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Designing construction processes in buildings by heuristic optimization

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Abstract

This paper describes a computer tool for calculating and validating loads on floor slabs and shores in the construction of multistorey buildings with in situ casting. Its chief novelty lies in its optimization unit, designed to produce appropriate and optimum construction processes, which was created by applying exact and heuristic methods: Random Walk (RW), Descent Local Search (DLS) and Simulated Annealing (SA). The system has shown that it can improve three of the most important aspects involved in construction: time, cost and safety. In some cases the optimal solutions were achieved while reducing up to 53% of the cost of the shoring system, in shorter construction time, and meeting all the usual requirements for the construction of this type of building.

Keywords: *shoring; building structures; optimization; heuristic methods; reinforced concrete*

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1. Introduction

Reducing building times, saving on costs and improving safety are three important aspects of efficient construction processes. At the present time savings in time and costs are achieved mainly by recovering all or part of the building construction components in the shortest possible time. Although striking time depends on many factors (building process, work requirements, weather, etc.), the financial aspect is always subject to structural safety considerations.

It should be remembered that a high proportion of building collapses take place during construction [1-3], so that an understanding of how loads are transmitted between shores and slabs under construction is required to ensure the safety of the structure and reduce building times and costs. Knowing how these loads are transmitted makes it possible to calculate the loads the slab must support.

Numerous authors have proposed a multitude of theoretical models to estimate shore/slab load transmission, including complex models such as those based on the finite element method [4-10] and simple calculation methods. Among others, Grundy and Kabaila [11], Duan and Chen [12], Fang et al [13] and Calderón et al [14] developed simplified methods to estimate load transmission between slabs and shores in multistorey buildings.

In order to develop a computer tool for the present study, a simplified calculation method to avoid having to resort to advanced software is used, but even when simplified methods are used it is by no means a simple or rapid task to calculate construction processes. Therefore, the first objective of this study was to develop and validate a software tool that would provide users with a quick and simple calculation method. The computer tool can be used to check the construction process defined and entered by the user.

Since the design of the optimal construction process is intimately related to the structural designer's experience, he has to follow a strategy of trial and error and continually redefine the process until he finds a better solution than the original. This strategy is not automatic, and as it usually leads to construction processes in which safety is given the highest weight, times are longer and costs are higher than those of the optimal solution. It is therefore advisable to apply optimization techniques to obtain the best construction processes; this is, in fact, the second objective of the study and involves two of the most important aspects of building works, construction time and costs.

Automatic methods of obtaining optimal solutions are generally either exact or heuristic. Even though the former are efficient for dealing with small numbers of variables, they still need long computation times and because of this may be limited when dealing with higher numbers of variables. A review of non-heuristic optimization studies can be found in Sarma and Adeli [15]. Heuristic search methods can also be used intelligently to obtain optimal solutions in a reasonable computation time [16]. Their first application to reinforced concrete in 1997 were by Coello et al [17] in a simply supported beam, and by studies on pre-tensed concrete beams by Leite and Topping [18], who used genetic algorithms (GA). Other studies also emerged that used both GA and simulated annealing (SA) [19], threshold accepting (TA) [20], ant colony optimization (ACO) [21] and particle swarm optimization (PSO) [22], applied to frames, beams, columns and slabs in RC buildings [16, 23-25]. Furthermore, Paya [16] applied heuristic search methods as Random Walk (RW) and Descent Local Search (DLS) in search of optimal solutions. Nowadays, many heuristic search methods are used [26-27], being more efficient when they are combined as hybrid optimization [28-30]. In this paper, single optimization algorithms are used as a first approach to building construction processes.

The principal novelty of this paper is that it applies three optimization strategies (RW, DLS and SA) by means of a specially developed computer tool programmed in FORTRAN language to obtain, for the first time, optimal construction processes in multistorey buildings.

2. Development and validation of computer-based tool for estimating and verifying loads on slabs and shores

The chosen calculation method was the new simplified procedure defined by Calderón et al [14], which is the latest and most complete and has better goodness of fit than the previous simplified methods [14,31-33]. It assumes that the mean deformation of the slabs coincides with the mean deformation of the shores that support them. Also, various boundary conditions are considered (internal, end and corner spans). Deformability is estimated by Scanlon and Murray's method [34]. It should be clearly understood that in this method the analysis of the loads transmitted between slabs and shores is for mean loads, which was the practice used in similar studies. The software was also programmed with the stiffness matrix method to calculate the required bending moments. In order to determine the resistant capacity of the floor slabs to the loads they had to bear during construction, the Calavera [35] and Fernández [36] condition was considered (see Eq. (1)), which is based on the critical evolution of the concrete tensile strength in relation to its other mechanical characteristics:

$$\beta = \alpha \cdot \frac{\gamma'}{\gamma} \leq \frac{f_{ckt,j}}{f_{ckt,28}} \tag{1}$$

where, on one hand, α is the proportion of loads received by the slabs under construction compared to the design loads, γ' is the construction safety factor, γ is the service safety factor, and therefore β is the proportion of the load measured on the slab weighted by the safety coefficients. On the other hand, $f_{ckt,j}$ is the tensile strength of the concrete at the age of the concrete under study, and $f_{ckt,28}$ is the concrete's tensile strength in service.

Thus, following Calderón et al's simplified procedure [14], the computer tool calculates the loads on both slabs and shores and verifies that the above condition has been satisfied for each slab and building operation, i.e. that β is equal to or lower than the proportion of the acquired tensile strength.

The next task was to choose suitable buildings to verify the computer tool. The first considered was the building studied by Alvarado [37] and Alvarado et al [38], which was built purely for research purposes. This experimental building contains three storeys with 0.25 m thick reinforced concrete slabs, 2.75 m height between floors and a 6.00 m clear span between columns. The second was the building studied by Gasch [31] in the Fine Arts Faculty of the Universitat Politècnica de València; this has six storeys and a basement with waffle slabs 0.40 m thick, 0.15 m rib and 0.80x0.80 m waffle. The spans were 5.50x8.00 m and 5.50x8.80 m.

Height between floors ranged from 2.90 m to 4.00 m. The estimation and verification of loads for each building can be seen in Tables 1 and 2. Figs. 1 and 2 give for each building the comparison between the results of the computer tool ($\bar{Q}_{NSP}$) and the results obtained from the simplified methods of Duan and Chen ($\bar{Q}_{D\&C}$) and Fang et al ($\bar{Q}_{F}$), with respect to experimental measurements. As can be seen in Figs 1 and 2, the results obtained from the computer tool calculated show a better fit than those obtained from the other methods.

Table 1. Estimation and verification of loads on slabs and shores in the experimental building.

Stage of construction	Level	$\bar{Q}_{slab}$ [kN/m2]	$\bar{Q}_{shores}$ [kN/m^2]	β	$\frac{f_{ckt,j}}{f_{ckt,28}}$
Casting Level 1	1	0.00	5.64	-	-
Clearing Level 1	1	1.75	3.89	0.14	0.60
Casting Level 2	2	0.00	5.64	-	-
	1	3.76	7.52	0.29	0.78
Clearing Level 2	2	2.43	3.21	0.19	0.75
	1	2.94	5.90	0.23	0.89
Striking Level 1	2	4.51	1.13	0.35	0.78
	1	6.77	-	0.52	0.90
Casting Level 3	3	0.00	5.64	-	-
	2	7.78	3.50	0.60	0.84
	1	9.13	-	0.71	0.93
Clearing Level 3	3	2.44	3.20	0.19	0.60
	2	6.38	2.45	0.49	0.89
	1	8.09	-	0.63	0.96
Striking Level 2	3	3.29	2.35	0.25	0.78
	2	7.99	-	0.62	0.93
Striking Level 3	3	5.64	-	0.44	0.93

Table 2. Estimation and verification of loads on slabs and shores in the Fine Arts building.

Stage of construction	**Level**	$\bar{Q}_{slab}$ **[kN/m2]**	$\bar{Q}_{shores}$ **[kN/m^2]**	**β**	$\frac{f_{ckt,j}}{f_{ckt,28}}$
Casting Level 1	1	0.00	5.76	-	-
Clearing Level 1	1	1.58	4.18	0.12	0.60
Casting Level 2	2	0.00	5.76	-	-
	1	3.23	8.29	0.25	0.78
Clearing Level 2	2	2.33	3.43	0.18	0.60
	1	2.58	6.61	0.20	0.84
Striking Level 1	2	4.70	1.06	0.36	0.66
	1	6.82	-	0.53	0.86
Casting Level 3	3	0.00	5.76	-	-
	2	8.03	3.49	0.62	0.78
	1	9.25	-	0.72	0.90
Clearing Level 3	3	2.73	3.03	0.21	0.60
	2	6.48	2.31	0.50	0.84
	1	8.07	-	0.63	0.93
Striking Level 2	3	3.61	2.15	0.28	0.66
	2	7.91	-	0.61	0.86
Casting Level 4	4	0.00	5.76	-	-
	3	6.95	4.57	0.54	0.78
	2	10.33	-	0.80	0.90

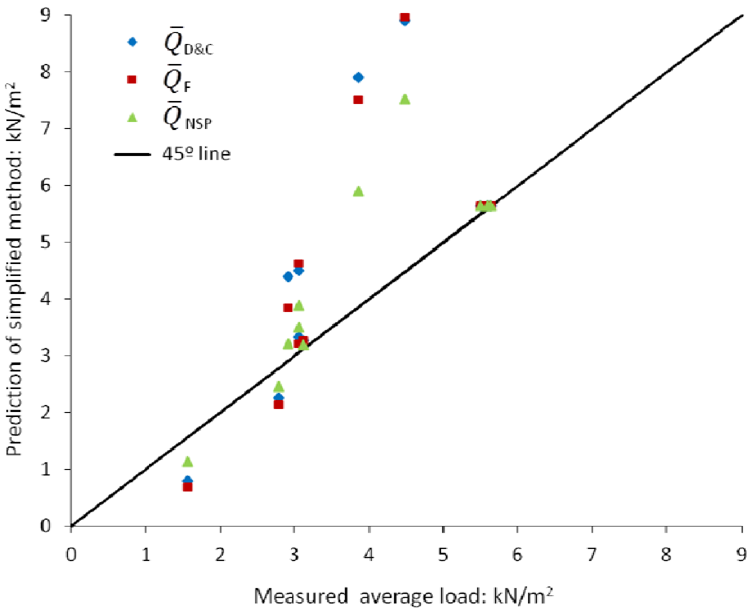

Fig. 1. Experimental building: comparison of calculated mean load on shores with that obtained from Duan and Chen [12] and Fang et al’s [13] simplified methods with respect to experimental measurements

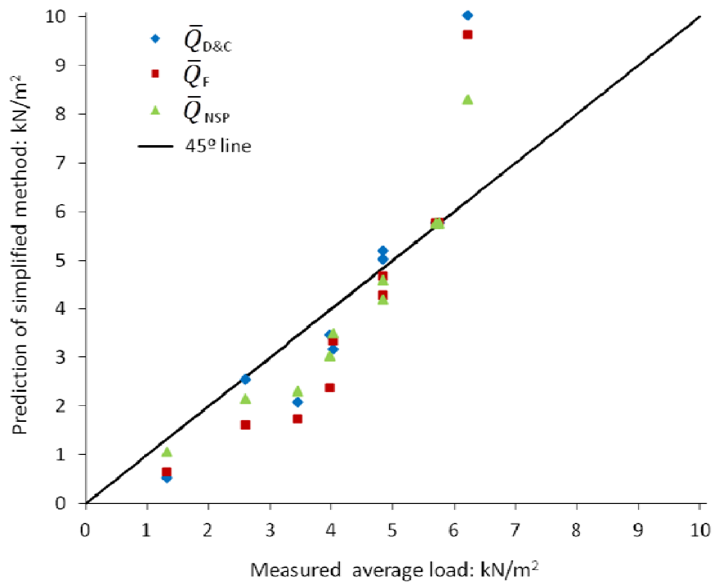

Fig. 2. Fine Arts Building: comparison of calculated mean load on shores with Duan and Chen [12] and Fang et al's [13] simplified methods, with respect to experimental measurements.

3. Definition of the optimization problem

3.1. Definition of problem

The problem of obtaining optimal construction processes consists of minimizing an objective function F (cost of the shoring system) defined according to Eq. (2) which must comply with the different constraints g_k considered in the Eq. (3).

$$F(x_1, x_2, \dots x_n) = cost\ of\ the\ shoring\ system \tag{2}$$

$$g_k(x_1, x_2, \dots x_n) \leq 0 \tag{3}$$

where x_i are the values of the different variables that make up the complete construction process.

3.2. Variables

A total of (5+4*n) variables define a complete construction process as a function of the number of floors (n) in the building. The first five variables adopt constant values in the whole building, defined as follows:

1. Type of process in habitual operations such as shoring, reshoring, clearing and striking. Several of these operations are normally carried out on each floor, normally chosen from: shoring/striking (SS), shoring/clearing/striking (SCS) or shoring/reshoring/striking (SRS).
2. When an intermediate operation is involved (SCS or SRS) a decision must be made on the percentage of shores to be removed. For SCS, clearing consists of removing a certain number of shores, their associated straining pieces, and bottom formwork panels. The different alternatives consisted of removing 33, 50 or 66%. In SRS, reshoring involves removing 100% of shores and then replacing a certain percentage. We considered that 100% were replaced, as this is the usual practice.
3. The number of consecutively shored floors; possible values being 1, 2, 3 or 4.
4. Straining piece separation according to slab type: for waffle or girderless hollow floor slabs 1, 2 or 3 times the distance between ribs; for flat slabs, 1, 2 or 3 m.
5. Type of shore throughout its area. Only one type was considered in this study.

The four remaining variables can adopt different values on different floors:

1. Shores may be separated by 0.5, 1.0 or 2 m.
2. Number of days after which a new slab begins casting, counting from the casting of the previous slab; with possible values of between 5 and 14 days.
3. Number of days after which an intermediate clearing operation is carried out, counting from the casting of the slab in question, choosing from possible values between 2 and 7 days.

4. Number of days after which an intermediate reshoring operation is carried out, counting from the casting of the slab in question, with possible values of between 2 and 9 days.

A reasonable interval of values was in general chosen for each of the variables. Minimum and maximum values were established, within which high-cost solutions, and unusual or unsafe construction processes could be found. The variables and the values of the different variables considered can be seen in Table 3.

Table 3. Variables and values considered.

Variables	**Values**	**Variables**	**Values (each floor)**
Type of process	(SS*, SCS**, SRS***)	Separation of shores [m]	0.5, 1, 2
Percentage clearing or reshoring [%]	Clearing (33, 50, 66) Reshoring (100)	Casting of new slab [days]	5-14
Number of consecutively shored floors	1, 2, 3, 4	Clearing of slab [days]	2-7
Separation between straining pieces [m]	(1, 2, 3)*(rib spacing) If flat slab then (1, 2, 3)	Reshoring of slab [days]	2-9
Shore area [cm^2]	2.89 (one type only)		

$^{(*)}$ *Shoring / Striking*
$^{(**)}$ *Shoring / Clearing / Striking*
$^{(***)}$ *Shoring / Reshoring / Striking*

It should be emphasized that all the variables considered were discrete and not continuous, so that by correctly combining different variables all the possible construction processes in the solution space could be defined. In this case, if we maintain the variables and each of their values for the two buildings, the dimension of the space solution is defined by the Eq. (4):

$$Dimension = 4 * 3 * 3^n * 10^{(n-1)} * (1 + 3 \cdot 6^n + 1 * 8^n) \quad (4)$$

In the case of the experimental building, the dimension of the space solution is of the order of $4 \cdot 10^7$ and that of the Fine Arts Faculty building is of the order of $8 \cdot 10^{16}$ different solutions. In the hypothetical case of a 30-floor building, this dimension would be of the order of de $3 \cdot 10^{71}$. The financial cost of each of these solutions is shown in the Eq. (2), and if the different constraints to the problem in the Eq. (3) are satisfied, it will be identified as a feasible solution. Those that do not satisfy any of the constraints are identified as non-feasible solutions.

3.3. Parameters

The parameters of construction processes consist of all the values taken as problem data that do not form a part of the search for the optimal solution and are constant for all possible solutions. In the case of obtaining optimal construction processes for buildings, the parameters are the values that are normally set in the building design phase. Table 4 lists all the parameters considered in this work.

Table 4. Parameters of the building processes.

Data on each floor	*Building data*
Type of slab	Type of span
Thickness	Continuity of span
Concrete strength	Number of floors
Fast, normal or slow hardening concrete*	Ambient temperature
Lengths of analyzed and adjacent spans	Concrete density
Cantilever lengths	Elasticity modulus of shore steel
Height between floors	Construction and project safety coefficients
Construction loads	
Service loads	

**s = 0.20 (fast); s = 0.25 (normal); s = 0.38 (slow) according to MC-2010 [39]*

3.4. Objective function

The objective function considered consisted of minimizing the cost of the shoring system of the construction processes in multistorey buildings with *in situ* casting. As either rental or depreciation costs could have been adopted, it was decided to consider the rental costs of the required material according to the following values:

- Rental of shores: €0.03/shore/day
- Rental of formwork panels: €0.10/m^2/day
- Rental of straining pieces: €0.04/m^2/day
- Rental of pivoting mechanism for clearing: €0.03/m^2/day

The prices cited in the above costs were provided by specialist shoring companies and are those currently charged in Spain. Changing the study to consider the equivalent prices in other countries would simply involve adopting the corresponding rental values of the different elements in the objective function.

The result of the objective function is expressed in €/m^2 in order to make it applicable to the entire building, as only one span was actually analyzed. Also, by considering this objective function as the cost of renting the shoring equipment, building time and fewer shoring system components are also considered indirectly. In fact, the shorter the time and the fewer the resources required, the lower the cost assessed by the objective function.

3.5. Structural constraints

The constraints in Eq. (3.2) express the limiting conditions of the different solutions considered, both in verifying loads and building conditions. Firstly, as already mentioned, for building and safety reasons, the periods of time which the building operations could last were set between minimum and maximum values. Secondly, as can be seen in Table 1, the separation between straining pieces was considered the same on all floors. In this way the transmission of loads between the shores on the different floors is exclusively vertical, without introducing additional shear forces. On the optimization process, both these constraints form part of the definition of a new solution, as they enter in the definition of the variables (Section 3.2). Finally, the loads were verified throughout the entire optimization process. The third constraint is based on the condition of Calavera [35] and Fernández [36], as explained in Section 2, which verifies the loads on the slabs during the different building phases and determines whether or not the different solutions considered are feasible.

4. Search methods applied

According to Eq. (4), the dimension of the solution space is exponentially dependent on the number of floors (n) in the building. Although it is therefore possible to apply exact methods to obtain the optimal solution for buildings with only a few floors, the calculation time is usually high, so that heuristic search strategies are often used, such as Random Walk (RW), Descent Local Search (DLS) and Simulated Annealing (SA).

The first method used in this work was an exact search method for the optimal solution, which consisted of generating all possible solutions and assessing the cost of all the feasible ones. In this way the solution with the lowest cost was obtained, in accordance with the objective function defined in Section 3.4.

The second method used was the well-know algorithm called *Random Walk* [16], which generates solutions by randomly selecting values for each variable. After generating the solution, the constraints are applied to determine whether or not it is feasible, and if so, the objective function is evaluated in order to obtain its cost. The process is repeated a certain number of iterations and the solution with the best cost is selected. This strategy is known as a non-intelligent search method and does not guarantee finding the optimal solution. However, low cost solutions may be found and it is also useful for exploring the solution space to determine the percentage of feasible solutions. Another advantage of RW is that it can be used as a starting point for other heuristic methods, so that the initial solution may in fact be good. The results of the percentage of feasible solutions and the iterations carried out are given in Section 5.2.

The third method was *Descent Local Search* [16], which takes the initial solution as a feasible random solution, and gradually alters it by means of small movements in the values of the variables. A movement consists of a small up or downward variation in the value of a variable. The new solution is then assessed and is adopted as the best if its cost is lower than the previous best solution. Two types of random movements are considered, Mov1 and Mov2, in which the number indicates the number of randomly modified variables when generating a new solution. In this way, the most efficient type of method is determined for application in the next strategy. The process is repeated for a given number of iterations until no further improvement of the solution is found. This strategy is known to sometimes stay with a local optimal solution, which, although better than the initial, is not the best possible, and the method is unable to improve on it without accepting worse solutions, in which case the optimal solution will not be found. In addition, as this method depends on a great extent on the initial solution adopted, the calculations were repeated five times to observe its influence. The results obtained by this strategy are presented in Section 5.3.

The fourth method was *Simulated Annealing*, originally proposed in 1983 by Kirkpatrick et al [19], based on an analogy with the formation of crystals melted at high temperatures and allowed to cool slowly so that they remain in a state of minimum energy. This process is governed by the Boltzmann factor, $exp(-\Delta E/T)$, when ΔE is the increase in energy of the new configuration and T is the temperature. The optimizing process begins with a randomly generated solution at the initial high temperature. This is altered by small movements, as in Descent Local Search. The cost of the new solution is then assessed. Feasible low cost solutions are immediately accepted, while those with higher costs are accepted when a random number between 0 and 1 is less than the expression $exp(-\Delta E/T)$, when ΔE is the absolute value of the cost increase and T the present temperature. A specific number of iterations, known as the *Markov chain*, are carried out at this temperature, which is then reduced by means of the expression $T = k \cdot T$ where k is the coefficient of cooling, so that the likelihood of accepting higher cost solutions is reduced. The process usually ends when the temperature is reduced to a small proportion of the original, or after a certain number of Markov Chains with no improvements to the solution [16]. With this strategy, which allows worse solutions to be accepted, locally optimal solutions can be avoided in which strategies like Descent Local Search would become stuck. In this method the different parameters, such as initial temperature, length of the Markov chain and coefficient of cooling, must be calibrated. The results obtained by this strategy are given in Section 5.4.

5. Results of the search methods

The different methods of searching for optimal solutions were applied in a normal type of PC with a 3.2 GHz Intel Core i7, which puts this building process design tool within the reach of practically any user.

Before looking for optimal solutions, and with the aim of making it possible to compare the solutions obtained with those actually applied in the experimental and Fine Arts buildings as described in Section 2, the costs of each were assessed according to the objective function defined, and were found to be €6.14/m^2 and €11.97/m^2 respectively. Below, these costs are compared to those obtained from applying the different search methods.

5.1. Exact method

Applying the exact method to the experimental building required a computation time of 31.44 hours. The optimal solution obtained (see Table 5) was a cost of €2.88/m^2. It should be emphasized that this was the best solution to the problem considered and involves a cost reduction as defined by the objective function of 53.09 %.

From the computation time and the dimension of the solution space of this building, a mean ratio of 332 calculated solutions per second is obtained. After different numerical simulations for the Fine Arts building a mean ratio of 27 calculated solutions per second is obtained. As accepting this ratio would imply a computation time of 904,608 centuries, the exact method is clearly impractical and the use of heuristic methods is necessary.

5.2. Random Walk

The percentage of feasible solutions to the problem under study obtained by this method was 47.01% for the experimental and 23.63% for the Fine Arts building. Fig. 3 gives the financial cost of the feasible solutions obtained in relation to the execution time of this strategy up to 100,000 iterations. The best solution found has a cost of €3.02/m^2 for the experimental building and €11.08/m^2 for the Fine Arts building. These costs involve reductions of 50.81 % and 7.44 %, respectively. The main characteristics of each solution are summarized in Table 6.

Table 5. Best solution obtained for experimental building by the exact method

Variable	Experimental Building
Process	SCS
Clearing or Reshoring Percentage [%]	66
Consecutive Shored Floors	2
Separation of Straining Pieces [m]	3
Shores Area [m^2]	2.89E-04
Separation of Shores Level 1 [m]	2
Separation of Shores Level 2 [m]	1
Separation of Shores Level 3 [m]	2
Casting Level 1 [days]	0
Casting Level 2 [days]	5
Casting Level 3 [days]	5
Clearing Level 1 [days]	2
Clearing Level 2 [days]	2
Clearing Level 3 [days]	2
Reshoring Level 1 [days]	-
Reshoring Level 2 [days]	-
Reshoring Level 3 [days]	-

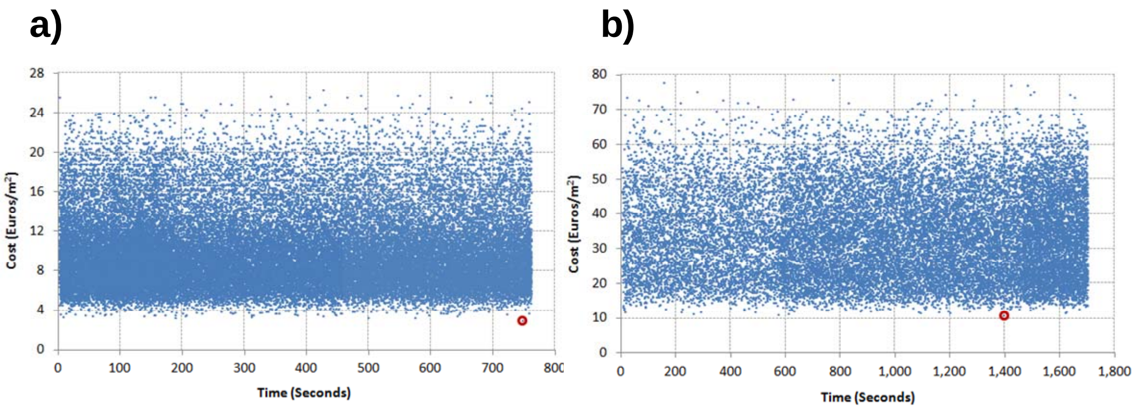

Fig. 3. Search process for optimal solution by Random Walk for 100,000 iterations for a) Experimental Building and b) Fine Arts Building

Table 6. Best optimal solutions obtained by random Walk for 100,000 iterations.

Variable	Experimental Building	Fine Arts Building	Variable	Experimental Building	Fine Arts Building
Process	SCS	SCS	Casting Level 6 [days]	-	7
Clearing or Reshoring Percentage [%]	66	66	Casting Level 7 [days]	-	6
Consecutive Shored Floors	2	2	Clearing Level 1 [days]	2	6
Separation of Straining Pieces [m]	2	2.49	Clearing Level 2 [days]	2	5
Shores Area [m^2]	2.89E-04	2.89E-04	Clearing Level 3 [days]	2	2
Separation of Shores Level 1 [m]	2	2	Clearing Level 4 [days]	-	6
Separation of Shores Level 2 [m]	0.5	2	Clearing Level 5 [days]	-	4
Separation of Shores Level 3 [m]	2	0.5	Clearing Level 6 [days]	-	3
Separation of Shores Level 4 [m]	-	2	Clearing Level 7 [days]	-	3
Separation of Shores Level 5 [m]	-	2	Reshoring Level 1 [days]	-	-
Separation of Shores Level 6 [m]	-	2	Reshoring Level 2 [days]	-	-
Separation of Shores Level 7 [m]	-	2	Reshoring Level 3 [days]	-	-
Casting Level 1 [days]	0	0	Reshoring Level 4 [days]	-	-
Casting Level 2 [days]	5	12	Reshoring Level 5 [days]	-	-
Casting Level 3 [days]	5	10	Reshoring Level 6 [days]	-	-
Casting Level 4 [days]	-	5	Reshoring Level 7 [days]	-	-
Casting Level 5 [days]	-	10			

5.3. Descent Local Search

As this method requires a randomly generated initial solution, each building was calculated five times. The results of the five different solutions for each type of random movement (Mov1 and Mov2) and both buildings can be seen in Figs. 4 and 5. The financial cost is also given in relation to the calculation time of the solutions obtained by this method. The calculation process is shown on the left followed by the method with only one movement (Mov1) for the five calculations. The 2-movement case (Mov2) is shown on the right. The results were obtained after establishing a stopping criterion of 1,000 iterations without finding an improvement.

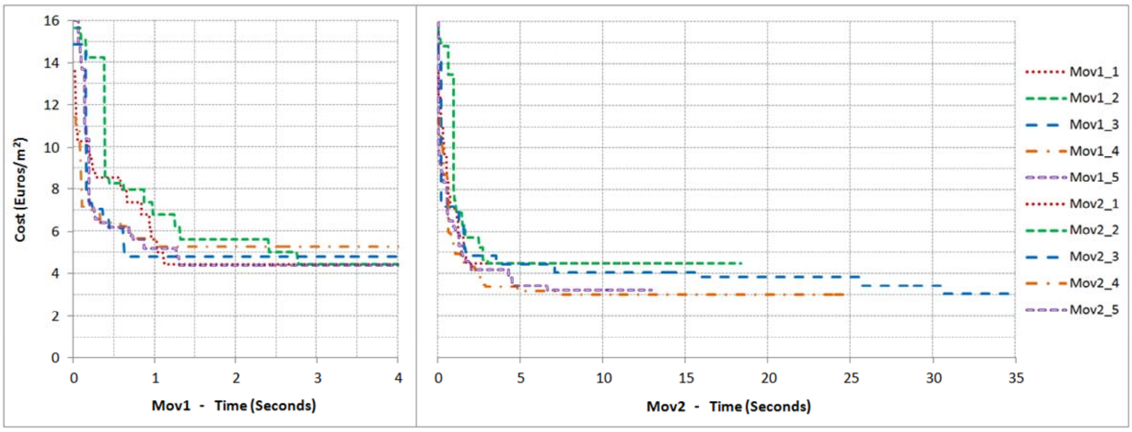

Fig. 4. Search process for optimal solution by Descent Local Search in the Experimental Building.

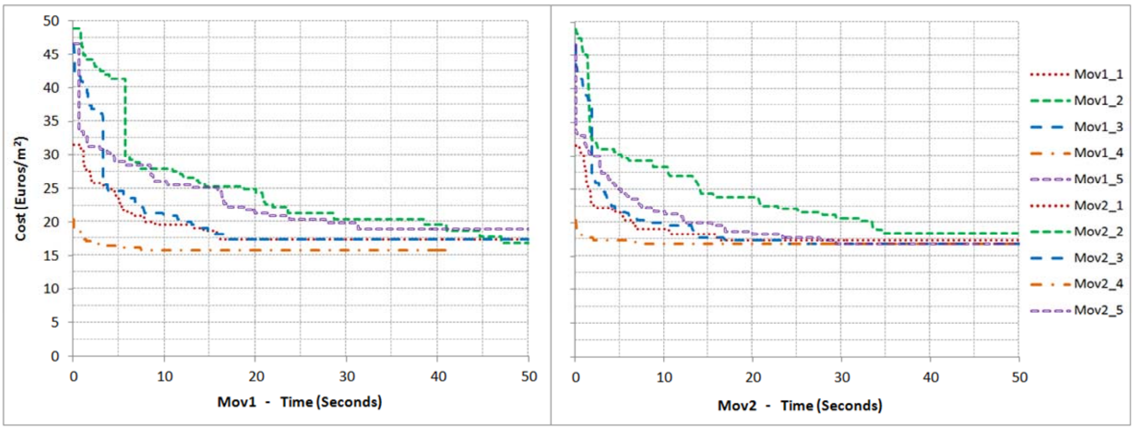

Fig. 5. Search process for optimal solution by Descent Local Search in the Fine Arts Building

In the case of the experimental building (see Fig.4), it is more efficient to perform two random movements than one. In the Fine Arts building (see Fig.5) there are no significant differences in the financial cost obtained by the different solutions, since the mean of the optimal solutions is the same with one movement or two. In the following section therefore only two movements will be applied when randomly generating new solutions for both buildings.

The best solution found gave a cost of €3.00/m^2 for the experimental and €15.81/m^2 for the Fine Arts building, with computation times below 40 and 90 seconds, respectively, which involve a cost reduction of 51.14% for the experimental and a worse solution for the Fine Arts buildings. The main features of the solutions are given in Table 7.

Table 7. Best optimal solutions obtained by Descent Local Search.

Variable	Experimental Building	Fine Arts Building	Variable	Experimental Building	Fine Arts Building
Process	SCS	SS	Casting Level 6 [days]	-	8
Clearing or Reshoring Percentage [%]	50	0	Casting Level 7 [days]	-	7
Consecutive Shored Floors	2	2	Clearing Level 1 [days]	2	-
Separation of Straining Pieces [m]	3	2.49	Clearing Level 2 [days]	2	-
Shores Area [m^2]	2.89E-04	2.89E-04	Clearing Level 3 [days]	2	-
Separation of Shores Level 1 [m]	1	2	Clearing Level 4 [days]	-	-
Separation of Shores Level 2 [m]	2	2	Clearing Level 5 [days]	-	-
Separation of Shores Level 3 [m]	0.5	1	Clearing Level 6 [days]	-	-
Separation of Shores Level 4 [m]	-	0.5	Clearing Level 7 [days]	-	-
Separation of Shores Level 5 [m]	-	1	Reshoring Level 1 [days]	-	-
Separation of Shores Level 6 [m]	-	0.5	Reshoring Level 2 [days]	-	-
Separation of Shores Level 7 [m]	-	2	Reshoring Level 3 [days]	-	-
Casting Level 1 [days]	0	0	Reshoring Level 4 [days]	-	-
Casting Level 2 [days]	5	6	Reshoring Level 5 [days]	-	-
Casting Level 3 [days]	5	5	Reshoring Level 6 [days]	-	-
Casting Level 4 [days]	-	11	Reshoring Level 7 [days]	-	-
Casting Level 5 [days]	-	6			

5.4. Simulated Annealing

This method requires a randomly-generated initial solution, initial temperature, Markov chain length, cooling coefficient and a stopping criterion. Medina's method [40] was chosen to set the initial temperature; this consists of choosing an initial temperature value and determining the number of solutions accepted. Obtaining between 20 and 40 % of accepted solutions is considered an appropriate threshold for this value. If the percentage is higher than the upper limit, the initial temperature is halved and if below the lower limit it is doubled until it converges. A double condition was adopted as the stopping criterion: reaching a Markov chain without improving the solution and a temperature below 0.01% of the initial. To calibrate the length of the Markov chain and cooling coefficient, a study was made of the values shown in Table 8 for both buildings.

Table 8. Study for the calibration of the length of the Markov chain and cooling coefficient.

	Experimental Building	*Fine Arts Building*
Length of Markov Chains	500 - 1,000 - 2,000 - 5,000	500 - 1,000 - 2,000 - 5,000
Cooling Coefficient (k)	0.85 - 0.90 - 0.95	0.85 - 0.90 - 0.95

After this study, Markov chain lengths of 5,000 and 1,000 and cooling coefficients 0.85 and 0.95 were adopted for the experimental and Fine Arts buildings, respectively.

Even though in this strategy the dependence of the initial solution is minimal, each building was calculated five times and each time the same optimal solution was obtained. Fig. 6 shows the results obtained in one calculation for each building, considering two movements (Mov2), as described in Section 5.3. This figure also gives the financial cost in relation to the computation time of the solutions accepted by this method. Also shown are the temperature variations adopted by the method; it can be seen that as the calculations advance the temperature drops, which reduces the probability of accepting solutions worse than the latest being accepted. In fact, it can be seen that the variation of the financial cost gets smaller as the calculations advance and in both cases converges on the optimal result obtained.

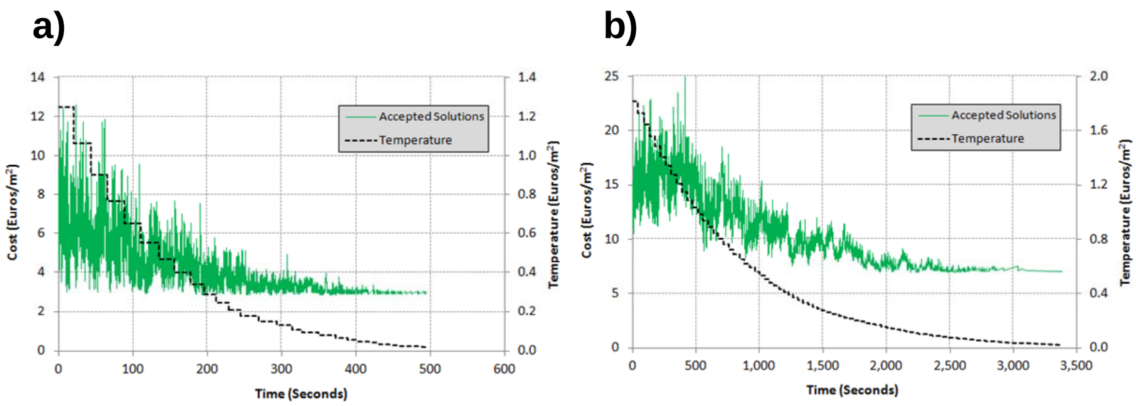

Fig. 6. Search process for optimal solution by Simulated Annealing for a) Experimental Building and b) Fine Arts Building

The best solution obtained had a cost of €2.88/m^2 for the experimental and €6.96/m^2 for the Fine Arts building. Computation times were 26.57 and 95.90 minutes, showing cost reductions of 53.09 % and 41.85 %, respectively. The main features of the solutions are summed up in Table 9.

Table 9. Best optimal solutions obtained by Simulated Annealing.

Variable	Experimental Building	Fine Arts Building	Variable	Experimental Building	Fine Arts Building
Process	SCS	SCS	Casting Level 6 [days]	-	5
Clearing or Reshoring Percentage [%]	66	66	Casting Level 7 [days]	-	5
Consecutive Shored Floors	2	2	Clearing Level 1 [days]	2	2
Separation of Straining Pieces [m]	3	1.66	Clearing Level 2 [days]	2	2
Shores Area [m^2]	2.89E-04	2.89E-04	Clearing Level 3 [days]	2	2
Separation of Shores Level 1 [m]	2	2	Clearing Level 4 [days]	-	2
Separation of Shores Level 2 [m]	1	1	Clearing Level 5 [days]	-	2
Separation of Shores Level 3 [m]	2	2	Clearing Level 6 [days]	-	2
Separation of Shores Level 4 [m]	-	1	Clearing Level 7 [days]	-	2
Separation of Shores Level 5 [m]	-	2	Reshoring Level 1 [days]	-	-
Separation of Shores Level 6 [m]	-	1	Reshoring Level 2 [days]	-	-
Separation of Shores Level 7 [m]	-	2	Reshoring Level 3 [days]	-	-
Casting Level 1 [days]	0	0	Reshoring Level 4 [days]	-	-
Casting Level 2 [days]	5	5	Reshoring Level 5 [days]	-	-
Casting Level 3 [days]	5	5	Reshoring Level 6 [days]	-	-
Casting Level 4 [days]	-	5	Reshoring Level 7 [days]	-	-
Casting Level 5 [days]	-	5			

6. Analysis of results

A summary of the minimum financial costs (defined by the objective function) can be seen in Table 10, together with the construction times and mean computation times of the solutions obtained by the different optimization methods applied.

Table 10. Summary of minimum costs, construction times, and mean computation time of the four optimization methods applied to both buildings.

	Experimental Building (€6.14€/m^2 and 27 days)			*Fine Arts Building (€11.97€/m^2 and 49 days)*		
	Mean Time [min]	*Minimum Cost [€/m^2]*	*C. Time [days]*	*Mean Time [min]*	*Minimum Cost [€/m^2]*	*C. Time [days]*
Exact Method	1,886.40	2.88	15	-	-	-
Random Walk	12.66	3.02	15	28.28	11.08	56
Descent Local Search	0.41	3.00	15	1.30	15.81	50
Simulated Annealing	26.57	2.88	15	95.90	6.96	35

As could be expected, the results show that SA is the most efficient heuristic optimization strategy in terms of financial cost. The financial cost of the experimental building, as defined by the objective function (see Section 3.4), is 4.00% lower than DLS and 4.64% lower than RW, while for the Fine Arts building the reductions are 55.98 % and 37.18 %, respectively. Furthermore, although the computation time required is slightly higher than the other heuristic methods, the longer time is acceptable in practice. In the case of the experimental building, it can also be seen that SA was able to find the optimal solution to the problem in a drastically reduced computation time respect to the exact method. Although we cannot know whether the best optimal solution to the problem was found in the case of the Fine Arts building, SA's solution is considerably lower than the construction method actually used when it was built. After applying the different optimization methods, the construction times were also reduced by 12 days (44.44 %) and 14 days (28.57 %), respectively, for each of the buildings.

It can therefore be concluded that any user of this type of tool will be able to find an optimal solution to the shoring problem that will reduce both costs and construction times, without the need to previously consider a specific construction process or to have any experience in designing these processes. As can be seen from the optimal solutions obtained (Table 9), they are based on finding a feasible solution with the maximum possible separation between straining pieces and shores and shortest possible operating times to further reduce costs. In this way, the minimum amount of equipment is used and all or part of it is soon recovered. The SCS process was found to be the optimal process for achieving this objective.

7. Conclusions

A tool was developed to calculate and verify the loads on slabs and shores with the aim of obtaining the optimal construction processes for multistorey buildings with *in situ* casting. Both exact and heuristic methods were used to search for the optimal solutions. From the results obtained it can be concluded that, in general, the exact method is only suitable for buildings with fewer than four floors. Heuristic methods must be applied to obtain the optimal processes in buildings with more than this number of floors. Of the strategies considered, Simulated Annealing was found to be the most efficient search method.

Optimal solutions were obtained for the two buildings studied that involved savings of up to 53% of the cost of the shoring system and reduced construction time while fulfilling the constraints considered. The authors recommend that future lines of research conduct detailed analyses of maximum loads on shores and their local effects on slabs, two aspects that in certain cases could have a strong influence on optimal construction processes. It would be also interesting to use different techniques such as multiobjective analysis, population methods and hybrid optimization.

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