Wind Farm Construction Critical Activities Optimization: Cost Reduction Through Logistics, Planning, Maintenance, Paving and Concrete Modelling

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ABSTRACT

Aiming to obtain cost reduction in wind farm construction projects, this study presents the conception and utilization of new civil works optimization initiatives, by creating specific modelling of critical activities. This theme is particularly relevant in Brazil, for the wind sector has presented a steady growth in the past decade, construction productivity indicators present historic low levels and there is considerable margin in applying infrastructure academic studies in new wind farm projects. This article has been applied in six recently built Brazilian onshore wind farms, with more than 1.4 GW of installed capacity and average turbine power of 2.0 MW. The modelled activities are: layout design; construction planning; heavy equipment maintenance policy; roads and pads paving; and foundations concrete pouring. These activities have been identified as critical using a work breakdown structure approach. First implementation tests obtained financial gains such as: reduction of 53 thousand km in concrete truck routing (56% reduction); 20% less field time for the foundation, steeling and concrete teams; root cause identification for issues in dump truck performance; 25% cost reduction in concrete transport; and conception of optimal maintenance policies depending on local geographies. Continuing these initiatives in new projects has the potential to further enhance wind energy's position as a technically and financially feasible energy alternative for Brazil.

KEYWORDS

Wind Energy; Civil Engineering; Modelling; Optimization; Cost Reduction.

1. INTRODUCTION

This article presents cost reduction models of wind farm construction works' specificities, with the aim to enhance this energy solution's technical and financial feasibility, particularly in the Brazilian scenario, since it is the basis for the models' conception, tests and validations.

The fact that this energy mode has acquired recent market maturation and is now a relevant part of that nation's power matrix illustrates this field of study's importance.

New wind farms installation presents logistics challenges, due to Brazil's historic infrastructure gap. This, alongside low work force qualification levels, make the Brazilian scenario, and more specifically the civil construction stage, one in which new optimization models have high potential for applications. Some specificities that motivate this potential are: intense heavy equipment mobilization in the construction site; great number of people of different specialities present in each project; and current management models with an empirical characterization.

Five different optimization initiatives are presented in this article: 1. key logistics systems allocation; 2. location-based planning methodology applications; 3. maintenance team scaling; 4. paving operations simulation; and 5. a predictive model for the foundation's concrete process.

These initiatives contemplate different stages in the project's timeline: design (first initiative); scheduling and scaling (second and third ones); and operations (fourth and fifth ones). Their conception has been motivated by an analytical study of a wind farm construction processes' work breakdown structure (WBS), in which these topics present themselves as cost critical. Thus, even though modelled individually, all five initiatives can be contextualized in a global view of a wind farm construction project.

2. LITERATURE REVIEW

Since this article has a multidisciplinary nature, different mathematical concepts that constitute the optimization models are presented. These concepts exist in different fields of study within the civil engineering and project management areas.

The first field is planning and costs modelling of construction works. There should be a better understanding on the root causes for time and costs overruns in infrastructure project. Gkritza and Labi (2008) [1] show a positive correlation between project size (in duration and financial terms) and overruns occurrence. This correlation shows that large projects, such as wind farm construction ones, demand special procedures for their planning models. To bring more predictability to large infrastructure projects, Bhargava *et al.* (2010) [2] present an econometric model that associates overruns to their root causes, through an ordinary least squares (OLS) methodology. Besides predictability, mitigation procedures are also common in the literature. Oliveri, Granja and Picchi (2016) [3] show that three main strategies are adopted in order to address the overrun challenge: traditional planning, location-based management system (LBMS) and last planner system (LPS).

Since traditional planning does not have a positive history in dealing with overruns in large projects, this article only uses LBMS and LPS. Kenley and Seppänen (2010) [4] present the theoretical ground for LBMS, which considers the location as its control item and thus is specially recommended for projects with repetitive processes in different locations. Kim and Ballard (2010) [5] present LBS, an activity-based model, in which planning occurs in two levels: a masterplan and a short-term scheduling.

Considering that wind farm construction presents repetitive processes for each tower foundation, LBMS is chosen as the most relevant approach. Büchmann-Slorup, Niclas and Lars (2012) [6] introduce the criticality concept in location-based projects. This concept is used in actions to improve productivity indexes.

The second field of study is discrete-event simulation (DES), a mathematical tool widely used in systems engineering literature, but still avant-garde in Brazil's construction sector. Smith *et al*. (1995) [7] conceive a DES application in earthmoving processes; Zankoul and Khoury (2014) [8] apply an original model in a wind farm construction case study; and Fernandes (2015) [9] similarly does it, but in a Brazilian project case study. Sztrik (2012) [10] and Harris and Ioannou (2012) [11] present, respectively, concepts for queuing theory and repetitive scheduling method, which are the theoretical foundation for the DES model used in this article.

The third field of study is graph theory, a graphical and mathematic representation of real systems, according to Ballobás (1998) [12]. Graphs are particularly useful in modelling wind farm layouts. Some classic problems and solutions, such as Dijkstra's algorithm, traveling salesman and Chinese mailman, are presented by Golumbic (2004) [13], Hoffman, Padberg and Rinaldi (2016) [14] and Farahani and Miandoabchi (2013) [15].

The fifth field of study is construction works operations. Halpin and Riggs (1992) [16] introduce the first models in specific planning and analysis for construction operations. Catalani and Ricardo (2007) [17] present common approaches to earthmoving and paving operations in Brazilian projects. Lima *et al*. (2013) [18] use operations research to model earth materials transport and distribution. Prata *et al.* (2005) [19] use coloured Petri nets to scale heavy equipment teams. Côrtes (2011) [20] presents a concrete scheduling model, for delivery processes that use a fixed concrete mixer.

The sixth and final field of study is maintenance policies. Dekker (1996) [21] reviews the literature in terms of heavy equipment maintenance models with different strategies, such as preventive, corrective and predictive. Edwards and Holt (2009) [22] present a thematic review specifically for maintenance in construction projects. Wu *et al*. (2007) [23] propose a predictive model that uses neural networks with a decision support algorithm, which uses the previous conditions of each equipment as its main variables.

3. METHODOLOGY

To obtain more robust results, this research has been developed in a multidisciplinary work framework. Alongside theoretical approach and model conception, interactions with field teams in the construction sites were also a foundation of this work. This framework allowed for the conception, application and validation for the proposed initiatives.

The activities were: literature review; field trips to wind farm construction projects; interviews with contractors; work breakdown structure definition; critical activities identification; data collection from direct sources in the construction sites; model conception for each specific optimization initiative; generation of recommendations and execution of actions within the new framework; and field tests and validations.

Six wind farm projects were used as the main database for this research. They are located in the Brazilian Northeast and have a combined installed capacity of more than 1.4 GW.

The main *in situ* collected data are: concrete traceability spreadsheets; geotechnical tests and characterizations; heavy machines' reports; organizational charts; personnel listings; fuel traceability; procurement reports; water transport and consumption history; trucks routing; locations of main land-fills and deposits; wind farm layout; and foundation design sheets. As well with these analytical data, interviews were conducted with several professionals. The most relevant interviews were conducted with: site managers; field engineers; design engineers; planning managers; geotechnical engineers; mechanical engineers; environmental engineers; financial technicians; quality technicians; mechanics; concrete truck drivers; earth truck drivers; masons; field workers; topographers; carpenters; electricians; and several types of heavy machines' operators.

Model validations were developed in two steps: first, through interviews the models were present to and pre-approved by the contractors; second, through actions based on models' recommendations the models were tested and the results were obtained.

4. RESULTS

This section presents the five models' conceptions and the results obtained in using these models in the construction sites.

4.1. Critical activities modelling

4.1.1. Key logistics systems allocation. Logistic planning optimization's main goal is to find the most suitable location for key systems within a wind farm layout. This brings considerable cost reduction by minimizing transportation distances since the start of the project – thus the importance of applying the model during design phase. Based on the work breakdown structure of wind farm construction projects, the key logistics system, in terms of costs, is the foundation concrete process. Therefore, allocating the concrete mixer in an optimal position is the main goal of this model. Here, weighted graphs are used as the modelling tool.

In order to translate a wind farm layout into a graph, it is required to define points of interest – entrances, tower pads, concrete mixer, land-fills and deposits – and to classify them as nodes, with specific classification codes for each different type of node. Roads that connect these points of interest are classified as arcs. These classifications create a graph G that represents the wind farm as a whole. Based on that, it is possible to create sub-graphs, for example graphs in which the roads are divided in nodes with fixed distances between each other, but with no specific functions.

Since this model deals with the optimal allocation of the concrete mixer, it is important to present a general context on the wind tower foundation concrete process. This process is characterized by a cycle of: concrete preparation; truck loading; transport from the mixer to the tower pad; truck unloading; material quality tests; and transport from the tower pad to the mixer. It is a repetitive process; therefore, the mixer-pad distances are considerably relevant cost-wise, for they are covered many times within a single day.

To mobilize a concrete mixer, it is required a significant, in relative terms to a civil works project, amount of labour, time, planning and funds. Therefore, it is usual for contractor's to only mobilize a mixer once for each project. The model, then, uses the mixer location as a fixed point in the graph. This fixed point is the final result that model provides to its user. To obtain the optimal solution, the objective function is as follows:

$$MIN \sum_{v=1}^{n} D[u,v] \tag{1}$$

where n is the number of pads, $D[a,b]$ is the application of Dijktras's algorithm (or a similar solution approach to the minimum path problem) between nodes a and b in the graph, v indicates the pad node and u is the control variable – the concrete mixer node, which the model aims to define optimally. The conditions for this application are: u should belong to graph G and its derivate graphs; and u should be in the domain that contains every possible location node within each access road.

4.1.2. Location-based planning modelling. Wind farm projects have several scale gain factors that make them more viable when designed with several towers – in Brazil usually around a hundred for each major project – constructed in the same time period. Therefore, civil works are characterized as a repetitive process, with the same activities (pad preparation; pad excavation; steel frame assembly; mould assembly; concrete process; pad filling and paving; crane pad quality tests) occurring sequentially and being repeated in different locations (different tower pads). As presented in literature, this type of situation is ideal for the application of location-based planning models, such as line-of-balance – a relatively simple model that, if applied correctly, minimizes teams' idleness if compared to usual models, such as Gantt graphs or critical path method.

4.1.3. Maintenance personnel investment policy. Brazilian wind farm projects are characterized by isolated locations with little previous installed infrastructure. Therefore, access roads construction is a fundamental part of such projects, which thus require investments in heavy machinery. This type of equipment is cost intensive, which means its maintenance policies are a critical aspect for optimization.

Equipment failures are a random event, in a way that they can only be analysed stochastically, due to their undesired nature. Many aspects can be considered in analysing failures: *e.g.* maintenance personnel size and experience; parts availability; procurement response times; common recurring types of failure; physical characteristics of the type of labour being executed; equipment conditions at the beginning of the project; operators experience; and accountability and management practices. Due to data quality and availability, the current modelling focus on scaling maintenance teams, in terms of investment in personnel. The model, then, consider failure history in different wind farms and takes into consideration both investments and local geographies, and uses an OLS regression model.

4.1.4. Earthmoving and paving operations. In wind farm construction, paving operations are related to the construction of access roads and crane pads that contain wind towers' foundations. Most Brazilian wind farms accesses are remote and paving operations are restricted to base and sub-base, therefore there is a common ground between earthmoving and paving operations. The main challenge in these activities is to balance the scaling of heavy equipment that are necessary for such works. This modelling should consider several external factors, such as: geographic characterization (*e.g.* type of soil); earth deposit layout (*e.g.* excavators positions); access roads conditions (*e.g.* irregularity indexes) and equipment performance (*e.g.* maintenance quality). DES is the chosen tool for this individual model, for it is capable of including stochastic variables that better represent the external factors. The DES model is presented in Figure 1.

The model uses a pre-fixed volume of earth as its working unit. The definition of this unitary volume should be based on the average dump truck capacity, with all the conversion – expansion and compression – factors considered. The model then shows each resource idle time, therefore running different scenarios until a scenario with the best cost-effective solution, *i.e.* lowest idleness, cost and total operation time.

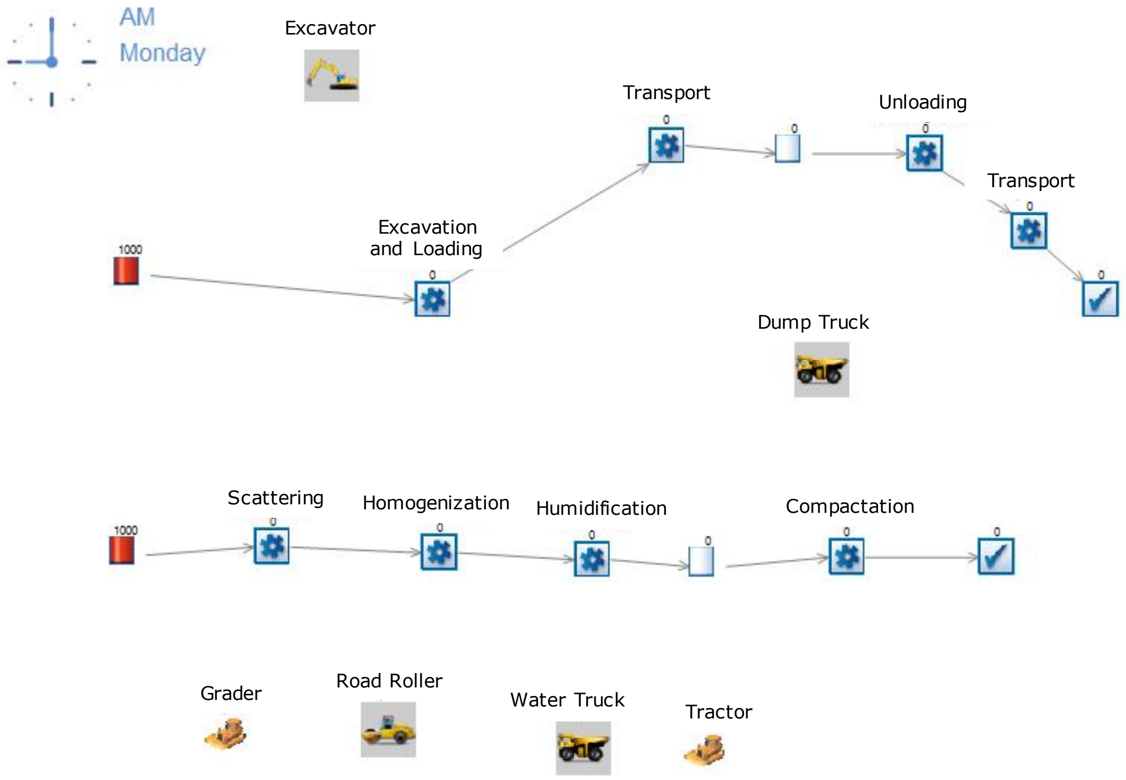

Figure 1. DES earthmoving and paving operations model

<u>4.1.5. Wind tower foundation concrete process.</u> Reinforced concrete is used to provide structural stability to wind tower foundations, alongside other possible solutions, such as pile foundations. The concrete process, which refers to the mixing, transportation, quality control and pouring, has already been described in this article. Based on a Pareto cost analysis, logistics is classified as the main cost item for operations optimization, particularly concrete trucks scaling. Schedule planning procedures indicate that filling one foundation per day is recommended. Therefore, a predictive model is required to define the optimal number of concrete trucks by answering the following question: what is the minimum number of trucks that are necessary to fill one foundation per day with minimum operational risks?

The predictive model uses critical path method and queuing theory as its main mathematical tools. The model predicts the duration of the concrete process of an individual foundation based on three main variables: concrete volume; number of trucks used; distance mixer-pad distance. Analytical equations are used to solve the problem. Stochastic variables are included for the durations of specific processes, such as loading, unloading and quality tests.

4.2. Optimization initiatives applications

4.2.1. Logistics initiative. A concrete mixer allocation project was successfully tested in a wind farm project with more than 300 MW of installed capacity. The logistics model was used to evaluate the original solution adopted by the site contractors, recommend a new optimal location and build a mixer in it. The original solution – which was not based on the presented model – was initially adopted by the local team was already implemented before the model application. After the evaluation, it was concluded that, even considering the costs of building an additional mixer, the optimal location would bring great cost reductions in terms of less fuel consumption and less mobilized concrete trucks. Figure 2 shows the comparison between both positions (original and optimal).

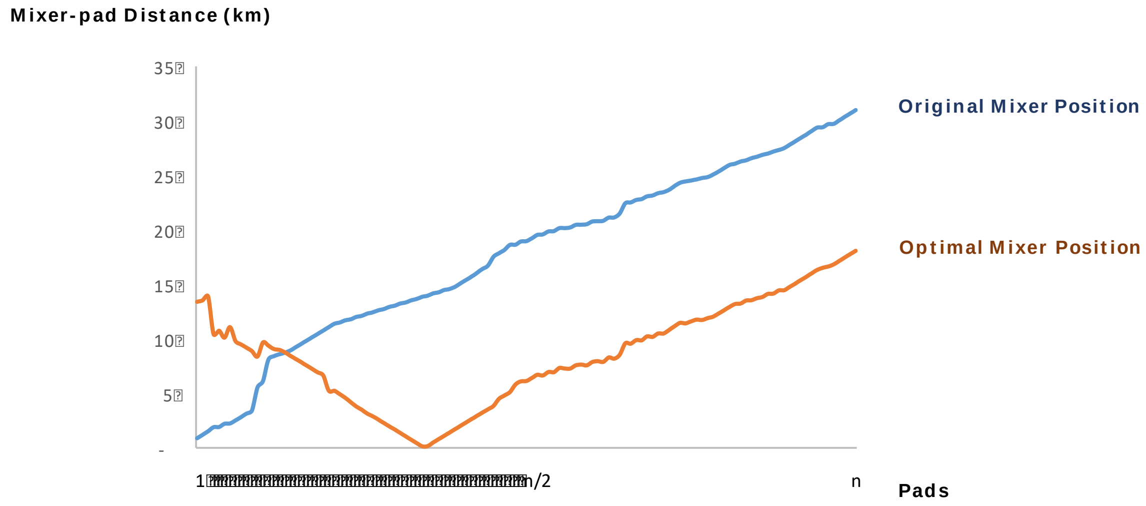

Figure 2. Transport distances reduction due to logistics optimization

A total of 53 thousand kilometres were saved during the concrete process. This means a 56% reduction in the total distance covered by concrete trucks. Beyond the financial gains, the model aggregates environmental and safety gains to the project, lowering carbon emissions and also accident risks.

4.2.2. Planning initiative. The wind farm construction location-based planning model was applied in a project that presented pile foundations as its main schedule bottleneck. The original low investments in the foundation team had consequences in idle times for subsequent teams, such as steel assembly, mould assembly and, most importantly, concrete pouring teams. The model application resulted in a new pile foundation team scaling, which reduced total mobilization times – and therefore costs – for these subsequent teams in 20%, as shown in Figure 3. The Figure show a basic line-of-balance approach.

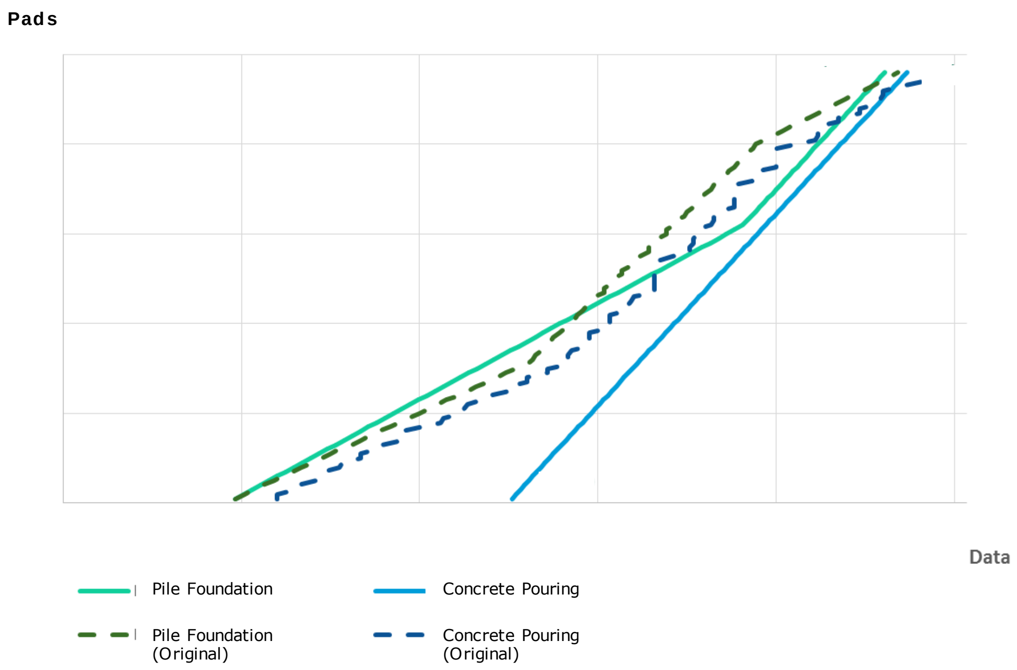

Figure 3. Line-of-balance application with concrete pouring team field time reduction

4.2.3. Maintenance initiative. By crossing maintenance team investment and failure indicators, the model has found a negative correlation in all the projects to which it has been applied. After running the regression model, different results were obtained for different natural conditions. Figures 4 and 5 present examples of, respectively, less harsh conditions (Project 1, countryside project) and harsher conditions (Project 2, coastal project). Both graphs are in the same scale, but scale values in both axis were removed due to confidentiality limitations. Each point represents monthly data.

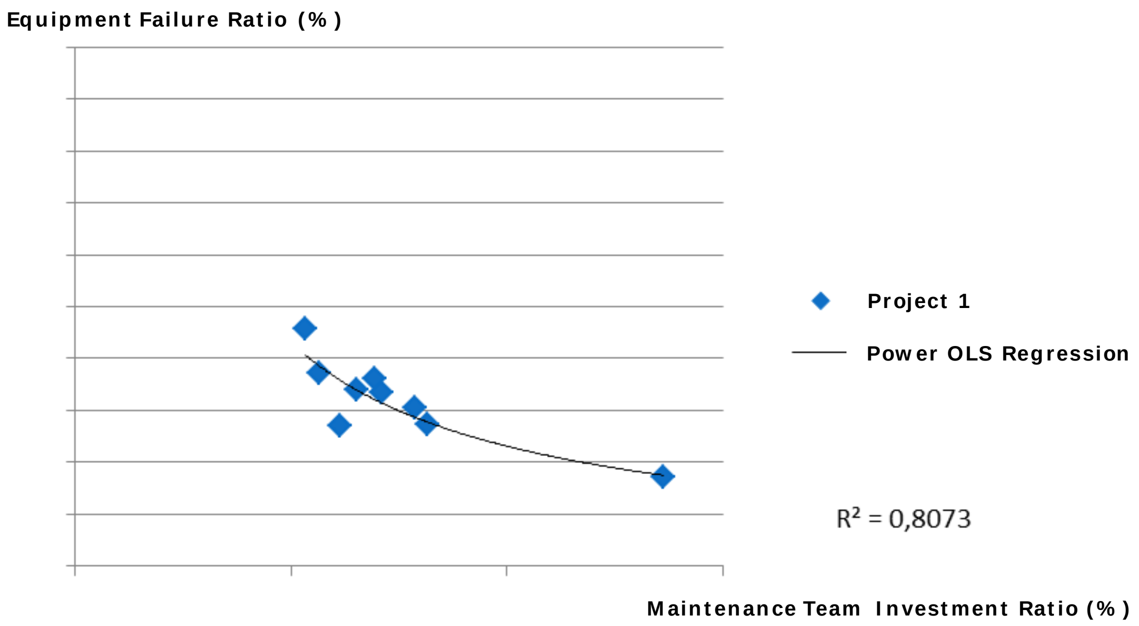

Figure 4. OLS regression for maintenance investment policy in non-harsh natural conditions

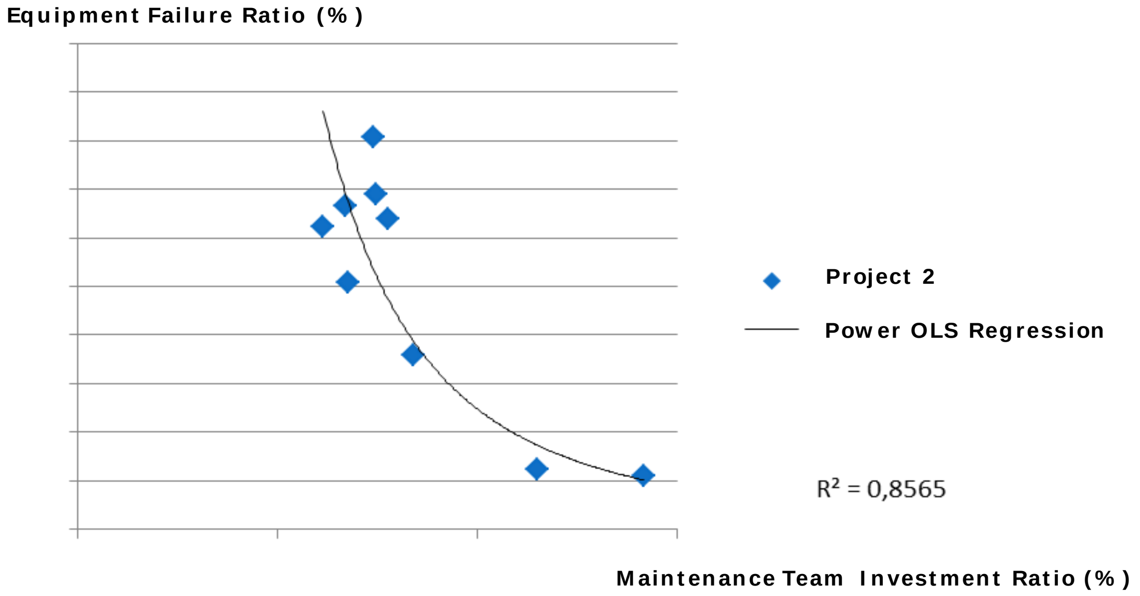

Figure 5. OLS regression for maintenance investment policy in harsh natural conditions

The optimal point for maintenance investment (x axis represent its ratio as a total of the investment in heavy machinery) is the one where *dy/dx* equals -1.

4.2.4. Paving initiative. The paving model, which also includes earthmoving operations prior to the paving process, was applied in one wind farm with two goals: first, to obtain an optimal scaling of the heavy machinery used in it; and second, to evaluate individually each equipment. The first goal is attained by using the DES model presented in this article. It is fundamental to solve this problem first in order to address the individual performances, for the DES model gives not only the optimal scaling, but also the expected optimal durations for each activity – and thus the optimal performance for each type of equipment.

For having a higher variability, due to the larger number of machines mobilized, dump trucks are chosen as a focus on the individual analysis basis. The DES model shows that dump trucks performance should be within the two inferior areas in Figure 6 – which is the area of lower costs per transported volume. The actual results, though, show that most trucks present higher costs than expected, meaning worse performances. A root-cause analysis has shown that the payment type – per day *versus* per volume – was the main driver for performance. The model, then, served not only to give the quantitative solution to paving team scaling, but also to substantiate site managers' decision making in equipment contracts.

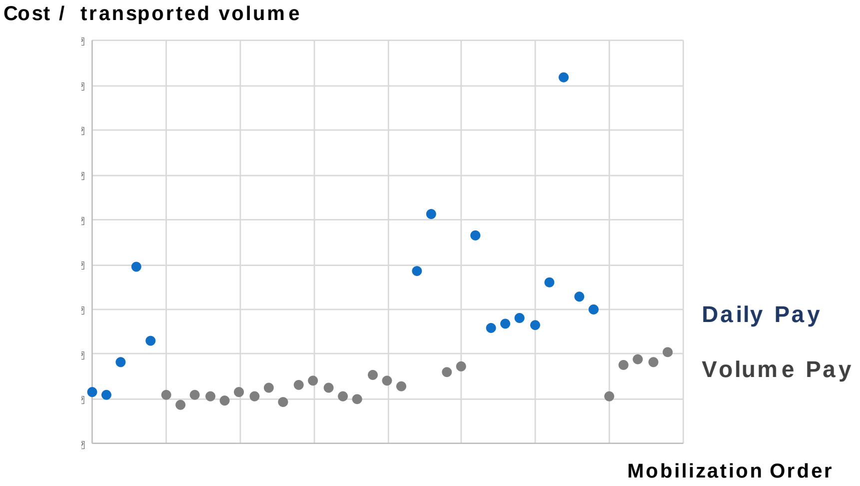

Figure 6. Individual performance analysis in concrete trucks, based on the DES model

4.2.5. Concrete initiative. The concrete process modelling presents a predictive model for its duration, based on total transported volume, number of trucks and mixer-pad distance. This confers better predictability to the managerial team, allowing them to optimize the number of concrete trucks in the field, based on having one filled foundation per day as the goal. By running the model in one wind farm project, there was a 25% cost reduction in concrete transport, due to better scaling of the main critical assets: concrete trucks.

Figure 7 presents the model performance when compared to actual duration times. Note that the predictive model is analytical and not auto-regressive. After comparing results, it was noted that the model has been overestimating individual activities durations, but the general behaviours of both time series are similar. Additionally, absolute errors were considered within a safety margin, showing that the model is robust enough to sustain universal cost reduction optimizations.

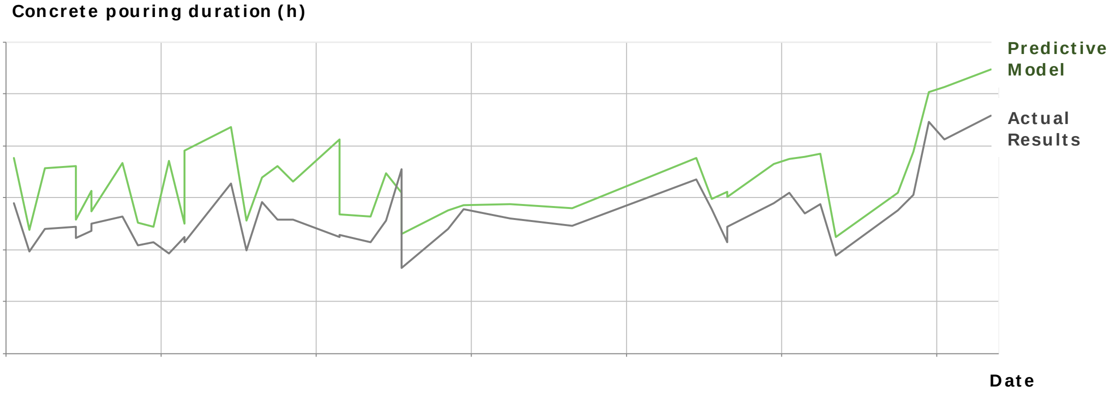

Figure 7. Concrete pouring duration predictive model *versus* actual results

5. CONCLUSION

With access to a robust set of data from six major wind farm construction projects in Brazil, and by applying concepts from a multidisciplinary literature review and using several mathematical tools, this paper presents five new optimization initiatives that have brought considerable cost reductions in field applications. These initiatives – in logistics, planning, maintenance, paving and concrete – are related to the most critical activities – time and cost wise – within this specific type of construction projects.

Each initiative contains a specific optimization model that has been applied in the field and all of them presented validated results. These results are such as: the logistics model has reduced concrete trucks covered distances in 53 thousand kilometres, or in 56% of the original distances; the planning model has reduced in 20% the mobilized time for most relevant teams in civil works for the wind tower pad construction, including its foundation; the maintenance model has found an optimal investment policy based on different natural conditions for each project; the paving model has optimized heavy machinery scaling and created a framework for individual machine performance analysis; and the concrete model has predicted with validated accuracy the duration of the wind tower foundation concrete pouring process, reducing its transportation costs by 25%. Besides the obtained financial gains, utilization of the presented models aggregates environmental and safety benefits to contractors, for they are able to reduce key risk factors, such as covered distances, number of mobilized heavy machinery, and project duration.

Even though each initiative is analysed individually, each model has interfaces with the others – they are therefore complementary. A relevant example of this is the concrete pouring process, which is modelled by four of the five presented models. Therefore, it is possible to integrate these initiatives in a global optimization model which, with the continuation field applications, has the proven potential to confer greater technical and financial viability to the Brazilian wind energy sector.

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