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Construction Labour Measurement in Reinforced Concrete Floating Caissons in Maritime Ports

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Abstract

This research work attempts to approach the measuring of the working equipment necessary to make floating caissons for maritime work and their performances. With this objective, an empirical study has been carried out based on the construction of five floating caissons with a rectangular layout of 34.00 meters in length, 17.00 meters in width, and 19.00 meters in depth, lightened with 32 vertical cells. This work was carried out in the port of Granadilla, Tenerife (Spain). The updated scientific literature related to the execution of this type of floating structure refers to the importance of the calculation hypotheses, the actions to be taken into account, the service states or the importance of the choice of materials (concrete and steel). However, scientific research does not seem to face the problem of how to size the working team necessary to execute this type of structure. The work force is approached from the point of view of the adequate sizing of working groups. The important contribution of the article to the project and construction management literature is the development and capability of an easy-to-use optimization model for planning the labour and labour days required in floating caisson construction. The optimization model proposed in this research allows the project managers of a construction company to estimate the labour costs and teams necessary in the execution of the construction. This gives it a competitive advantage both in the construction phase and in the bidding phase for the award of the work.

Keywords: Concrete Caisson; Floating Caissons; Caissons Breakwaters; Sliding Concreting; Construction.

1. Introduction

Seaports are nodes that are integrated into commercial, logistical, and transportation networks. Their main function is the safe and efficient transfer of goods and passengers between maritime and land transport nodes, such as roads, railroads, and shipping routes. Today, ports have acquired a commercial, industrial, logistical, leisure, or even military function. The service area of ports now has infrastructure related to the following: (a) control of sea oscillations (breakwaters and maritime structures); (b) maritime safety and operability of the area (berthing and mooring areas); (c) land use and exploitation of the area; and (d) land transportation access modes [1].

The technology of vertical concrete walls was introduced 2,000 years ago by Roman port engineers, in contrast to the Greek tradition of rubble mound breakwaters. The first vertical wall breakwater was built with a low rubble base in Naples in 1900. The vertical breakwater consisting of solid concrete blocks was first constructed in Otaru Harbor (Japan), which lasted from 1897 to 1907 [2, 3]. In rough seas, caisson breakwaters become the most suitable option [4].

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The main objective of a breakwater is to ensure that port operations and logistics related to maritime transport, its interconnection with other modes of transport, and the comprehensive management of vessels are carried out smoothly and safely [1]. Vertical breakwaters are large structures that, due to their lightweight, multi-cellular cross-section, can float once completed. This provides great versatility in terms of construction (by sliding concreting), transport in floating mode, and placement at the port site. Typical infrastructures using this type of box are docks and other berthing structures, vertical shelter docks, and special floating docks. This type of floating structure is a widely used typology in the construction of docks in international ports [5].

When water depths are greater than 15-20 meters, vertical breakwaters are preferred. Most of the existing vertical breakwaters were constructed using massive precast cellular reinforced concrete. The caissons are floated and then towed to the desired location. These are ballasted and sunk into the base of the existing mound, and their weight can be augmented with rubble, concrete, or sand fill. This type of breakwater is also known as "vertical", "vertically composite" or "vertical-faced or caisson breakwater" [5]. In Spain, the construction of floating caissons for docks, piers, or any other type of port work has experienced great progress and is well established. It is in this field that the largest prefabricated reinforced concrete structures have been built, using up to 10,000 m^3 of material and with dimensions of up to 70×32×34 meters. Once these structures are built, they are towed afloat to their final location [1, 6].

The first works carried out with prefabricated reinforced concrete floating caissons were the Levante quay in the port of Huelva, on the banks of the Odiel estuary (8 m maximum draught), in 1932, and the Sagrado Corazón quay dock in Tarifa (10 m maximum draft), in 1945. From then on, various docking works were built using this technique in different ports such as Pasajes, Avilés, Gijón, Cádiz, or Cartagena [1, 6].

During the 1980s, the need for deeper drafts, motivated by the growth of the State's commercial ports, further boosted the use of this technique. During the 1990s, this method was used for the construction of deep vertical breakwaters: the Reina Sofía breakwater in Las Palmas (26 m draft) and the breakwater at the Escombreras dock in Cartagena (28 m draft) were built. At present, Spain is among the most advanced countries in the construction of precast reinforced concrete caissons, comparable only to Japan.

From an economic point of view, there are reasons to support the construction of floating docks. They produce significant savings compared to breakwaters or gravity dams at great depths since their construction cost is practically independent of depth, while that of a sloping dock grows exponentially with depth. This saving is mainly due to the savings in the volume of riprap and filling materials, compared to sloping breakwaters or the banks of vertical breakwaters.

Maritime works differ from other types of civil works in several ways. When we refer to this type of work and, specifically, to the manufacture of vertical dikes, it is where caisson technology comes into play. The use of caissons in vertical dams has several advantages over embankment, pile, and deck dams. Some of the characteristics that have led to the widespread use of caisson technology are its strength, its durability in the aggressive environment to which it is exposed, and its versatility.

Several studies were conducted in order to investigate and optimize the use of construction resources so as to accelerate the completion of construction projects. These models were developed using various optimization techniques, including (1) heuristic methods to optimize crew configuration to minimize project time and cost and to analyze the time-cost trade-off; (2) mathematical methods to optimize resource utilization to minimize repetitive project time and cost and analyze the time-cost trade-off; and (3) metaheuristic methods to optimize resource utilization and to analyze the time-cost trade-off [7-9].

The updated scientific literature related to the execution of this type of floating structure refers to the importance of the design assumptions, the actions to be taken into account, the service states or the importance of the choice of materials (concrete and steel). Workmanship is approached from the point of view of the appropriate sizing of working teams. However, scientific research does not seem to address the problem of how to size the working teams necessary to build this type of structure [7-9]. Labour costs are one of the most important variables to take into account when sizing this type of infrastructure. The weight within the project could represent more than 50% of the total construction cost. The correct sizing of work teams is revealed as an important element to be studied by project managers and a determining factor in controlling construction costs.

Around 30–40% of the total project cost is spent on labour [10]. Improving productivity is a major concern for any company in the construction industry [11]. One of the most important factors influencing construction labour productivity is manpower [12]. Despite many technological advances, labour is still an important asset for the construction industry, as the quality of its products is dependent on labour. Proper manpower management is key to the successful completion of the project. Controlling only the cost of labour by hiring more unskilled labour may prove to be counter-productive. Human labour is one of the most important ones, as it is the humans who take the work forward. Proper management of manpower is key to the successful completion of the project [11].

Dixit et al. [13] attempt to summarize the evolution of research in Construction Productivity through a systematic literature review from the papers published from 2006 to 2017. By analysing the literature review, the majority of the countries are facing the issue of decline and low productivity trends, and poor productivity of skilled workforce is a standout amongst the most critical human resource issues in developing and developed countries, which impacts the development and economic growth of a nation. The findings of the study concluded that the factors affecting construction productivity in the majority of the studies are tools and consumables, coordination, drawing management, material availability, labour skills, training, and rework [14].

Dai et al. [15] present a literature review on the research activities and developments of floating breakwaters over the past few decades. Floating breakwaters may be categorized into seven main types, namely, the box-type, the pontoon-type, the frame-type, the mat-type, the tethered float type, the horizontal plate type and other types. The box-type and pontoon-type floating breakwaters are the most common designs, and they are effective in protecting the shoreline mainly by reflecting incoming wave. An advanced computer-based system is presented to support port construction management [16]. The system can improve by 10% the available working days for breakwater construction. Construction budget is reduced by the early identification of safe-working windows.

This piece of research work attempts to approach the dimensioning of the working teams necessary to build floating caissons and their performance. With this objective, an empirical study was carried out based on the manufacture of 5 floating caissons of rectangular layout of 34.00 meters length, 17.00 meters beam and 19.00 meters depth, lightened with 32 vertical cells. This was a project carried out in Port of Granadilla - Tenerife – Spain, by Syconca, S.L. as Subcontractor Company. The optimization proposed model in this research allows the project managers of a construction company to estimate the labour cost and teams necessary in the execution of the construction. This gives it a competitive advantage both in the construction phase and in the bidding phase for the award of the work. The following lines detail the process used.

2. Research Methodology

This study aims to develop an optimization model to estimate the labour cost and teams necessary in the execution of the floating caissons. Figure 1 shows the flowchart all the steps to achieve its objective. Firstly, a literature review of the subject under study is conducted. Then a case study is selected, at Port of Granadilla – Tenerife (Spain), and a conceptual model was detailed in relation to the tasks in the manufacture of a floating caisson. Datasets from the case study is collected for analysis and development an optimization model. Finally, the results of the research and its applications are analysed.

Figure 1. Flowchart of the research methodology

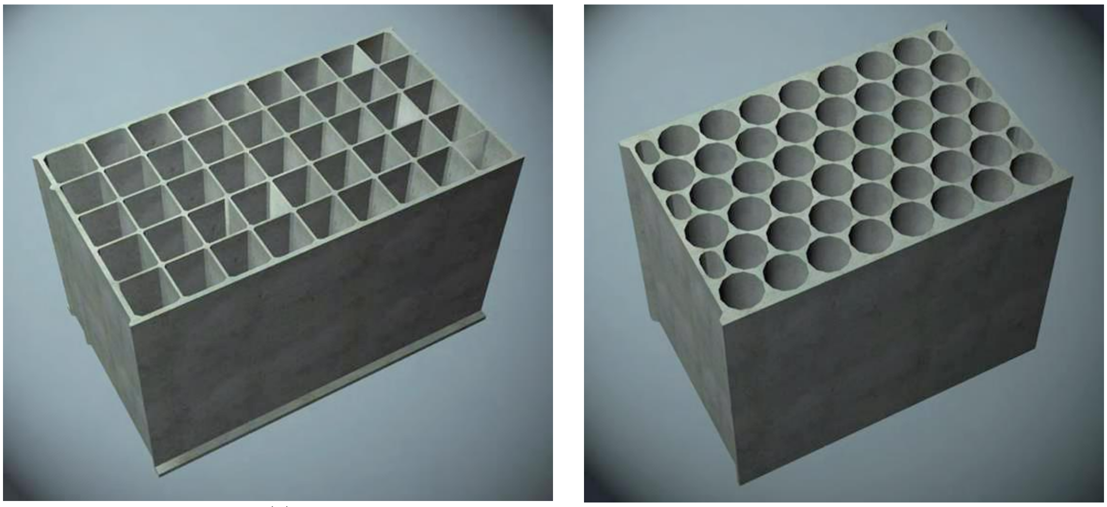
3. Construction Process in the Manufacture of a Reinforced Concrete Floating Caisson. A Case Study in the Port of Granadilla – Tenerife (Spain)

A floating caisson is a structural element of rectangular layout, in most cases, lightened with vertical cells, usually circular or rectangular. They are manufactured in floating installations, called caisson builders. There are different types of caisson builder: submersible platform catamarans, floating docks or submersible pontoons. Reinforced concrete caissons are parts that are designed and built to form part of the structure of some maritime works. They are designed in such a way that they can remain afloat and be towed for transport.

In the caissons, it is possible to distinguish the following parts:

- Sill plate: solid reinforced concrete slab, usually rectangular in shape with a uniform thickness between 0.40 m and 1.20 m.
- Shaft: straight prism with lightening along its entire height.
- Footings: overhanging areas of the sill plate with respect to the shaft.

There are two common types of caissons: rectangular cell caissons (Figure 2a) and circular cell caissons (Figure 2b). Reinforced concrete caissons are usually built in floating or semi-floating facilities, such as: floating docks, catamarans with submersible platform, submersible pontoons guided from fixed structures.



(a) (b)

Figure 2. (a) Caisson with rectangular cells. (b) Caisson with circular cells

Floating or semi-floating equipment for caisson construction consists of a metal pontoon on which turrets are installed (Figure 3). Their configuration allows them to perform submersion or emersion maneuvers by ballasting and deballasting their tanks, which makes it possible to carry out launching operations of structures built on their deck.

Figure 3. Floating dock in construction in Tenerife (Spain)

They have certain specific elements:

- Formwork support structures: they slide vertically along guides welded to the dike turrets.
- Formwork: made up of metal plates and forming the horizontal section of the caisson shaft.
- Sliding equipment: It consists of a series of hydraulic jacks that ascend by means of metal bars arranged for this purpose by means of clamps, dragging the structure and the formwork hanging from it.
- Concrete distribution equipment: It consists of a system of pipes through which the concrete circulates driven by pumps.
- Ballasting equipment: They carry out the filling and emptying of the dike tanks for their controlled immersion and emersion.
- Working platforms: working areas that accompany the formwork and which can be accessed from the pier, allowing the passage of personnel and the stockpiling of materials, especially reinforcement steel.

The following sections describe an empirical study based on the construction of five rectangular reinforced concrete floating caissons of 34.00 meters in length, 17.00 meters in breadth (width) and 19.00 meters in depth (height) (10,982.00 m3), lightened with 32 vertical (rectangular) cells and the tasks that make up the construction process of the floating caissons.

The study area is located in the in the Port of Granadilla,– in the southeast coastal of the island of Tenerife (Spain). It is the largest industrial port of the Canary Islands, which is off the northwest African coast (20º04'56''N 16º29'30''E, Atlantic Ocean), as shown in Figure 4. The port has a contradique of a length of 1,150 meters. The Exterior Dock extends longitudinally at 2,512 meters. The "*Muelle de Ribera"* has 160 meters with a draft of sixteen meters and an associated esplanade of approximately fifteen hectares. The significant wave height was $H_{s, 95\%}$ = 3.8 m for Exterior Vertical Dock (return period = 70 years) and $H_{s, 95\%}$ = 5.1 m for Exterior Slope Dock (return period = 300 years) with associated peak period Tp of 13 s for both.

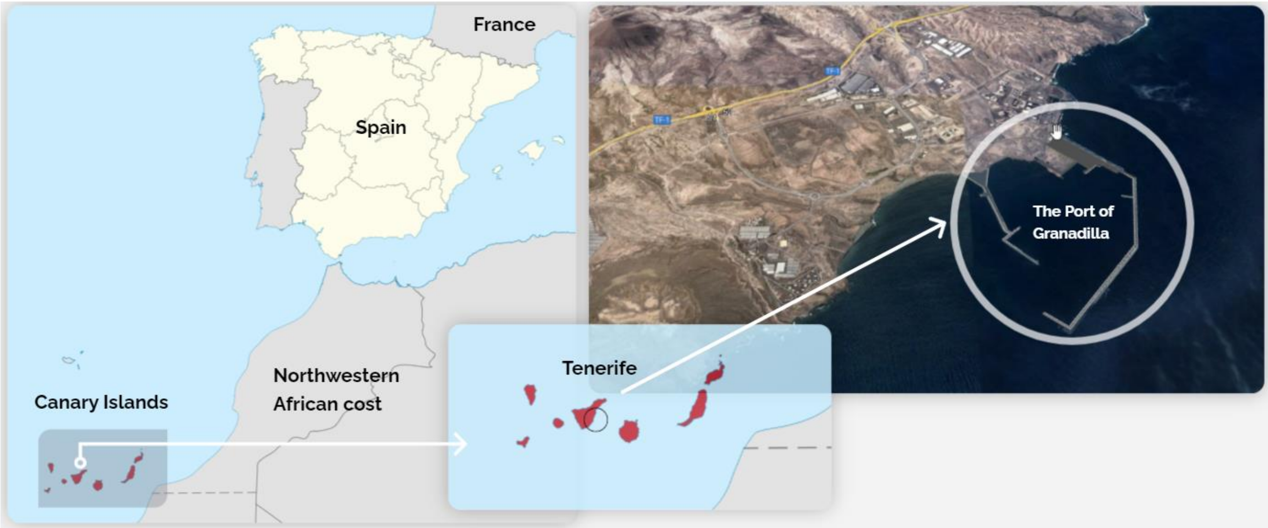


Figure 4. Location of the Port of Granadilla

The tasks proposed in the following lines is based on the know-how of the construction company in this type of construction works, after carrying out a significant number of reinforced concrete floating caissons works over the last few years. The proposed task planning presents the experience of the company's project managers.

3.1. Tasks in the Manufacture of a Floating Caisson

The sequence of fabrication of a caisson in a floating dock is detailed below. The tasks contemplated are those shown in the graph (Figure 5) and described underneath.

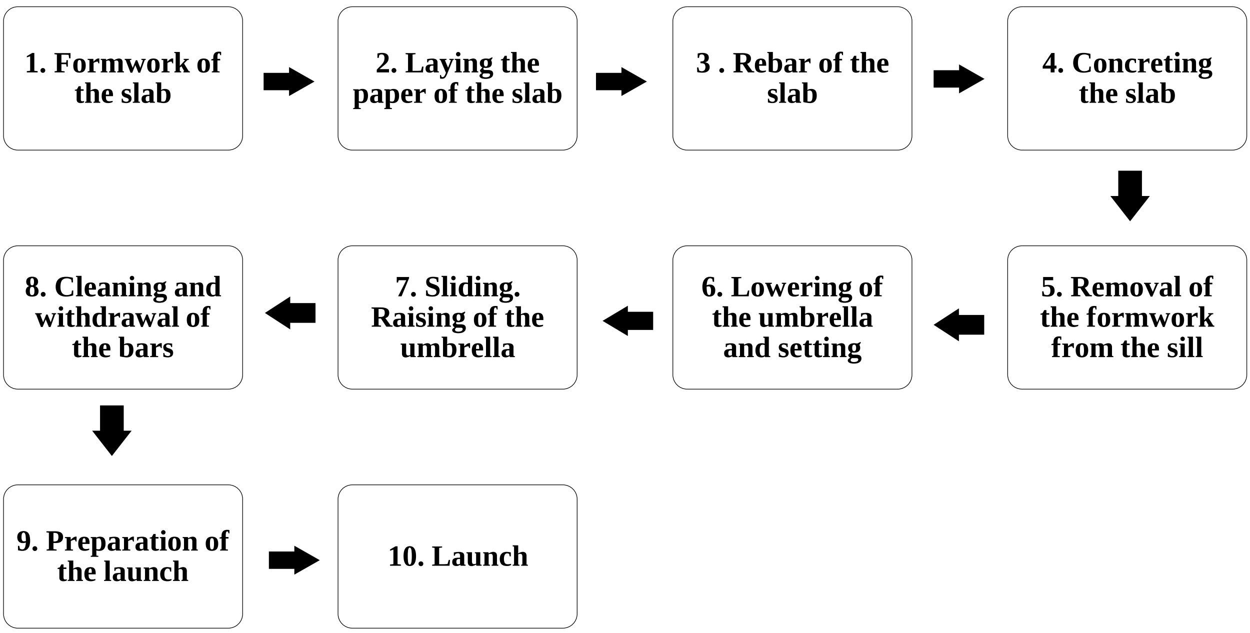


Figure 5. Tasks in the manufacture of concrete caissons.

T1. Formwork of the slab. The formwork of the slab is similar to that of any type of reinforced concrete foundation, with the difference that it is carried out on a floating platform. It involves the placement of metal plates that form the perimeter to house the concrete and steel that will form the 34.00x17.00x0.70 meter slab or floor slab (Figure 6).

Figure 6. Pontoon with reinforcing steel for the slab

T2. Laying the paper of slab. The platform on which the caisson foundation slab is reinforced and concreted has a surface layer of porous concrete in order to drain the water that may flood this surface when the dock is sailing or being built. To prevent this concrete from adhering to the caisson foundation slab, a sheet of paper is placed. This will have a sufficient density to allow the separation of the caisson and the porous concrete surface, on which the caisson is executed, without the latter being damaged or torn away by the contact of the caisson slab (Figure 7).

Figure 7. Placing the paper for the slab

T3. Rebar of the slab. The reinforcement of the caisson foundation slab will begin once the perimeter of the caisson has been formed and the slab paper has been put in place. The reinforcement of the slab can be carried out in-situ, as in the case study, or it can be carried out outside and then placed on the platform (Figure 8). This work will be divided into two processes. First of all, the main base reinforcement of the sill will be assembled, properly staked out, as well as the reinforcements of the lower part of the sill. Then this process will be repeated with the upper part of the reinforcement of the slab. Once the floor, bottom reinforcement, top reinforcement, reinforcements and shear reinforcement have been completed, the layout is checked and the second phase begins, the assembly of the wall starts. This phase constitutes the vertical and horizontal reinforcement of the walls of the first meters of the caisson shaft, divided into three different zones depending on the height and varying the reinforcement between them. The sea-side and the land-side of the caisson must be perfectly differentiated, since the reinforcement varies due to the stresses to which it will be subjected once it is put into service.

Figure 8. Concreting of the slab

T4. Concreting the slab (Figure 9). The concreting work is not very different from that of a foundation on land, and aspects such as concreting must be taken into account, such as the fact that the concreting must follow a logical sequence to facilitate the following formwork stripping activity. This concreting will be carried out cell by cell, introducing the hose of the concreting boom through a hole in the bell of the vertical formwork, through which the access of the workers for concreting is also arranged.

Figure 9. Concreting of the slab

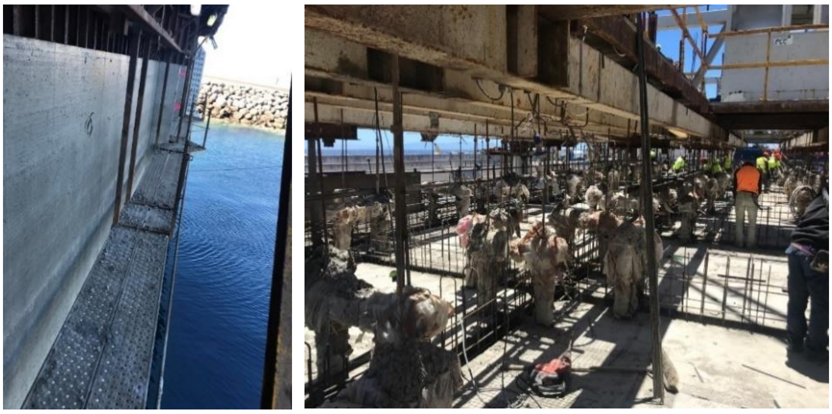
T5. Formwork removal from the slab. This work consists of removing the molds placed around the perimeter of the geometry of the foundation slab, which confined the concrete as shown in Figure 10.

Figure 10. Removal of formwork from the slab

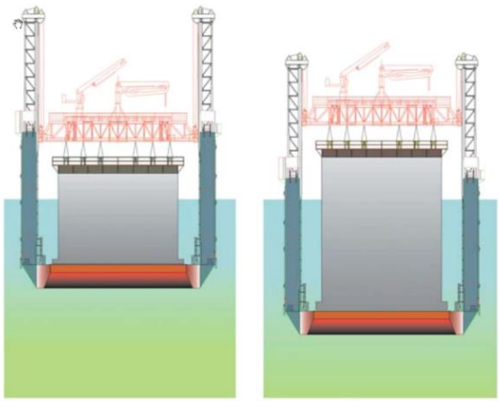
T6. Lowering the umbrella or sliding formwork (Figure 11). This task consists of setting up formwork of little height (between 1.00 and 1.50 meters), whose vertical upward movement is ensured by means of jacks and climbing bars supported on the base of the caisson or pontoon of the floating dock, or other drive mechanisms that carry out the displacement supported on fixed guides arranged on the floating dock. To carry out this operation, it is necessary to pay special attention to ensure that the concrete of the foundation slab or floor slab has set and hardened optimally.

Figure 11. Removal of the sliding formwork [17]

T7. Sliding (Figure 12). Caisson construction is carried out with slipforms. Formwork removal and placement can be done by hanging from a structure (floating docks), or by an external crane (submersible pontoons). The concrete is poured into the formwork more or less continuously and the formwork is lifted progressively as the concrete hardens. The lifting speed of the formwork is in the order of 10 to 30 cm/h (depending on several factors such as weather conditions, concrete conditions, equipment set up for rebar placement, concreting, etc.), in intervals between 1 to 4 cm at a time. In this way, the concrete separates from the formwork between 4 and 12 hours after concreting.



(a)



(b)

Figure 12. Sliding: (a) image in carrying out construction works; (b) graphic about the construction process of floating caissons [17]

This method, which results in high yields and is particularly appropriate for a structure as regular as a port caisson, implies the need for uninterrupted work, for which 2-3 working shifts must be arranged, and also requires very specific conditions from the concrete: a) speed of setting (after 4-6 hours it must have a minimum strength of 0.2 MPa, so that it is able to support its own weight); b) Its resistance must grow faster than the applied load; c) Docility, ease of compaction, good adherence to the reinforcement and reduced friction to the formwork surface; d) Its quality and docility must remain unaltered throughout the execution of the work, which implies a strict control of the dosage and transport times; e) The cement to be used must have high initial strength and low shrinkage; f) The use of rolled aggregate is recommended, although it is not always possible; g) The maximum aggregate size must be between 1/5 and 1/7 of the wall thickness and must always be less than 30mm (Floating caisson design and construction manual).

Within the construction cycle of a caisson, the time dedicated to sliding is the most resource-consuming. The difficulties or unforeseen events can be many: the learning curve of the personnel in the first caisson, the presence of wind, crane breakdowns, and adjustments of the concrete plant.

T8. Raising the umbrella or sliding formwork. Once the sliding has been completed and the flushing or top finishing of the caisson has been carried out, the formwork continues sliding until the entire caisson structure is free, as shown in Figure 13. There is no waiting time in this activity, since it is a mechanized activity.

Figure 13. Raising the umbrella or sliding formwork

T9. Cleaning and removal of climbing bars. This task consists of the removal and cleaning of the climbing bars that have been used for the vertical sliding of the formwork. It also includes the cleaning of the formwork to leave it ready for the execution of the next caisson. This process is linked to the operation of the crane.

T10. Launching. Preparation for launching, launching, deballasting and refloating of the pontoon. Simultaneously with the cleaning, the launching preparation works begin, which include safety aspects: placement of nets, platforms, etc. The caisson is then launched, which consists of removing it from the floating dock. This operation is carried out with a tugboat as shown in Figure 14. After the caisson is removed, the tanks are unballasted from the dock and refloated.

(a) (b)

Figure 14. Launch the floating caissons: (a) image of the construction works; (b) graphic about the construction process of Launch [17]

4. Number of Work Force in the Manufacture of Floating Caissons

4.1. Times of the Work Force in the Manufacture of Floating Caisson

Based on the experience of the construction company, the execution is planned in two daily shifts of 12 hours each, in which the needs of the work must be met, sizing and differentiating the workers by activities.

- Workers for the preparation and placement of the framework for the caisson.
- Workers engaged in pouring the concrete.
- Support workers: other support workers who are considered to be permanent and who are necessary at a rate of one per work shift:
  - One worker to aid in sliding.
  - One crane operator.
  - The pump operator.

It must be taken into account that, once the construction of a floating caisson of these characteristics has begun, the work must be carried out continuously. This is mainly due to the need to avoid stoppages in the execution of the slab and shafts and, therefore, unions in the concrete mixes.

Table 1 shows the total time in hours spent in the manufacture of 5 caissons, broken down by caissons and tasks. These are values taken in the manufacture of caissons for the work called UTE Granadilla II, whose main constructor was the UTE FCC-SATO and labour subcontractor Syconca, S.L. Tasks T9 and T10 of caisson number 5 are not considered, because being the last unit of the series, a more thorough cleaning of the materials (machinery, formwork, etc.) was carried out.

Table 1. Tasks and times spent on the manufacture of each caisson (hours)

No.	Description of the activity	Caisson 1 (hours)	Caisson 2 (hours)	Caisson 3 (hours)	Caisson 4 (hours)	Caisson 5 (hours)
T1	Shuttering of the slab	2.00	2.00	2.00	2.00	2.00
T2	Placement of the paper for the sill	1.50	11.00	1.50	3.00	1.50
T3	Reinforcing of the slab	48.00	42.00	40.00	36.00	29.00
T4	Concreting of the slab	15.50	14.00	11.50	12.00	10.50
T5	Stripping of the slab	3.00	3.00	3.00	3.00	3.00
T6	Lowering of the umbrella or sliding shuttering	18.00	18.00	14.50	12.00	8.00
T7	Sliding	158.00	116.00	105.00	99.00	96.00
T8	Raising of the umbrella or sliding shuttering	4.00	4.00	4.00	4.00	4.00
T9	Cleaning and removal of the climbing bars	44.00	36.00	24.00	26.00	-
T10	Preparation for the launch, launch, deballasting and refloating of the pontoon.	7.00	5.00	5.00	5.00	-

4.2. Incidents in the Conduct of the Tasks

From the initial analysis of the data shown in Table 1, we can detect differences in the execution times of the different tasks to manufacture the different caissons. The complexity of the work to be carried out and the different agents involved produce incidents which are summarized below and which it is important to take into consideration for the planning of works in this type of infrastructure:

- Wind. The presence of wind is common in marine environments in which these works are carried out. It is necessary to have weather forecasts that allow us to foresee possible delays and minimize them. In this case, the wind caused delays in the placement of the paper in caissons number 2 and number 4.
- Authorizations: delays in the authorization of the works by the technical management. The delay in the authorization of the slab reinforcement caused delays in caisson 2.
- Crane (tower). The choice of the type of crane to be used is a critical element in the tasks of this process and, especially, in rebar activities. The presence of wind or different types of crane failures can cause the crane to be inoperative. In this case, caisson number 5 was built with a tower crane, while 1, 2, 3 and 4 were built with a mobile crane (truck crane). The times detailed in Table 1 show how rebar works with a tower crane are carried out in much less time than with a truck crane.
- Specialization of the workforce: Since the work becomes repetitive, the workforce acquires a skill that allows them to perform the tasks in less time. In the case of the slab reinforcement task, we see how the times go down from box 1 to 5 due to this specialization.
- Concrete supply: properly scheduling the supply of concrete is a critical task, since running out of material creates significant inconveniences and delays in execution, as happened in box number 1. It must be taken into account that the supplying plant is able to serve the number of concrete trucks that we need in a sequential way and to guarantee that the resolution of possible breakdowns in the trucks, booms, pumps, etc., is guaranteed.
- Concrete conditions: the characteristics of dosage and condition of the concrete must be ensured and adequately planned with the supplying company. This can also cause delays in the execution, and in this case, it was repeated in the execution of caissons 2, 3, 4, and 5.
- Availability of auxiliary resources: the lack of auxiliary resources such as radials, used discs, electric hammers, pressure washer, etc., may cause delays in the execution of the work.

4.3. Times on the Task of Sliding (T7)

One of the most critical activities in the manufacture of floating caissons is the sliding task (T7). The number of workers (concrete and reinforcement workers) involved in this operation has been analyzed in four of the five caissons executed. Table 2 shows the summary of the times employed and the advance in centimeters achieved by the crews of operators in work shifts (day and night). It should be taken into account that the times are influenced by the incidents mentioned in the previous section. These data have served as the basis for developing the optimization model described in the following section. The sliding task is the most time-consuming task in the manufacture of floating caissons. The correct sizing of the team for this activity has a significant influence on the total time for this type of project.

Table 2. Tasks of sliding: labour, times and sliding in centimetres

Caisson No.	Shift No.	SHIFT Day (D) / Night (N)	Concrete Workers No.	Steel Workers No.	Time Hr.	Sliding in CMS
2	1	Day	9	17	8.5	136
2	2	Night	11	16	12	180
2	3	Day	10	18	12	175
2	4	Night	11	16	12	193
2	5	Day	11	19	12	204
2	6	Night	11	17	12	210
2	7	Day	11	18	12	206
2	8	Night	10	17	12	204
2	9	Day	11	19	12	121
2	10	Night	10	15	12	201
3	1	Day	12	17	1,5	25.5
3	2	Night	11	16	12	204
3	3	Day	11	16	12	215
3	4	Night	11	18	12	226
3	5	Day	11	16	12	228
3	6	Night	11	18	12	230
3	7	Day	11	14	12	237
3	8	Night	10	19	12	220
3	9	Day	11	15	12	215
3	10	Night	11	19	7	29.5
4	1	Day	10	14	4	72
4	2	Night	10	15	12	197
4	3	Day	10	16	12	203
4	4	Night	10	16	12	204
4	5	Day	10	16	12	245
4	6	Night	11	16	12	240
4	7	Day	10	17	12	223
4	8	Night	10	17	12	226
4	9	Day	10	16	11	220
5	1	Night	9	15	3	60
5	2	Day	10	16	12	231
5	3	Night	10	15	12	237
5	4	Day	11	16	12	205
5	5	Night	9	16	12	240
5	6	Day	11	16	12	235
5	7	Night	11	16	12	245
5	8	Day	11	16	12	237
5	9	Night	9	15	9	140

5. Proposal of Optimization Model for the Manufacture of Vertical Caissons

In order to determine the optimal number of workers (rebar and concrete workers), as well as the number of work shifts and the hours of each shift required, an optimization model has been developed. The variables to be optimized are n_F (number of rebar workers), n_H (number of concrete workers), n_T (number of shifts) and n_{HT} (number of hours per shift). This purpose, the cost per hour of labour for each type of operator is considered constant, c_H^{Ferr} and c_H^{Hor}, respectively. For the resolution of this system, they have been set at 40 and 70 Euros respectively, although these amounts mainly influence the total cost and not so much the optimal solution. The objective function to be minimized is the total labour cost for the manufacture of a caisson. The restrictions considered on the variables to be optimized are reflected in Equation 1 and are as follows:

- The number of rebar workers, n_F, is at least 30% greater than the number of concrete workers. This restriction is considered based on the experience of the construction company in the conduct of this type of work.
- The number of concrete workers, n_H, shall not exceed 12. This restriction is due to the limited space on the work site.
- The number of shifts, n_T, may not exceed 10. The shifts should not exceed 8.75 because in the sliding reference we have a forecast of sliding in 105 hours and if we divide these hours by 12 hours, we have this 8.75 value. If the shifts were of 8 hours, they should not exceed 13.125 shifts.
- The duration of each shift, n_{HT}, shall not exceed 12 hours or be less than 6 hours. This should be a constant, since the shifts proposed were 12 hours, 2 shifts of 12 hours. The shifts could also be set at 8 hours, 3 shifts of 8 hours and compare the cost of going to 2 or 3 shifts.

The total sliding to be completed will be at least 1,830.00 centimeters (total height of the entire perimeter of the caissons). An average slide per worker per hour of g_{WH} = 0.66 cm has been considered based on the data obtained. All these considerations lead to the proposal of the following entire non-linear model:

$$Min\,\{n_T * n_{HT} * (P_H^{Hor} * n_H + P_H^{Ferr} * n_F)\} \tag{1}$$

Subject to:

$$n_F \geq 1.3 * n_H \tag{2}$$

$$n_H \leq 12 \tag{3}$$

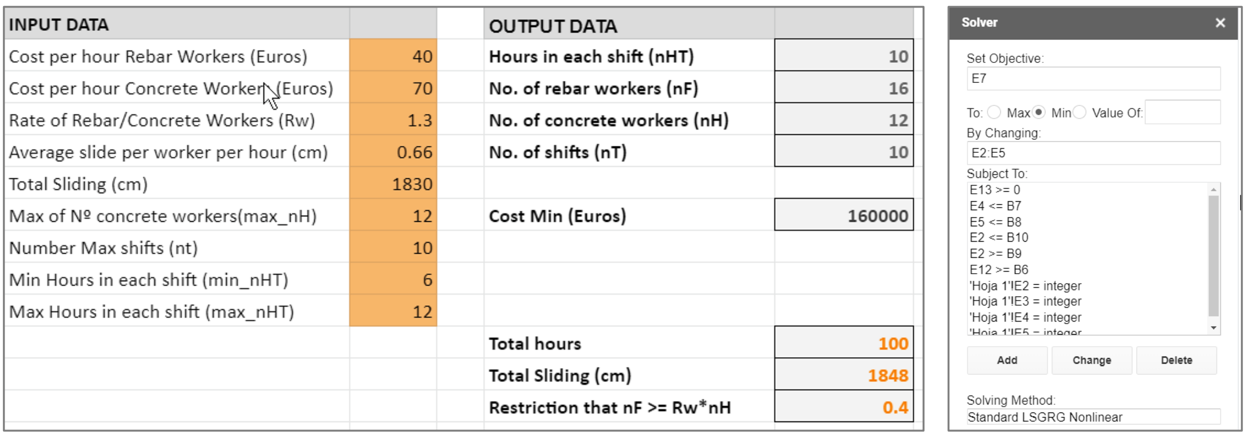
$$n_T \leq 10 \tag{4}$$

$$6 \leq n_{HT} \leq 12 \tag{5}$$

$$(n_H + n_F) * n_H * n_{HT} * g_{WH} \geq 1{,}830 \tag{6}$$

$$n_F, n_H, n_T\ y\ n_{HT}\ integer \tag{7}$$

The Solver module, incorporated in Microsoft Excel, has been used to solve this problem. This optimization tool uses three algorithms depending on the data set: Nonlinear GRG (generalized reduced gradient), used for smoothed nonlinear problems; Simplex LP, used to solve linear problems, and Evolutionary, to solve unsmoothed problems.



(a) (b)

Figure 15. Design of the data entry panel and calculation in Solver (a) and restrictions in solver module (b) [19]

In this case, given the nature of the data set, the Nonlinear GRG algorithm was used. According to Frontline Systems (developer of the Solver add-in for Excel), its nonlinear solver is based on the work published by Leon Lasdon in 1973; in 1978, Lasdon and Waren published the implementation of the code [18]. Equation 1 represents the objective function, while expressions 2 to 7 represent the constraints. In the model, the objective Equation 1 minimizes the total labour cost with the optimal number of operators and working days. The results of the optimal plan were prepared by the authors using the solver in an online spreadsheet. Project managers could duplicate and used the proposed model (see on reference [19]). It is necessary to install the solver online module. Figure 15 shows the data input panel, variables, and constraints in Solver.

6. Discussion

This research demonstrates the use of the optimization model and systematic approach for planning the labour and time required for the caisson breakwater construction project to obtain cost-effective logistics plans. As the spreadsheet has become a more widely used tool among managers, research shows the ability of optimization combined with Excel or Google Spreadsheet and Solver module to assist project managers in decision making and project logistics planning.

The important contribution of the article to the project and construction management literature is the development and capability of an easy-to-use optimization model for planning the labour and labour days required in floating caisson construction. The limitation of the model is the assumption of input data based on the experience of the construction company.

The model can serve the project manager and the person in charge of the floating dock to know, before the start of the execution of each caisson, not only the necessary manpower to be hired, both for the reinforcement and concreting works of the caisson, but also the effective work shifts required and the mandatory rest cycles. With all this data in hand, the project manager has control of the cost and the optimal execution time of the project. Scientific research does not seem to face the problem of how to size the working team necessary to execute this type of structure. For this reason, the paper makes a novel contribution in the field of how to size the working team necessary to execute concrete floating caissons for maritime work.

The proposed optimization model is currently being tested by Syconca, S.L. construction company in the execution of 10 caissons at the project "Extension of the Playa Blanca Port" in Lanzarote (Canary Islands, Spain), in collaboration with "FCC Construcción" construction company. The model is working correctly in the execution of the first 3 caissons.

7. Conclusion

The proposed methodology is able to provide an indication of the expected time and cost to complete an entire caisson breakwater construction project. This could serve as the basis for a management tool to help in the development of a construction plan for a caisson breakwater. By modifying the various parameters (rate of rebar/concrete workers, maximum number of concrete workers, total sliding to achieve, maximum number of shifts, minimum and maximum hours in each shift, cost per hour of rebar workers or concrete workers, etc.), the project managers can gain an insight into the expected time that it would take to build a certain breakwater and the cost and labour involved. The model can be used to provide data on the amount of time and money that could be saved. This can be an important tool to convince policymakers and engineers to improve the quality of construction procedures.

8. Declarations

8.1. Author Contributions

Conceptualization, P.P.D. and N.M.D.; methodology, P.P.D.; validation, F.J.G.G. and N.M.D.; investigation, P.P.D.; data curation, P.P.D. and N.M.D.; writing—original draft preparation, P.P.D. and N.M.D.; writing—review and editing, P.P.D., F.J.G.G. and N.M.D. All authors have read and agreed to the published version of the manuscript

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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8.5. Conflicts of Interest

The authors declare no conflict of interest.

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