Extended Abstract

Intelligent Optimization Systems for Process Management in Pavement Rehabilitation

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Abstract

Pavement rehabilitation, especially in a highway context, comprises a complex set of operations from milling the old pavement to paving the new layers, while also ensuring the traffic passage. The importance of having functioning and safe highway networks makes this type of operations very time sensitive, since this usually involves closing lanes that will inevitably cause delays to users and in extreme situations end up in bottlenecks. On top of that, this construction type also relies on heavy mechanical equipment that is very expensive. Even though there is an increasing interest in completing these interventions of rehabilitation with the lowest costs and durations, little has been done to optimize this process. This thesis focuses on developing an intelligent optimization system based on an evolutionary multi-objective approach (NSGA-II), capable of supporting the decision makers in planning road pavement rehabilitation processes. To do this, the system searches for an optimum allocation of pavers that minimize both cost and duration simultaneously, while using linear programming to distribute the remaining equipment to support the pavers. Finally, the capability of the system was tested with a real motorway pavement rehabilitation project. Not only did this experiment shown the ability of the system to find the solution used in the case study, but also its ability to present a set of other optimal solutions regarding different objectives.

Keywords: Pavement Rehabilitation, Intelligent optimization systems, Project Management, Metaheuristics, Resource allocation.

1. Introduction

The road network is undoubtedly the most important infrastructure for the development of a country, it should not be seen solely as a mean of transportation, but as a crucial asset to economic and social growth and development. This network helps create jobs and promotes social and territorial cohesion while ensuring the mobility and accessibility of people and goods throughout the country.

A paramount component of this type of network is the pavement that, besides the bearing capacity, should also provide a smooth travelling surface that allows the vehicles to circulate with comfort and safety under various climatic conditions, during the pavement's design life. However, these pavements, once built, suffer from deterioration over time, in consequence of the ever-growing traffic volumes and conditions of the environment. Therefore, pavement often need to undergo some maintenance or rehabilitation actions throughout their life cycle, in order to maintain its condition acceptable.

Time and cost are clearly two of the most important criteria in choosing the methods and resources to develop a project and, therefore, can be seen as two objectives that are important to minimize simultaneously. What happens currently is that, instead of optimizing the distribution and allocation of the aforementioned variety of equipment to various work fronts, planners either rely on their experience or on a random trade-off of those two objectives.

Regarding the interventions planning process, (Morgado & Neves, 2014) developed a model to support decision makers in planning such interventions in a highway context. Their model generates a set of feasible alternatives for a specific project and compares those alternatives regarding cost, duration and user effects.

However, there is a lack of developments regarding the optimization of road pavement constructive processes, especially in the context of the rehabilitation of highways, i.e., in terms of considering equipment and operation modeling in order to obtain an optimal work sequence and equipment allocation. Actually, the little that has been done concerning optimization in the field of rehabilitation of highways, mainly focuses either on work zone planning (Abdelmohsen & El-Rayes, 2017) or time-cost- quality trade-off analysis (El-Rayes & Kandil, 2005).

Nonetheless, the optimization of constructive processes has been extensively studied in other fields, such as earthworks (Marzouk and Moselhi 2004; Moselhi and Alshibani 2009; Zhang 2008; Parente et al. 2015) or bridge construction (Salimi et al. 2018). Most of these optimization systems deal with complex problems with large search spaces and conflicting objectives, where traditional optimization methods alone (e.g., linear programming) have proven to be unsuitable to solve them. Thus, metaheuristics are presented as a feasible alternative to solve this kind of complex problems. On that note, an evolutionary metaheuristic was chosen as the optimization method in this work, more precisely genetic algorithms. This choice was supported by the existing literature, which featured attempts at solving similar problems in different fields. Even though several studies adopted other evolutionary algorithms, like ant colony optimization (Miao et al. 2009) and particle swarm optimization (Nassar & Hosny 2012; Zhang 2008), it was clear that the most popular among researchers was genetic algorithms (Marzouk and Moselhi 2004; El-Rayes and Kandil 2005; M Parente et al. 2015; Salimi et al. 2018), due to their ease of implementation and intuitive interpretation.

The genetic algorithm based multi-objective evolutionary algorithm that was chosen to develop this work was the Non-Dominated Sorting Genetic Algorithm II (NSGA-II), which has among many interesting features the ability to perform Pareto optimality (Deb 2002). This feature allows the algorithm to output a set of non-dominated solutions, which means that none of the objectives can be improved in value without worsening the other, instead of just only one solution that tries to satisfy both conflicting objectives. The decision makers are therefore presented by a set of equally good solutions to choose from according to their own criteria.

This paper is organized as follows. Section 2 describes all the components of the developed intelligent optimization system, starting with the definition of the problem, the objectives and the constraints, and proceeds to explain the main processes that compose the system, which are verification and repair and solution quality assessment. Section 3 details the experiments conducted over a case study to both validate the system and demonstrate its flexibility. Finally, in Section 5, conclusions are drawn and some directions to future research are presented.

2. Intelligent optimization system

2.1. Problem definition

Pavement rehabilitation can be depicted as a set of similar production lines based on resources that execute a set of tasks in a specific sequential order throughout different work fronts, until a certain parameter is reached. In this case, the parameter is the completion of the paving of a certain volume (m3) of bituminous mixtures. The resources that make of the production line are the heavy equipment essential for the development of the project, namely milling machines, trucks, pavers and rollers, and the sequential tasks that they perform are milling, transportation, paving and compaction, respectively, as depicted in Figure 1.

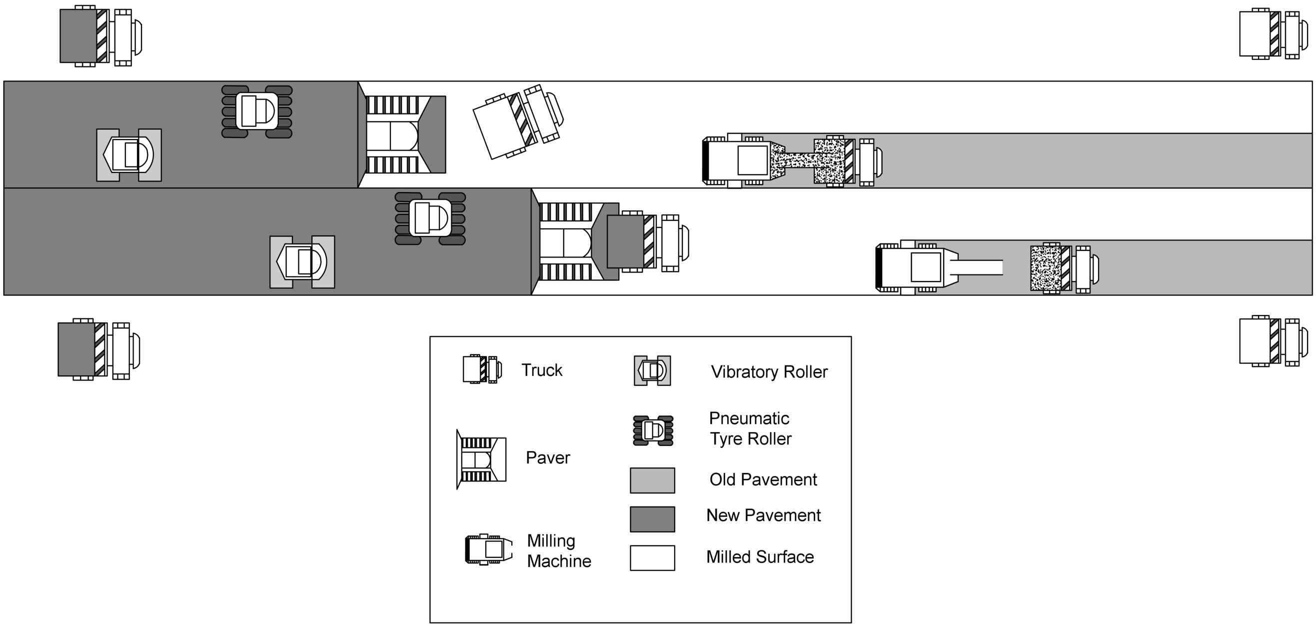


Figure 1 - Pavement rehabilitation production line (adapted from Zhang 2015)

In production lines there is always a critical path that determines the speed at which the whole process progresses, comprised by one or a set of critical tasks. In this specific case, the most relevant critical task corresponds to the paving by the pavers.

The pavers are allocated to work fronts as to form a production line, which has the objective of paving a certain volume of a new mixture, and the work fronts considered for this application are the lanes that need to be rehabilitated. Most of the times, as it is the case with the rehabilitation in a highway context, the project is not complete with just one production line, because there are usually more than two lanes to be rehabilitated at the same time, so, in this point of view, the rehabilitation construction projects are divided into a number of production lines equal to the number of paving fronts. In the case studied in this thesis the paving fronts will be limited to one lane per front.

This reallocation of each available resource every time a new phase starts makes this a time-evolving process that grants the problem a dynamic characteristic, meaning that the solution must also adapt over time. Thus, this type of optimization problem features as variables the amount and type of resources to be optimally allocated for each task in each construction phase.

2.2. Objectives and constraints

The amounts of equipment allocated are the decision variables of this optimization problem, and the objective is to minimize both construction time and costs. The effect that the decision variables have in these conflicting objectives is that if one wants to decrease execution durations by increasing the amount of allocated equipment, the result will be the imminent increase in execution costs, and vice-versa.

In order to define the objective functions of time and cost, it is important to note that maximizing the productivity of the production line, is crucial to minimize both objectives, since they depend directly on this global work rate of the production line. Having this in consideration also guarantees that the available resources that are employed are working at their full efficiency (which also has beneficial side effects, such as minimization of carbon emissions and environmental impact). This global work rate in an ideal solution should correspond to the maximum paving task work rate, which was considered the most conditioning task in this type of production line.

However, due to the interdependence between tasks, the work rate that should be considered in the calculation of the objective values corresponds the minimum work rate between all tasks that comprise these production lines (e.g., when the trucks that serve the paver are not enough to ensure its maximum work rate, the global work rate then becomes equal to the total work rate of the trucks, since the paver has to spend idle time waiting for trucks to be available, thus reducing its productivity).

The time for each work front (T_{wf}) is obtained by dividing the volume of material paved in the corresponding front, V_p (m^3), by the minimum work rate within the production line, Q_{min} (m^3/h) (Equation 1). Consequently, the duration of a construction phase (T_{CP}) corresponds to the duration of the fastest production line (Equation 2)

$$T_{wf,l} = \frac{V_{p,l}}{Q_{min,l}} = \frac{V_{p,l}}{min\{Q_{P,l}, Q_{C,l}, Q_{TP,l}, Q_{M,l}, Q_{TM,l}\}} \quad (1)$$

$$T_{CP} = min\{T_{wf,l}\} \quad (2)$$

The cost for each equipment (C_E) can be divided into fixed and variable costs. While the fixed cost (C_f) corresponds to constant expenses, such as equipment rental (when applicable) and manpower costs, the variable cost (C_v) is related to time dependent costs, such as equipment fuel or maintenance (Equation 3.3). In turn, the cost of a production line allocated to an active work front (C_{wf}) is given by the sum of the cost of all the equipment that comprise that production line (Equation 3.4), and the cost of a construction phase (C_{CP}) is simply obtained by summing all the cost of the active work fronts during that phase (Equation 3.5).

$$C_{E,k} = \sum C_{v,k} \times T_{CP} + \sum C_{f,k} \quad (3)$$

$$C_{wf,l} = \sum C_{E,k} \quad (4)$$

$$C_{CP} = \sum C_{wf,l} \quad (5)$$

In this given optimization procedure, as it will be further explained in the following section, in each iteration, corresponding to a new construction phase, both time and cost related to that phase will be obtained through equations 2 and 5 and in the end the total project cost (C_{Total}) and duration (T_{Total}) will be the sum of every phase costs and every phase duration, respectively (Equations 6 and 7).

$$T_{Total} = \sum T_{CP,j} \quad (6)$$

$$C_{Total} = \sum C_{CP,j} \quad (7)$$

Concerning the constraints, it was mainly considered space and quantities restrictions, like limiting the number of pieces of equipment that could be allocated to a front at the same time. Another relevant restriction taken into consideration is related to the fact that the paving process, and therefore the whole production line allocated to a front, is not able to work if a team of rollers is not available, since paving requires the support of at least two different types of rollers: tire rollers and vibratory rollers.

2.3. Optimization system development

In this proposal, only the equipment corresponding to the most critical task (pavers) of the production line is allocated, while the support equipment for the remaining tasks comprising the production line is allocated in a later stage by resorting to linear programming (LP). The latter focuses on distributing equipment teams in such a way that the productivity in each team is guaranteed to match as closely as possible the productivity in the critical task, while minimizing operational costs.

The algorithmic flow of the optimization system for the pavement rehabilitation problem can be seen in Figure 2. Before starting the optimization, it is necessary to define the algorithm parameters (i.e., population size, number of generations, probability of crossover and mutation) as well as input the required work-related data (i.e., work front information and equipment information). Then, the initial population, consisting of the front indexes associated with the allocation of each paver, is randomly generated.

Each solution is composed of a sequence of integer genes g_j^i that denotes the paving front to which the j_{th} paver is allocated in the i_{th} construction phase (Figure 3). Each gene can take an integer value ranging from 0 to the maximum number of paving fronts, L, which in this case are the number of lanes to be paved. Thus, the length of a solution's chromosome depends on the total number of pavers available, P, and the total number of lanes to be paved, L, and it is obtained by multiplying both numbers: $P \times L$. In the example shown in Figure 2, with $P = 3$ pavers and $L = 5$ lanes, the chromosome is composed of 15 genes.

Such as mentioned above, the genes can take values ranging from 0 to L , where a gene equal to 0 corresponds to a paver that will not be allocated to any lane during a construction phase. This option enables the optimization system to obtain solutions that could consider at the same time that a paver would not be working in one construction phase, but still in the end of the project obtaining a lower overall cost. Moreover, it allows the algorithm to assess and discard solutions that employ lower efficiency equipment (e.g., equipment with high cost but low productivity), since these may be held from being allocated entirely.

The intelligent optimization system relies on the interactions between the evolutionary algorithm and the fitness function. While the NSGA-II generates the population of solutions in every generation, the fitness function keeps the solutions feasible and calculates the objectives values for each solution.

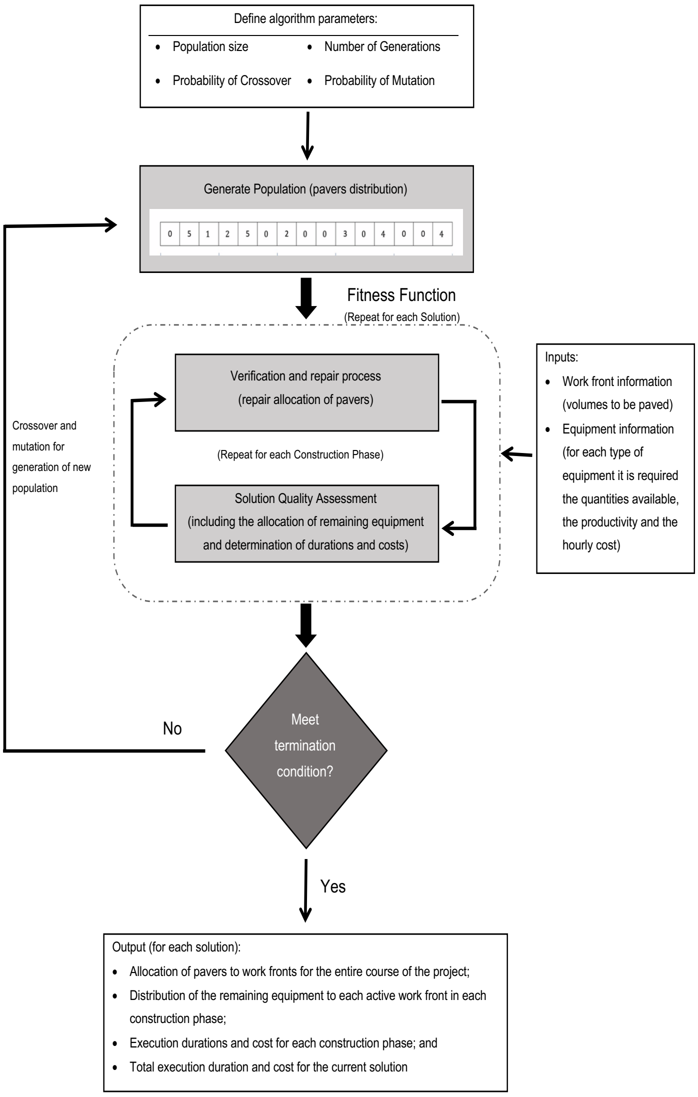


Figure 2 – Algorithmic flow of the optimization system

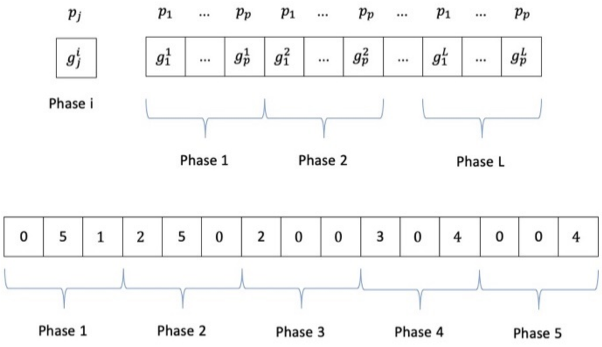


Figure 3 - Chromosome representation and example

The fitness function is executed for each solution and includes the verification and repair process, and the solution quality assessment process. On the one hand, the verification and repair process examines if portions of the solution called construction phases are feasible, and if not, the allocation of that construction phase is corrected. On the other hand, the solution quality assessment process includes the LP models and aims to distribute the remaining equipment to active fronts and to obtain construction phase durations and costs, ultimately leading to the determination of the total cost and duration of the solution.

2.3.1. Verification and repair process

The verification and repair process comprises the following four sequential steps:

1. Verify if there is an unfinished front that started in the previous construction phase. If it is verified, the paver allocated to this front will remain allocated to it, as to avoid unnecessary interruptions and reallocations.
2. Verify if at least one paver is allocated to a front in a construction phase. This verification is necessary for the specific case when the algorithm generates a solution with a value of 0 assigned to every paver in one construction phase. When such situation occurs, the value of the first gene changes from 0 to the first front which state is categorized as Not Started, effectively forcing at least one work front to be active in every construction phase.
3. Verify if any gene value of the current construction phase corresponds to an already completed front (i.e., already paved). Whenever this is true, simply change the paver allocation to a front that has not started yet, by changing the gene value corresponding to that paver to a front categorized as Not Started. As one can easily infer, this step guarantees that pavers are never allocated to lanes that are already paved and subsequently that a lane is not paved more than once.
4. Verify if there are no more than a maximum number of pavers (p_{max}) allocated to each front in the same construction phase. This verification is seen as a space restriction and, in terms of solution representation, this happens when at least $p_{max} + 1$ genes belonging to the same construction phase have the same value, meaning that $p_{max} + 1$ number of different pavers were allocated to pave the same lane simultaneously. When verified, this is solved by finding the duplicated genes, corresponding to the excess pavers in overcrowded fronts, and then change them to available fronts that have not been started, or 0 in case there are no more available fronts. Usually, the maximum number of pavers applied in highway construction and rehabilitation context is one. However, this optimization tries to be as broad as possible and admits that this number can be changed.

The sequence of verification steps is not random, the order was chosen in a way to prevent harmful interactions between the four verifications. In other words, it prevents that the repair done in one verification will not be undone in the next one. In Figure 4 the sequence and effects of applying each step to an example is represented.

2.3.2. Solution quality assessment process

As for the solution quality assessment process it can also be divided in steps as identified in Figure 5.

Bearing in mind that both time and cost depend either directly or indirectly of the productivity of the production line, it is paramount to optimize this value when allocating the equipment to paving fronts. To do this, after allocating the pavers to available paving fronts and calculating the total productivity in each front, the next step focus on allocating the remaining equipment to form a production line. On one hand, the amount of the first equipment to be allocated to a front still with only the pavers allocated to it, will be chosen considering factors such as the pavers total productivity and the available types and quantities of that equipment. On the other hand, the allocation of the following types of equipment to any front will not have in consideration the productivity of the paver as default, but instead it begins to consider the minimum productivity between all equipment already allocated, since it may happen that a certain type of equipment does not have enough available units to maintain the pavers level of productivity.

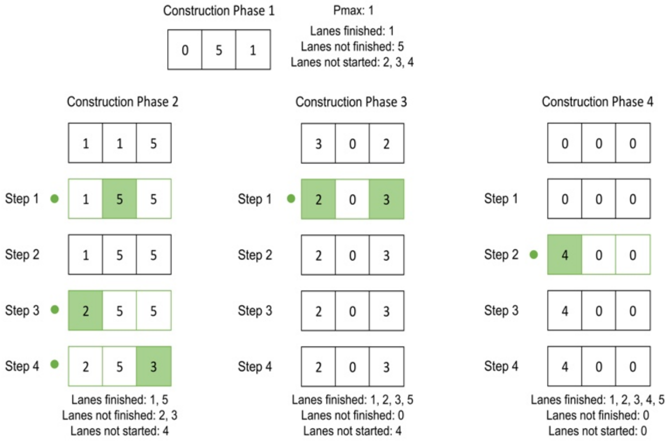


Figure 4 - Verification and repair process applied to an example

In order to distribute the equipment of the rest of the tasks to the active fronts a LP model is adopted which runs every time a type of equipment needs to be allocated to a task. Each LP model is used for every task in every front and has the main objective function of minimizing the total equipment cost of that task. Note that, even though the allocation of the equipment in these tasks implies tackling discrete variables, the adoption of a LP model is still viable, as results can be rounded to the nearest integer without hindering the quality of solutions. The LP model has two constraints, firstly the total work rate of the current task must be equal or greater than the total work rate of the pavers in that work front, if no other previously allocated equipment has a lower work rate (Q_{min}) than the paving task. Secondly, it is also constrained by the quantities available of the types of equipment (n_i) needed for that task. In the case that there is not enough equipment to satisfy the work rate of the pavers in the corresponding front, all the available equipment is allocated, and the corresponding new minimum work rate is defined by this task.

To illustrate the linear programming model used for each task (Equation 8), let us assume that there are N_e types of equipment that can be distributed to complete a certain task (e.g., two types of trucks with different capacities and hourly costs) and to each type k ($k = 1, \dots, N_e$) corresponds a different work rate (Q_k) and hourly cost (c_k), then a string x_k ($x_k = x_1, \dots, x_{N_e}$), would corresponds to the quantities of the selected equipment solution.

$$\begin{aligned} &Min: && \sum x_k \times C_{E,k} \\ &Subject\ to: && x_k \le n_k \\ &&& \sum x_k \times Q_k \\ &&& \ge Q_{min,l} \end{aligned} \qquad (8)$$

With every production line completed (all equipment allocated) for each active front, it is possible to determine the time for each production line by applying Equation 1 followed by the determination of the duration of the current construction phase, which corresponds to the fastest production line to complete a paving front. As the end of the current phase is reached, a new one ensues with the reallocation of the equipment that would become idle and available after the end of the construction phase to either strengthen a front already active and incomplete or to start a new one. Yet, before this step it is necessary to update the state of each front (Finished, Not finished, Not Started) and the work volumes still needed to complete each front.

Before checking if all fronts are completed in the end of this assessment process, there is a last step to calculate the total cost of the current stage, which only needs the total duration of the current stage and the costs for each active equipment used in each front.

In the end of this process, if there is still a lane to be paved a new construction phase will begin and the evaluation process goes back to the first step, but now, with updated work volumes and new available equipment to reallocate to the remaining incomplete fronts. If there are no lanes left to be paved no new construction phase will begin, but instead, the system will output the solutions values for the objective functions of total accumulated cost and time for the whole project.

After all the solutions in a population are evaluated according to their objective values, the optimization algorithm proceeds to generate a new population through operations of crossover and mutation. The process keeps repeating itself until the number of generations defined in the beginning is reached. Finally, at the end of this optimization process, the system outputs a Pareto-optimal set, and for each solution of that set the information about the pavers allocation, the remaining equipment distribution, and the cost and durations value.

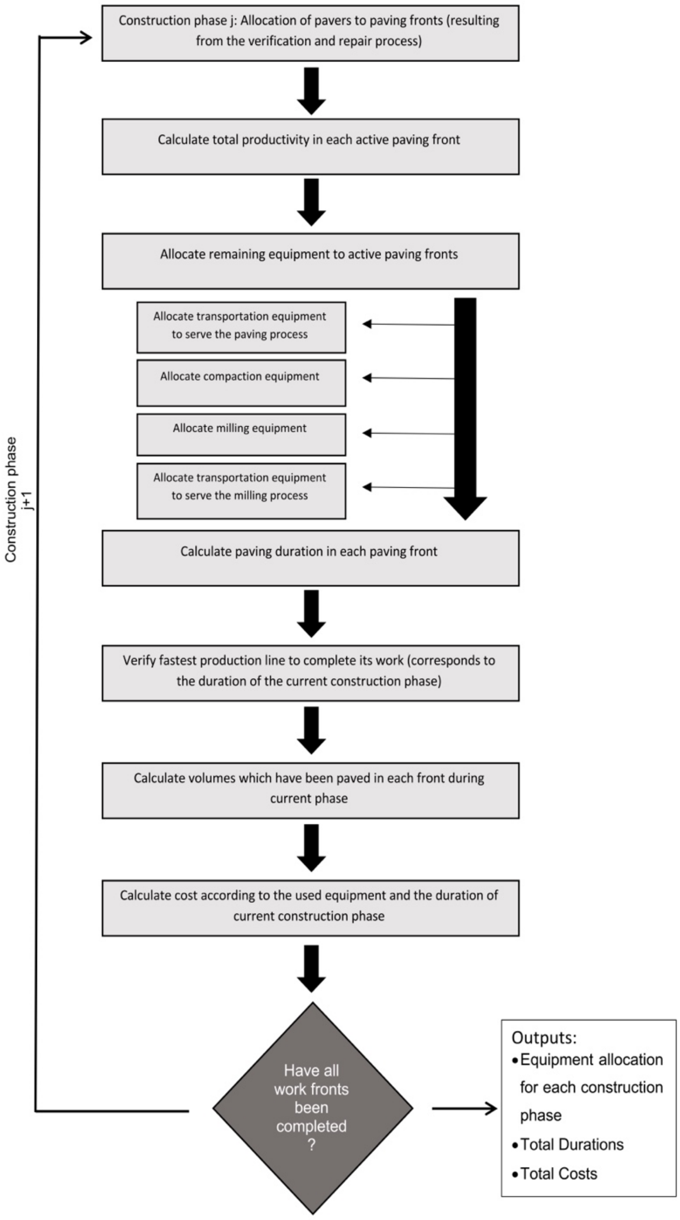


Figure 5 - Flowchart of the solution quality assessment process

3. Case Study

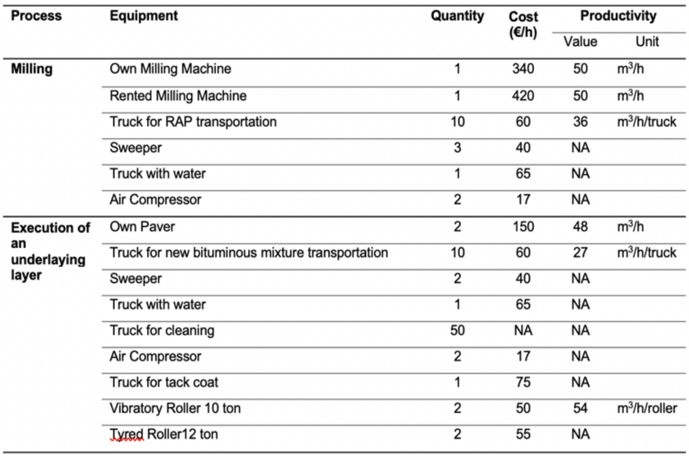
The case study refers to the rehabilitation with a structural character of a section of A5, a very trafficked motorway that serves the metropolitan area of Lisbon, displaying one of the highest daily traffic volumes of the entire Portuguese highway network. The rehabilitation consisted in removing the surface layer and an additional portion of the underlying layer, in both directions of the section between two nodes (Oeiras – Estádio Nacional) corresponding to the kilometer marker of 8,0 km to 11,4 km (comprising a total length of 3,400 m). The cross-section of this motorway is for most of its length a 2x3, which means that it has 3 lanes in both directions, which accounts for a total of 6 lanes to be rehabilitated.

The operations of rehabilitation consisted in milling the surface to a depth of 9 cm and applying two new layers. An underlying layer with 5 cm of thickness and a surface layer with 4 cm of thickness. Despite of having the possibility of recycling the old pavement since a milling process was performed, the RAP obtained was not included in the formulation of the new layers but instead it was transported to a ditch.

The equipment available for each construction process is quantified in Table 1, as well as their hourly costs and productivities. This equipment was all allocated to the different tasks in order to be able to mill up to 400 m of the old pavement as well as applying the new underlying layer per work day. Initially, the milling teams carry out their task, and only after the first 200 m were finished, would the paving teams start working. The milling team consisted in 2 similar milling machines. The paving team for applying the underlying layer consisted in 2 similar pavers served by 2 rollers (different types). Both milling and the application of the underlying layer are consecutive processes, however the application of the surface layer is usually done some days after the application of the first two processes. In other words, the first two processes can be executed one after the other in several fronts before the application of the surface layer begins.

The productivities of the pavers given for the application of the underlaying and surface layers were different, mostly due to the different material applied. However, in order to simplify the modelling of the pavement rehabilitation operations, it was considered that the application of the underlaying layer was immediately followed by the application of the surface layer, and the productivity of the pavers for both processes was also considered the same.

Table 1 - Equipment available

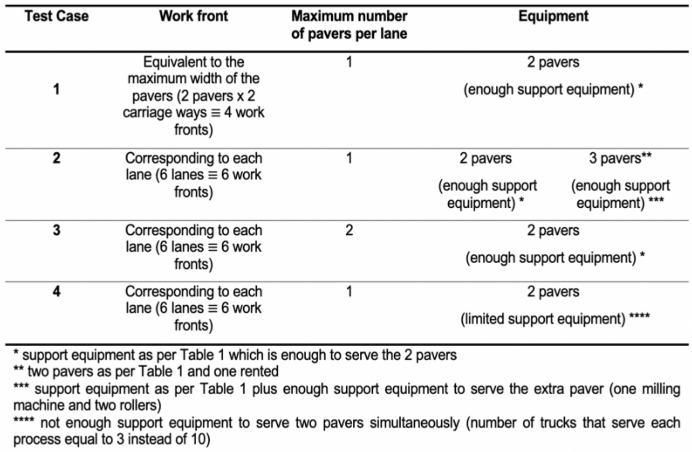


Process	Equipment	Quantity	Cost (€/h)	Productivity	
				Value	Unit
Milling	Own Milling Machine	1	340	50	m³/h
	Rented Milling Machine	1	420	50	m³/h
	Truck for RAP transportation	10	60	36	m³/h/truck
	Sweeper	3	40	NA	
	Truck with water	1	65	NA	
	Air Compressor	2	17	NA	
Execution of an underlaying layer	Own Paver	2	150	48	m³/h
	Truck for new bituminous mixture transportation	10	60	27	m³/h/truck
	Sweeper	2	40	NA	
	Truck with water	1	65	NA	
	Truck for cleaning	50	NA	NA	
	Air Compressor	2	17	NA	
	Truck for tack coat	1	75	NA	
	Vibratory Roller 10 ton	2	50	54	m³/h/roller
	Tyred Roller12 ton	2	55	NA	

4. Optimization Results

Several test cases were analyzed based on the case study. The test cases aim to validate the optimization system developed in this thesis, as well as to show its applicability and flexibility to deal with cases with the most varied types of equipment with different characteristics and quantities. Table 2 describes each test case, according with three main parameters that were changed between cases.

Table 2 - Test Cases Description



Test Case	Work front	Maximum number of pavers per lane	Equipment	
1	Equivalent to the maximum width of the pavers (2 pavers x 2 carriage ways ≡ 4 work fronts)	1	2 pavers (enough support equipment) *	
2	Corresponding to each lane (6 lanes ≡ 6 work fronts)	1	2 pavers (enough support equipment) *	3 pavers** (enough support equipment) ***
3	Corresponding to each lane (6 lanes ≡ 6 work fronts)	2	2 pavers (enough support equipment) *	
4	Corresponding to each lane (6 lanes ≡ 6 work fronts)	1	2 pavers (limited support equipment) ****	

* support equipment as per Table 1 which is enough to serve the 2 pavers
** two pavers as per Table 1 and one rented
*** support equipment as per Table 1 plus enough support equipment to serve the extra paver (one milling machine and two rollers)
**** not enough support equipment to serve two pavers simultaneously (number of trucks that serve each process equal to 3 instead of 10)

The genetic algorithm parameters chosen for each run of the optimization system in each test case were considered as the suggested default values in the R package mco: population size of 100; generations number of 100; probability of crossover of 0.7; probability of mutation of 0.2. Other smaller population sizes were also tested however, in some cases some of the solutions obtained for the default value of 100 were not found. Actually, the purpose of this study focuses more on assessing and validating the capabilities of the developed system, rather than calibrating the parameters of the optimization algorithm.

Figure 6 shows all the solutions obtained in every test case and Table 3 and Table 4 the cost and duration ratios obtained for each solution.

Test Case 1 served to validate the optimization system, by considering the same paver allocation method that was done in the real construction site, i.e., the work fronts were considered equivalent to the maximum width of one paver which in turn corresponds to paving half of one carriage way. Taking this into account, besides the original solution and original paver allocation of considering 2 pavers simultaneously paving one carriage way, other two solutions were obtained (Solution 2 and Solution 3) which are cheaper than the original one but take way longer.

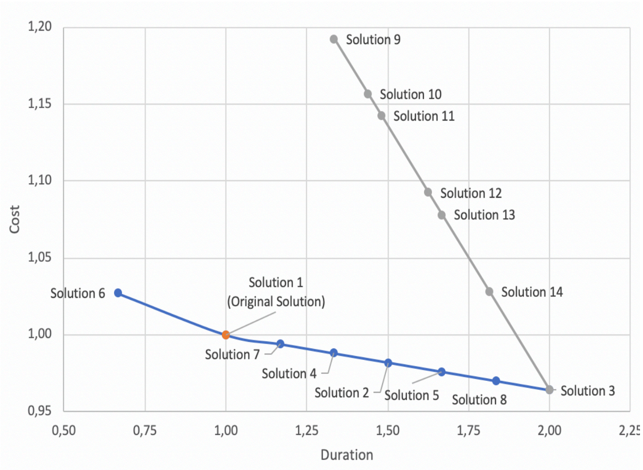


Figure 6 - Solutions obtained for all the test cases

In Test Case 2 the work front was changed to lanes and the rest of the conditions were maintained the same in a first instance, and in a second attempt to obtain interesting solutions more equipment was considered (i.e., one extra paver and enough support equipment was contemplated). In this test case, while just considering two pavers, Solution 4 and Solution 5 were obtained besides Solution 1 and Solution 3, which were again positioned at the right of Solution 1, which means that were less expensive but would take longer. On the other hand, while considering three pavers, a new solution was found that was faster but more expensive (Solution 6).

Table 3 – Objective values for all the solutions obtained for Test Cases 1, 2 and 3

Solution	**Test Case 1, 2 and 3**			
	Total Duration ratio		Total Cost ratio	
6	0.667	-0.333	1.027	+0.027
1	1.000		1.00	
7	1.167	+0.167	0.994	-0.006
4	1.333	+0.333	0.988	-0.012
2	1.501	+0.501	0.982	-0.018
5	1.667	+0.667	0.976	-0.024
8	1.834	+0.834	0.970	-0.030
3	2.000	+1.000	0.964	-0.036

In Test Case 3 the equipment was kept as the same in test case 1, and the paver allocation method the same as in test case 2 (work fronts corresponding to lanes), however the maximum number of pavers allowed in the same work front was raised to two, which meant that two pavers could be allocated to the same work front in the same construction phase. The conditions of this test case allowed the optimization to obtain more solutions than in the other test cases, being these solutions the same as in test case 1 (solution 1, 2 and 3) and the new solutions of 7 and 8.

Table 4 - Objective values for the solutions of Test Case 4

Solution	**Test Case 4**			
	Total Duration ratio		Total Cost ratio	
9	1.333	+0.333	1.192	+0.192
10	1.438	+0.438	1.157	+0.157
11	1.480	+0.480	1.142	+0.142
12	1.625	+0.625	1.092	+0.092
13	1.667	+0.667	1.078	+0.078
14	1.813	+0.813	1.028	+0.028
3	2.000	+1.000	0.964	-0.036

Finally, in Test Case 4 a shortage of equipment was tested, instead of having ten trucks serving each process (milling and paving), it was considered just three. As expected, the original solution was not obtained since there was not enough equipment to serve both pavers to their maximum productivity, instead the solutions reached (solutions from 9 to 14) revealed themselves as more expensive. The purpose of considering this test case served more to show the flexibility of the system to take into account different and exceptional conditions, as the shortage of one type of equipment, rather than to compare to the original solution.

It is important to note that each solution is characterized by a certain cost and duration and not exactly by a paver allocation. What this means is that, different test cases reached some similar solutions (in terms of objective value) by using different paver allocation methods.

Just as an example, in the original solution the equipment distribution obtained for each active work front was one paver, three trucks serving the paver with two rollers (one pneumatic tyre roller and one vibratory roller), one milling machine and more 3 trucks serving the milling machine.

With all these test cases presented, it was confirmed that with the quantities and types of equipment available to develop this project it was not possible to find a better solution, i.e., that was cheaper and faster at the same time, but it was possible to find other equally optimal solutions, that would either be slightly less expensive (less than 10% cost decrease) but would take longer (Solutions 2, 3, 4, 5, ,6, 7, 8), or one solution which was faster but more expensive (Solution 6). The purpose of having more than one optimal solution to choose from is that it provides the decision makers with a broad view of the options, and according to their own criteria this optimization system gives them the ability to choose the fittest option to complete the project in any condition.

5. Conclusions

This work presents an intelligent optimization system for road pavement rehabilitation process management that would be able to choose the optimal allocation for heavy equipment regarding objectives such as construction costs and duration.

The system can consider as many pavers to be allocated as needed. It has also shown the ability of the system of considering different types of work fronts and therefore different types of allocation methods.

The capability of the system was tested with a real project of a pavement motorway rehabilitation and it was fed the information given by the responsible entities behind the rehabilitation operations. The obtained results were enough to back up the original decision made to allocate the pavers in the real context of the construction. In spite of the fact that the original allocation was proven to be an optimal solution, it was also shown that there were several other viable solutions corresponding to optimal trade-offs, which could be chosen depending on the criteria adopted by the decision maker for each objective. It seems that in the situation studied, the objective that weighted more was the duration over the cost, probably because the deadline was tighter than the budget.

In the results, several other what if scenarios were presented, such as considering the possibility of paving one lane with two pavers simultaneously, or a scenario with an extra paver, or with not enough trucks to serve the pavers allocated. These several scenarios, as expected, did not improve the original solution, however their purpose was to show the flexibility of the system developed. Nevertheless, the system is still useful to support the decision making in both design and construction phases, by exploring scenarios and suggesting potential solutions that might not be so obvious at first glance.

Despite the work presented in this thesis, this is a fairly new area that still has a lot to be further developed. Actually, this kind of optimization system focusing on process management applied to the area of pavement rehabilitation and even to pavement construction is unique until now and is still in an embryonic phase. The development of optimization systems in general shows an immense potential to improve and aid the current construction methods that are very influenced by the experience of the engineers and designers.

In this case, since it was a first approach to this kind of systems applied to a new area, a few simplifications were considered. The system does not take into account the application of two distinct layers nor the rehabilitation of the side shoulders. The productivities of the equipment of intermediate tasks such as surface cleaning and the application of the track coat were not considered. Regarding the equipment productivities, they were based on approximate values and were also considered constant over time. It is important to note that these simplifications should be addressed in future developments, allowing for a superior adjustment and modeling of reality.

Besides the simplifications that need to be addressed in further studies there are still a few aspects that are worth being further studied and were not approached in this thesis.

Some studies have already been focusing their attention on the use of GPS technology in compaction rollers in order to keep track of the compaction levels and number of passes done by the rollers in paving situations such as the ones modelled by this system. The integration of technologies such as this could also improve the real time retrieval of information. In turn, the capability of gathering construction data in real-time also enables the real-time optimization of processes, in which equipment allocation is constantly adjusted in the face of unforeseen occurrences (e.g., equipment malfunction, unexpected material properties or atmospheric conditions), thus guaranteeing the optimal status of resource management throughout the construction project.

Also, and maybe most importantly, this optimization system was developed in such a way that it gives the ability to integrate traffic management and work zone planning processes. Applying a work zone planning optimization with the allocation of the equipment within the work zones and with multiple work zones working at the same time would be an interesting development, as it would allow the user to add a set of different constraints to the system to have more control over which lanes could be paved at certain times. In turn, the objectives considered could change or new ones could be added to the ones already considered, such as the minimization of user costs, environmental impacts (e.g. carbon emissions), or other objectives related with safety and mobility of the users.

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