladolid, Systems Engineering and Control Department, School of Industrial Engineering, 47011 Valladolid, Spain*

Abstract

Life Cycle Assessment (LCA) and intelligent data analysis can help in reducing carbon and water footprints of rail infrastructure construction projects. The goal is to improve the railway construction processes with regard to their environmental impact, mainly in those aspects related to climate change such as carbon and water footprints.

Based on a set of 27 indicators of every task in the construction process, a comprehensive compilation of basic information was performed, where the main project units and their sub-tasks were reviewed and analyzed.

Afterwards, focus was on analyzing the transformation from environmental impact to carbon and water footprints, by means of the development of a consolidated evaluation methodology. A tool is being developed based on data mining and computational intelligence approaches. It will allow knowledge-based alternative project units scheduling, conditioned to previously selected specific footprint values and environmental indicators. This decision support system (DSS), based on multi-criteria and multi-objective intelligent optimization algorithms, will help to reduce carbon and water footprints of rail infrastructure construction projects by around 10% and 5%, respectively.

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* Corresponding author. Tel.: +34-983-546-504; fax: +34-983-546-521.
E-mail address: frabar@cartif.es

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Tests are going to be performed on two real high speed railway construction projects. That way, a global search procedure provides an analysis of the best alternatives in the scheduling and execution of the project units and their environmental impact offering a front of solutions displaying different trade-off amongst several ‘footprints’.
Results will allow the development of a series of environmental impact indicators, which will support rail infrastructure construction companies becoming more sustainable and efficient by minimizing their environmental impact.

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Keywords: LCA; Social LCA; computational intelligence; carbon footprint; water footprint; sustainability; rail infrastructure

1. Introduction

Life Cycle Assessment (LCA) techniques, combined with intelligent analysis of data coming from rail infrastructure works, is helping to reduce their carbon and water footprints. The goal is to improve the rail infrastructure construction processes with regard to their environmental impact, mainly in those aspects related to climate change like carbon and water footprints and other environmental indicators. This is a rising trend, as illustrated by Botniabanan AB (2010) environmental product declarations (EPD) of railway infrastructures.

At a fast pace, water footprint of a process or infrastructure is getting relevant, due to scarcity of this natural resource. This paper presents a pioneer study on this matter, because no other reference about water footprint of rail infrastructures has been found on the specialized literature. The study here described is aligned with the European Water Initiative, EUWI (2002), fostering a correct water resources management. Also social impact estimation of rail infrastructures is a novel approach.

A threefold (environmental, economic and social) in-depth analysis has been performed on railway infrastructure project units. A multi-objective optimization has been performed on these three values, in order to find a trade-off solution for project units scheduling.

This paper is organized as follows: Section 2 describes the problem related to environmental and social impact of rail infrastructures' construction. Section 3 explains the proposed methodology. The analysis of some preliminary results is shown in Section 4. Finally, the main conclusions and further work and research are outlined in Section 5.

Table 1. Kilometers of high speed lines in Europe, source UIC (2011).

Country	In operation	Under construction	Planned	Total country
Belgium	209	0	0	209
France	1,896	210	2,616	4,722
Germany	1,285	378	670	2,333
Italy	923	0	395	1,318
The Netherlands	120	0	0	120
Poland	0	0	712	712
Portugal	0	0	1,006	1,006
Spain	2,056	1,767	1,702	5,525
Sweden	0	0	750	750
Switzerland	35	72	0	107
United Kingdom	113	0	204	317
Total	**6,637**	**2,427**	**8,705**	**17,119**

2. Environmental & Social Impact of Railway Infrastructures

Rail transport causes 0.2% of global emissions in EU27, and about 28% of total emissions associated with rail transport are due to the infrastructure, according to Skinner et al. (2010). Almost half of these emissions are caused by the construction of the infrastructure, showing the high environmental impact of this activity. Most of those emissions are due to materials production and transport, being this last issue a key point for environmental impact reduction. Table 1 illustrates the growing number of km of high speed lines in EU.

Construction of one kilometer of railway supposes around 1.04 CO_2 tons emissions, assuming most of the energy used for its construction comes from fuel oil (1 kWh=0.2674 $kgCO_2e$, according to Carbon Trust (2011) "Conversion Factors"). It is estimated that the amount of energy needed to build railway infrastructure, including tunnels and bridges, is 45,000 GJ/km track, according to Simonsen (2010), based on the work of Schlaupitz. Both, direct and indirect emissions, shows the high environmental impact of these activities. Thus, implementation of LCA techniques in railway construction can contribute to reduce those emissions, Campo et al. (2014).

3. Methodology

The goal of this study is the development of a methodology to optimize decision making process, reducing carbon and water footprints of railway infrastructure construction. The fixed goals are to reach a reduction around 10% and 5%, respectively. Other environmental indicators are also taken into account, like Acidification Potential, Photochemical Oxidation, Eutrophication Potential, as well as economic and social indicators. Thus, the environmental, economic and social impact of rail infrastructure construction process has been reviewed and analyzed, as illustrated by Fig. 1.

3.1. Project units compilation

The first step has been a comprehensive compilation of railway networks construction materials, solutions and processes, ADIF (2008), and the calculation of different sustainable aspects to analyze the environmental, economic and social impacts of the processes involved in the construction. Not every phase in the construction process is taken into account. This paper focuses on *Infrastructure* (subgrade and substructure) and *Superstructure* phases, as stressed by the dotted line in Fig. 2, because they produce the highest environmental impacts.

The first goal was to determine exactly what is to be considered as railway infrastructure, remembering that a sustainability assessment tool has to consider the entire subgrade and substructure and those items of superstructure performed more frequently, according to construction companies' experience. Catenary and signaling project units are excluded of this study.

To define the scope of the study, the second step has been the definition of what could be the life cycle of a rail structure, which could include the following stages: raw material extraction, transportation of raw materials, manufacturing, distribution, construction, use, maintenance & storage, and end of life.

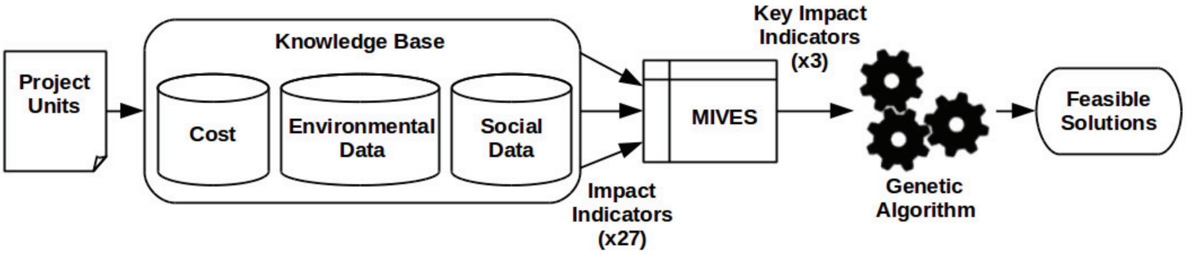

Fig. 1. Proposed methodology schema.

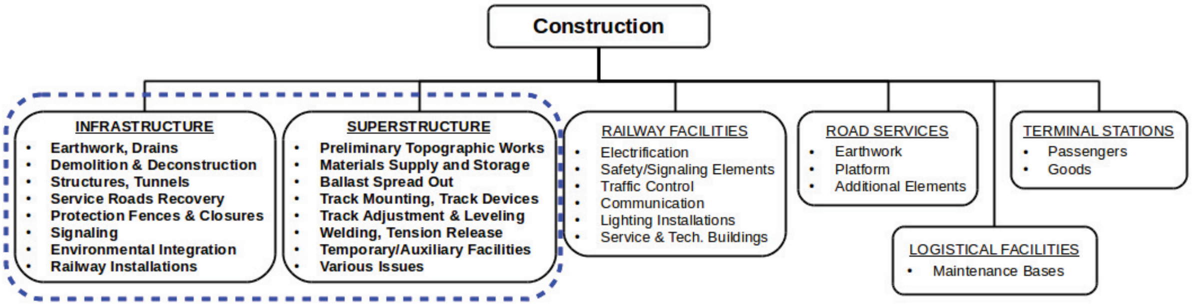

Fig. 2. Phases of railway infrastructure construction.

Based on this definition, the scope of the study, i.e. what stages of the life cycle must be included in a railway sustainability analysis, was defined as “cradle to gate.” It is because considering the maintenance phase and end of life phase would need for evolution models that allow estimations based on the design and implementation planning (maintenance needs and the frequency and type of track renovations) which would not be affordable under this study. Moreover, this assumption is supported by the work currently done on Environmental Product Declarations such as “Environmental Product Declaration (EPD) of Bothnia Line”, EPD (2015), and other similar documents where it was found that in the product category rules, maintenance and end of life phases appeared as optional because of the limited information that exist, hindering the development of a reliable assessment of this stage.

The first phase was an analysis of inputs/outputs inventory, including a detailed description and data compilation of the different project units typologies considered. This was the foundation for building the knowledge base.

The environmental indicators considered in this study are carbon and water footprint, Acidification Potential, Photochemical Oxidation (POCP), and Eutrophication Potential. The environmental impacts of these indicators have been established and calculated following the guidelines of three international standards referring to life cycle assessment: ISO 14040 (2006), ISO 14044 (2006), ISO 14025 (2006) and Sustainability of construction works - Environmental product declarations standard UNE EN 15804 (2012).

With respect to social impact, methodologies are less developed than environmental ones. Thus, and according to the limited specialized bibliography data, see UNEP (2009), the indicators shown in Fig. 3 have been selected. These indicators have been calculated using data from 253 countries obtained from Datacomex (2015). Another extra social indicator has been considered: **job creation (S6)**. It is directly related to the work hours needed to build the infrastructure and, unlike others it is considered as a positive indicator.

Economic indicator measures the cost of developing the infrastructure, including line items for workforce, materials and machinery, as well as overheads.

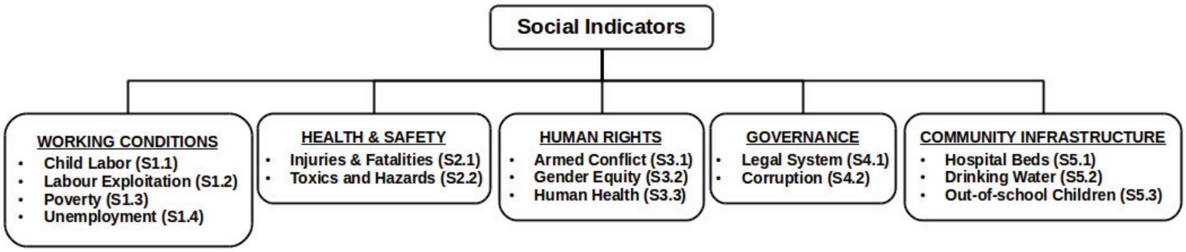

Fig. 3. Social indicators.

3.2. MIVES

MIVES, Viñolas et al. (2009), stands for Value Integrated Model for Sustainable Evaluations. It is a decision support methodology suitable for comparison of variables with different measurement units. One of the most important features of MIVES methodology is that evaluation model approach precedes the creation of alternatives. Thus, decisions are taken at the beginning, when the aspects taken into account and how to be assessed are defined. The advantage of this approach is that decision making is done without any influence of the assessments of the alternatives, preventing any kind of subjectivity happen. The phases of the MIVES methodology are:

- Decision delimitation: setting the system limits, boundary conditions and who is the decision maker.
- Decision-making tree introduction: aspects taken into account in the decision making are branched, i.e. sorted in a tree-like structure.
- Value functions creation: such functions provide a [0-1] interval rating for all aspects belonging to the last branch.
- Weights assignment: weights measure the relative importance of each of the aspects with regard to the remaining members of the same branch.
- Alternatives definition: various feasible alternatives to the decision-making problem are defined. In some cases, the alternatives are preset at the start of decision making and therefore this step should not be performed.
- Alternatives rating: the index value for each of the proposed alternatives is obtained.
- Sensitivity analysis: the possible change of the index value of each of the alternatives is analyzed, in the case of varying weights and value functions defined in the early stages. This step is optional.

3.3. Multi-Objective Evolutionary Algorithms (MOEA)

Evolutionary Algorithms (EA) are adaptive methods, generally used in search and optimization problems of parameters, based on sexual reproduction and on the principle of survival of the fittest. According to Goldberg (1989), genetic algorithms are search algorithms based on the mechanics of natural selection and natural genetics. They combine the survival of the fittest between sequences of structures with a structured exchange of information, but randomized, to constitute a better search algorithm.

To get the solution to a problem EA starts from an initial set of individuals randomly generated, called population. Each of these individuals represents a possible solution. These individuals will evolve based on the schemes proposed by Darwin on natural selection, and they will adapt better and better to the required solution after the passing of each generation.

Any potential solution to a problem may be represented by giving values to a number of parameters. The set of all parameters (genes, in the terminology of genetic algorithms) is coded in a value chain called chromosome. The first step is to select individuals to be copied to the next generation. In this case NSGA-II (Non-dominated Sorting Genetic Algorithm 2) method is used, Deb et al. (2002). Once the selection has chosen fitted individuals, they must be randomly altered in the hope of improving their fitness to the next generation. There are two basic strategies to carry this out. The first is called mating, and involves the election of two individuals to exchange their code segments, producing an artificial “offspring” whose members are combinations of their parents. The second method is called mutation. Like a mutation in any living organism changes a gene by another, a mutation in a genetic algorithm also causes small changes in specific points of the code of an individual. For the proper functioning of a genetic algorithm it is necessary to have a method to indicate whether population individuals represent good solutions to the problem, or not. This evaluation function provides a measure of the goodness of a solution.

Multi-objective programming can be defined as part of the Operational Research. It seeks to provide efficient methods for decision-making on issues that include diversity goals, usually contradictory, that are evaluated according to multiple criteria and where the best or optimal solution is not evident, Coello (1998).

Real problems usually require finding solutions that simultaneously meet multiple performance criteria or objectives, which can be contradictory, Zitzler et al. (2000). When it is feasible to combine the objectives of a problem properly, one goal to optimize might be considered. In this case, solving the problem means find the minimum or maximum of a unique feature that summarizes all the objectives to be optimized. However, when the best combination of objectives is unknown, or simply impossible, then the aggregation is not viable. In this case, the problem is a Multi-objective Optimization Problem (MOP) because the objective function has two parts: one is objectives performance in environmental, social and economic terms, and the other is adaptation function that measures solutions feasibility in terms of constraints violation. MOEA algorithms will provide a set of non-dominated feasible solutions, Deb (1999), i.e. satisfying all constraints, providing different execution alternatives for the rail infrastructure project being analyzed.

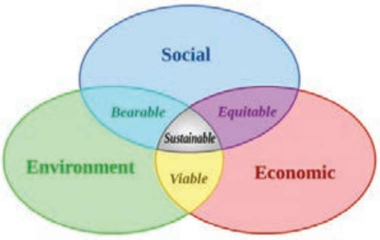

Fig. 4. Sustainability “triple bottom line”, source: Wikimedia, © Johann “nojhan” Dréo – CC-BY-SA.

3.4. Indicator evaluation

The total number of considered indicators is 27 and includes 11 environmental indicators: carbon footprint, acidification potential, photochemical oxidation (POCP), eutrophication potential and water footprint, that summarizes the values of 7 sub-indicators (water, cooling, lake, river, turbine, unspecified and well); 15 social indicators: those listed in Fig. 3 plus job creation and 1 economic indicator.

After calculating the values for these indicators, it is necessary to establish the methodology to evaluate the planning processes of railway infrastructure sustainability specifically. This study focuses on analyzing the transformation from environmental, economic and social indicators, by means of the development of a consolidated evaluation methodology. It should be pointed out that at international level the evolution of methodologies has been uneven for the three pillars of sustainability: environmental, economic and social, TCORP (2012), see Fig. 4, and this has influenced the development of the evaluation method itself. By means of MIVES methodology it is possible to summarize the 27 indicators in the 3 basic pillars of sustainability: Environmental, Social and Economic.

A tool is being developed from this information compilation, applying several data mining and computational intelligence techniques, e.g. multi-objective evolutionary algorithms (MOEA). Starting from the three values provided by MIVES, these algorithms will allow making alternative project units scheduling and will show different solutions, due to there could be more than one optimal solution.

Moreover, to improve the usability of the tool and make it simpler, work has been done on classifying which are usually the most common items to characterize and discriminate them later, in such way that it can be defined what the input data that the tool will ask to the user should be, and what data will be provided by statistical averages.

Table 2. Number of project units analyzed by phase.

Infrastructure	No.	Superstructure	No.
Earthwork	78	Preliminary Topographic Works	2
Drains	69	Materials Supply, Discharge and Storage	22
Demolition & Deconstruction	15	Ballast Spread Out	2
Structures	133	Track and Track Devices Mounting	20
Tunnels	61	Track Adjustment and Levelling	7
Service Roads Recovery	14	Tension Release	2
Environmental Integration, Protection Fences and Closures	40	Welding	5
Signaling and Railway Installations	59	Temporary/Auxiliary Facilities and other Issues	5
Total	**469**	Total	**65**

4. Results

Based on the 27 indicators previously identified, a comprehensive compilation of basic information was performed, reviewing and analyzing more than 450 infrastructure and superstructure project units, see Table 2. The sum of both columns is higher because some project units are present in more than one category, e.g. “concrete sleeper mounting” could be part of “track mounting” or “track devices mounting”. Every project unit involves several sub-tasks, as illustrated by Table 3. More than 520 sub-tasks have been analyzed. As in the previous case, a sub-task can be involved in more than one project unit.

Table 3. Example of compiled indicators for every project unit and its sub-tasks: general information.

Sub-Task	Quantity	Units	Description	Type	Cost
	1	**m3**	**Excavation at clearing site with systematic use of explosive demolition**		-
T1	0.004	h	Foreman	Workforce	-
T2	0.019	h	Skilled Workman	Workforce	-
T3	0.037	h	Unskilled Workman	Workforce	-
T4	0.224	kg	Dynamite with proportional share of detonator and fuse	Material	-
T5	0.019	h	Complete equipment of machinery for cut excavation	Machinery	-
T6	0.002	h	Bucket loader 375 HP, type CAT -988 or similar	Machinery	-
T7	0.012	h	Truck 400 HP, 32 T.	Machinery	-

Table 4. Example of compiled indicators for every project unit and its sub-tasks: environmental indicators.

Sub-Task	Carbon Footp.	Acidif.	POCP	Eutrop.	Water Footp.	WF1 Water	WF2 Cooling	WF3 Lake	WF4 River	WF5 Turbine	WF6 Unspec.	WF7 Well
T1	-	-	-	-	-	-	-	-	-	-	-	-
T2	-	-	-	-	-	-	-	-	-	-	-	-
T3	-	-	-	-	-	-	-	-	-	-	-	-
T4	1.1127	0.0056	0.0002	0.0018	2.5408	-0.1766	0.0219	0.0003	0.0025	2.6896	0.0016	0.0016
T5	0.1513	0.0011	0.0000	0.0003	0.0452	-0.0027	0.0005	0.0000	0.0001	0.0473	0.0001	0.0000
T6	0.3107	0.0023	0.0001	0.0005	0.0929	-0.0056	0.0011	0.0000	0.0001	0.0971	0.0001	0.0000
T7	1.7685	0.0133	0.0004	0.0031	0.5287	-0.0318	0.0064	0.0000	0.0007	0.5527	0.0006	0.0002
Total	**3.3432**	**0.0223**	**0.0007**	**0.0057**	**3.2076**	**-0.2167**	**0.0299**	**0.0003**	**0.0034**	**3.3867**	**0.0024**	**0.0018**

Table 5. Example of compiled indicators for every project unit and its sub-tasks: social indicators.

Sub-Task	S1.1 WC	S1.2 WC	S1.3 WC	S1.4 WC	S2.1 H&S	S2.2 H&S	S3.1 HR	S3.2 HR	S3.3 HR	S4.1 G	S4.2 G	S5.1 CI	S5.2 CI	S5.3 CI	S6
T1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.004
T2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.019
T3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.037
T4	0.007	0.039	0.056	0.033	0.019	0.004	0.036	0.059	0.058	0.068	0.140	0.057	0.218	0.026	-
T5	0.003	0.007	0.011	0.005	0.004	0.001	0.006	0.012	0.010	0.009	0.021	0.010	0.036	0.003	-
T6	0.005	0.015	0.022	0.010	0.008	0.003	0.012	0.025	0.020	0.018	0.044	0.021	0.073	0.005	-
T7	0.030	0.083	0.123	0.059	0.045	0.015	0.069	0.141	0.111	0.101	0.249	0.119	0.415	0.031	-
Total	**0.045**	**0.144**	**0.211**	**0.108**	**0.075**	**0.023**	**0.124**	**0.237**	**0.199**	**0.195**	**0.454**	**0.208**	**0.741**	**0.065**	**0.060**

Tables 3, 4 and 5 shows an example of the information compiled for every project unit, including its sub-tasks. Table 3 compiles the general information, while Table 4 and Table 5 summarize environmental and social indicators, respectively. Economic indicator depends on every construction company and the infrastructure owner requirements.

So, the cost column on Table 3 has been left empty. Workforce sub-tasks has no impact on environmental and social indicators, except for “S6 job creation”, while material and machinery sub-tasks are just the opposite case.

As explained in the Methodology section, MIVES is suitable for combining different variables. A weighting factor should be applied between the existing categories. For this, a priority relationship has been established that is directly proportional to the data source. Since (S6) “job creation” category is obtained directly from project data, it is assigned half of the weight, giving the other categories equal importance within the scope of “indirect sources of information”. Therefore, the weighting between categories has been made according to the values shown in Table 6. Weights are also assigned to the indicators within each category, considering 3 factors: severity, i.e. hardness and social difficulty for a country; duration, time while the effects are evident; and data variability, i.e. short-term data volatility. For instance, (S2.1) “injuries & fatalities” and (S2.2) “toxics and hazards” are assigned 0.25 and 0.75 weights, respectively, considering that both indicators have high severity, S2.2 last longer than S2.1 and data variability is medium for both cases. A similar procedure has been applied to environmental indicators, due to at least three different sources of environmental footprints have been considered. The economic indicator case is different, because cost is the only indicator and there is no need to apply any weight.

Table 6. MIVES weighting factors by category, for social indicators.

Data Source	Category	Weighting Factor	SUM(WF)
Indirect sources of information	(S1) Working Conditions	0.1	0.5
	(S2) Health & Safety	0.1	
	(S3) Human Rights	0.1	
	(S4) Governance	0.1	
	(S5) Community Infrastructure	0.1	
Direct sources of information	(S6) Job Creation	0.5	0.5

A decision support system (DSS) has been developed as a web application, using the R and Python programming languages for the backend and JavaScript for the frontend, see Fig. 5. The user can select a project unit, choose a color, assign the value and specify the kilometer points where the project unit will be executed. Once the project is completely defined, the tool will provide alternative solutions with equivalent project units or scheduling that optimize the environmental, social and economic impacts.

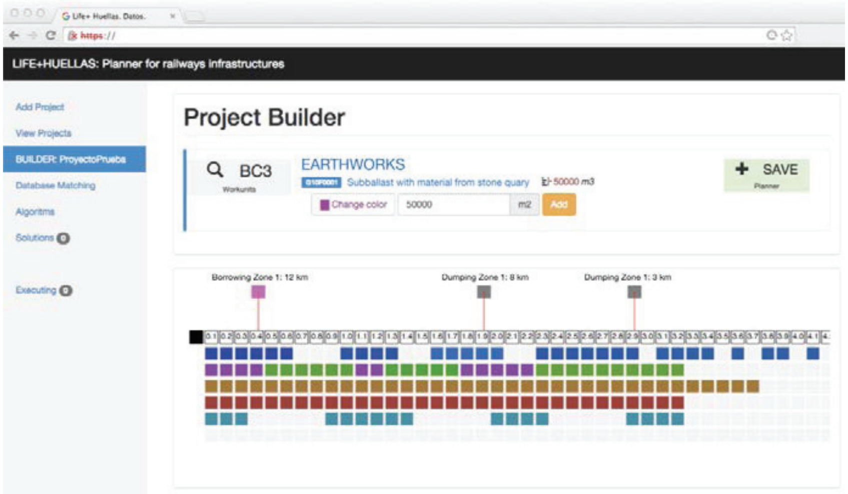

Fig. 5. DSS screenshot.

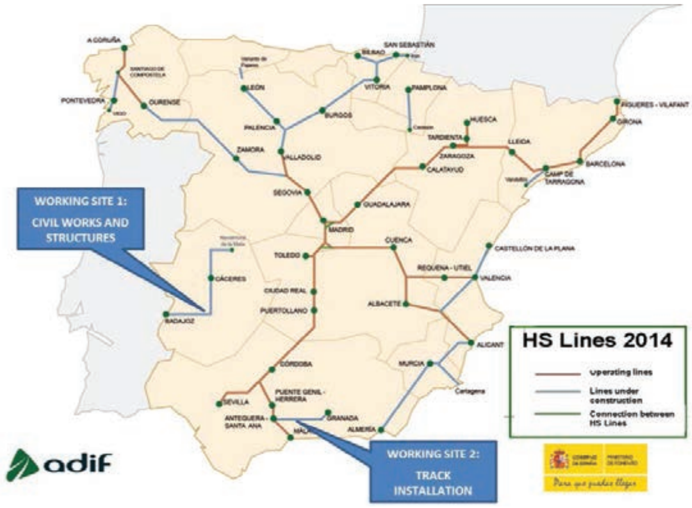

Fig. 6. Location of selected tests sites.

Tests will be performed on two high speed railway construction projects with different topologies. One pilot site is a 10.8 km section in the new Madrid-Extremadura high speed line that includes soils movements, embankments, drainages and a 90 m viaduct. The other pilot site is a 56.1 km high speed double track installation in the line Antequera-Granada (Antequera-Loja section). Both pilot sites are located in Spain, as illustrated by Fig. 6. That way, a parametric adjustment provides an analysis of the alternatives in terms of several ‘footprints’.

5. Conclusions

This paper shows an in-depth analysis of rail infrastructure project units. A threefold (environmental, economic and social) analysis has been performed on more than 450 project units, considering more than 520 sub-tasks. For every item, 27 indicators have been calculated and summarized in three values applying MIVES methodology. A multi-objective optimization has been performed on these three values, in order to find a trade-off solution.

Results have allowed the development of a series of environmental impact indicators, which will be collected in a best practices manual. The aim is to help rail infrastructure construction companies improving their performance, efficiency and profitability under several and different points of view, including environmental impacts.

On the other hand, the study promotes the incorporation of environmental criteria for public bodies or bidders, prevailing the use of this or similar tools. The Sustainable Public Procurement Initiative (SPPI) is nowadays the key policy instrument to promote sustainable development and move towards a green economy that fosters the development of products and services maximizing social and environmental benefits.

Several of the project unit implementation involves a multitude of decisions for railway companies, from supplier selection for each material or component, to the selection of machinery or execution methods. The proposed methodology integrates economic, social and environmental criteria for project optimization and impacts reduction. The availability of a methodology to promote not only the calculation of the carbon and water footprints, but also the analysis of alternative project unit scheduling, would be a substantial boost in reducing emissions and impacts associated with the construction of railway infrastructures, being an essential part of European transport policy.

Further work will be done on applying the methodology here described to those phases showed in Fig. 1 and not included in this study. Another field for improvements is on standardization of carbon and water footprints measures. According to the source, these values can change for the same item. Some efforts have been made, OECC (2015), by creating a Carbon Footprint Databases Working Group in order to share different sources of information and reach a consensus carbon footprint value by item, but further work is necessary.

Acknowledgements

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