

Challenges in the preventive maintenance of early 20th-century reinforced concrete architectural sculptures

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Abstract.

“Twentieth-century building materials and construction techniques may often differ from traditional materials and methods of the past. There is a need to research and develop specific repair methods appropriate to unique types of construction.”

Approaches for the Conservation of Twentieth-Century Architectural Heritage, Madrid Document 2011, ICOMOS

Natural deterioration caused by the ageing of the materials and their exposure to severe environmental conditions leads to a significant increase in the vulnerability of constructions. The conservation of reinforced concrete structures of the early 20th century brings challenges due to the specific characteristics of their construction processes. If at the structural level these processes are already somehow identified and linked to the systems of construction engineers such as Hennebique, Coignet, etc., at the level of decorative elements like ornaments, sculptures or others, their conservation deals with unknown techniques and requires greater care to maintain their authenticity and integrity.

Reinforced concrete, which is made of cement and steel, forms a material with a reduced lifespan when compared to natural and traditional construction materials such as stone or timber. Among other sources, the degradation of reinforced concrete is often caused by the corrosion of embedded steel, responsible for important losses of material which become particularly critical in sculptural elements.

When facing the need to make conservation interventions to preserve, rehabilitate, or restore degraded cultural heritage elements, several restrictions must be dealt with. Such restrictions are related to the safeguarding of the heritage’s cultural value and significance that must be weighed against safety and durability needs, as well as against the duration and budget constraints of the intervention. To assist the decision-making process about the type of interventions that can be carried out, an adequate balance of the several constraints must be sought. Therefore, in this paper, a two-step approach that can be integrated within the maintenance plan is proposed. The first step consists of a method to determine a case-by-case intervention index that gauges the referred criteria influencing the type of intervention. The referred index weighs the influence of several qualitative and quantitative criteria which are graded according to the characteristics of the cultural heritage element under analysis. The second step focuses on the development of maintenance indicators that can be used to assess the performance of the interventions that are carried out. This procedure was developed and implemented in the decision-making process related to the conservation of the decorative elements of a 20th-century building theatre in Portugal. A detailed analysis of the selected criteria for the intervention index and maintenance indicators is presented, as well as the advantages that might come from implementing the proposed procedure for the development of a sustainable conservation plan. A preliminary assessment of the maintenance indicators confirms that preventive measures decrease the number of repairs that are needed over time, meaning that the intervention index is correctly assessing the level of intervention required for a given decorative or sculptural element.

Keywords: Decision-making process, conservation, cultural heritage, management of interventions, intervention index, maintenance indicator

1 Introduction

The conservation of the built heritage in reinforced concrete from the beginning of the 20th century faces new challenges associated with the need for its consolidation, conservation, and repair. Natural deterioration, caused by the inevitable ageing of reinforced concrete and its exposure to atmospheric agents, has led to a considerable increase in the vulnerability of this type of structure. However, other degradation agents threaten these structures, such as inappropriate repair interventions, lack of maintenance or abandonment.

The concern with the conservation of reinforced concrete buildings from the beginning of the 20th century has been growing over recent years, particularly on how it would be carried out since its specificities are diverse from the ones regarding masonry and timber buildings. The main obstacles are related to the lack of specific know-how to intervene and

limited data regarding the compatibility of materials and assessment of the impact of interventions over long periods. These aspects are crucial when it comes to the rehabilitation of architectural sculptures executed in reinforced concrete (or cement) in which the *artist's hand* is a factor of authenticity.

Under the scope of the maintenance plan, a two-step approach is proposed in this paper. The first step focuses on supporting the decision-making process regarding what type of intervention on reinforced concrete architectural sculptures is appropriate. This was achieved through an intervention index, I_{TI} , which weighs the influence of several qualitative and quantitative criteria, classifying them according to the characteristics of the sculptural element under analysis.

The second step concerns the development of indicators that can support the assessment of the implementation of the maintenance plan. These indicators enable the classification of the importance of facades, which is crucial for the prioritization of actions, and for analysing the evolution of interventions according to their level of complexity/intensity.

The two-step procedure was applied to the architectural sculptures of the façades of the São João National Theatre, which is a national monument located in the city centre of Porto, built at the beginning of the 20th century. It should be noted that the I_{TI} was initially developed aiming at the 2013 interventions carried out on the façades of São João National Theatre, since the degradation was severe. It continued to be applied in the following inspections in support of the decision, which is briefly presented here, since the focus of the discussion is on the evaluation of the effectiveness of the implementation of the maintenance plan.

2 Concrete degradation and other factors to ponder in conservation interventions in architectural sculptures

Reinforced concrete, which is made of cement and steel, forms a material with a reduced lifespan when compared to natural and traditional construction materials such as stone or timber. Among other sources of decay, reinforced concrete deterioration is often caused by the corrosion of reinforcement steel [1]. Since the origin of this deterioration usually starts from within the concrete element, available repair approaches are seen as considerably intrusive. Therefore, this source of decay is especially difficult to address when dealing with the repair of reinforced concrete decorative elements or sculptures, where conservation operations could destroy their authenticity (Fig. 1).

Normally, the reinforcement steel is protected against corrosion by being embedded in the concrete and its high alkalinity. This protection, however, can be destroyed in two major ways [2]. The first is carbonation, which occurs when carbon dioxide in the air reacts chemically with the cement paste at the surface and reduces the alkalinity of the concrete. The second is through chloride ions from salts which combined with moisture produce an electrolyte that effectively corrodes the reinforcement bars. Chlorides may come from seawater additives in the original mix, or from prolonged contact with salt spray or de-icing salts. Regardless of the cause, corrosion of reinforcement bars increases their volume and causes expansive forces within the concrete [3] [4]. Cracking and spalling of the concrete are frequent results of this expansion phenomenon. Rust stains on the surface of the concrete are another indication that internal corrosion is taking place.



Fig. 1. Architectural sculptures in reinforced concrete with material degradation resulting from corrosion of the reinforcement.

To sum up, 20th-century constructions may present two types of problems associated with reinforced concrete degradation:

- Problems related to the structural stability of the building.
- Problems related to the conservation of architectural sculptures.

The problems related to the structural stability of constructions are the result of a reduction in the load-carrying capacity of reinforced concrete elements due to the loss of concrete, the loss of bond between steel and concrete, and due to the decrease in thickness of the reinforcing bars themselves.

The problems related to the conservation of decorative elements raise important questions associated with the safeguarding of the heritage cultural value and significance that have to be weighed against safety and durability needs. During the decision-making process about what intervention has to be carried out to preserve, rehabilitate, or restore degraded cultural heritage elements, an adequate balance of these constraints must be found. To assist in this decision-making process, the proposed methodology will enable the development of an intervention index that weighs the influence of several qualitative and quantitative criteria associated with the state of conservation and characteristics of the cultural heritage element under analysis.

2.1 The proposed intervention index I_{π}

The proposed index [5] was developed such as to establish a quantitative measure that would recommend either the *in situ* repair or the replacement of the element under analysis. This index weighs the influence of several qualitative and quantitative criteria which are graded according to the characteristics and the level of degradation of the element being analysed. This index was developed such as to account for several restrictions that may control the type of admissible intervention. Some of these restrictions are related to the safeguarding of the heritage's cultural value and significance that have to be weighed against restrictions related to safety and durability requirements, as well as duration and budget constraints.

The proposed intervention index is quantified for each decorative element and reflects the weighted combination of seven criteria (C1 to C7) according to:

$$I_{\pi} = \frac{\sum_{i=1}^7 C_i \times w_i}{\sum_{i=1}^7 w_i} \quad (1)$$

where C_i corresponds to the grade assigned to the i^{th} criterion and w_i is the weight factor of the i^{th} criterion. Some of the selected criteria are graded directly while others depend on the value of auxiliary parameters (P1 to P9). A description of the selected criteria, the information, and parameters considered for their quantification, and of their weight factors is presented in the following:

- C1 – Durability of the decorative element: the grading of this criterion combines information about the level of cracking of the element (P1), the existence and location of the reinforcement (P2), the level of corrosion of the reinforcement (P7), and the amount of repair required by the element (P8). The weight factor w_1 is considered to be 5.
- C2 – Meeting the deadline for the project completion: the grading of this criterion combines information about the size of the element (P3), the difficulty to make a cast of the element to replicate it (P4), the difficulty of fixing this replica to the façade (P5), and the amount of repair required by the element (P8). The weight factor w_2 is considered to be 5.
- C3 – Risk associated with the fall of the decorative element: the grading of this criterion depends on the life-threatening hazard due to the fall of a decorative element and on the possibility of observing the state of conservation of that element from the ground. The weight factor w_3 is considered to be 5.
- C4 – Authenticity of the decorative element: the grading of this criterion depends on the decorative element being authentic or not (i.e. the decorative element is a replica or it has been previously repaired). The weight factor w_4 is considered to be 4.
- C5 – Repetitiveness of the decorative element: the grading of this criterion depends on the number of times a given decorative element is repeated on the façades (P6). The weight factor w_5 is considered to be 3.
- C6 – Evolution of the state of degradation of the decorative element since 1995: the grading of this criterion reflects the evolution of the state of degradation of the element based on its condition in 1995 when the state of conservation of the façades was surveyed and conservation interventions were carried out in some parts of the building. The weight factor w_6 is considered to be 1.
- C7 – Replacement potential of the decorative element: this criterion depends on information about the level of cracking of the element (P1), the level of corrosion of the reinforcement (P7), and the amount of repair required by the element

(P8), and its grading combines data about the size of the element (P3), the difficulty of making a cast of the element to replicate it (P4), the difficulty of fixing this replica to the façade (P5), and the level of cracking of the element (P1). The weight factor w_7 is considered to be 5.

By combining the grading of the several criteria using Eq. (1), the intervention index I_{TI} is then obtained. The index ranges between 0 and 3 and if a value lower than 2 is obtained, the decorative element under analysis is recommended to be repaired and consolidated. Otherwise, the replacement of the element with a replica is suggested.

With respect to C2, it is noted that, when it comes to interventions in cultural heritage, it is not uncommon for there to be a lack of prior inspection and diagnosis actions. Even when such actions are taken, they may not always provide a conclusive assessment due to various observational challenges. Unfortunately, this can result in a planning of prices and work schedules that may not be in line with the requirements of the necessary conservation works. As a result, it might be necessary, in some cases, to adjust the conservation approach by either rescheduling certain tasks or prioritizing the most crucial elements that may be addressed within the allotted time for the works.

2.2 Maintenance Plan Indicators

After the major conservation intervention in 2013/2014, and since the continuous degradation of the reinforced concrete decorative elements was expected, a periodic maintenance plan was defined for the façades. This maintenance plan includes regular inspections followed by targeted conservation actions on the façades to repair damaged elements. Between 2014 and 2022, three inspections and two conservation actions were carried out, with the first and second inspections corresponding to a conservation action in 2019, and the third inspection in 2022 corresponding to a subsequent conservation action to optimize means and efforts. The parameters recorded in each action were the number of damages per façade detected in the inspection, the intensity level of the intervention need to address each observed damage, and the location of the damage. The importance level of each façade was defined based on the percentage of decorative elements and the percentage of unique decorative elements.

The maintenance plan is rooted in prevention rather than repair, therefore preventive actions should always be the majority of actions. In addition, to correctly implement the maintenance plan, it is necessary to balance the level of interventions with the importance of the façade. Hence, the proposed indicators aims to account for both issues.

The classification of the importance of the façade enables the prioritization of interventions, which is critical for implementing the maintenance plan. It is based on the distribution of decorative elements and sculptures across a façade and on which of these elements are unique, meaning elements that are not repeated throughout the façade may require a specific cast of single-use. The presence of decorative elements and sculptures on the façade, and the fact that they might be unique, increase the cultural value of each façade. The importance of each façade was determined using the relation between the total area of the façade and the area of decorative elements and sculptures, also weighing the uniqueness or the repetitiveness of the decorative elements and sculptures of the façade.

The following three types of interventions were defined based on purpose and complexity (increased level of action from Type I1 to Type I3): Type I1 – preventive action, which encompasses the repair of fine cracks with mortar or replacement of the protective and/or water-repellent layer (Fig. 2); Type I2 – remedial action, which encompasses repair of cracks or fractures with stabilization of metallic components (e.g., steel reinforcements) and/or restoration of the previous form (Fig. 3); and finally, Type I3 – remedial action, which encompasses repair of fractures or missing parts, with the removal of the metallic component and grout injection, stitching or restoration of the previous form (Fig. 4). Therefore, each intervention that is planned should be classified with one of these levels of intensity, whenever they take place. Consequently, it will be possible to have a track record of the interventions being performed and assess their effectiveness over time.



Fig. 2. Example of intervention type I1

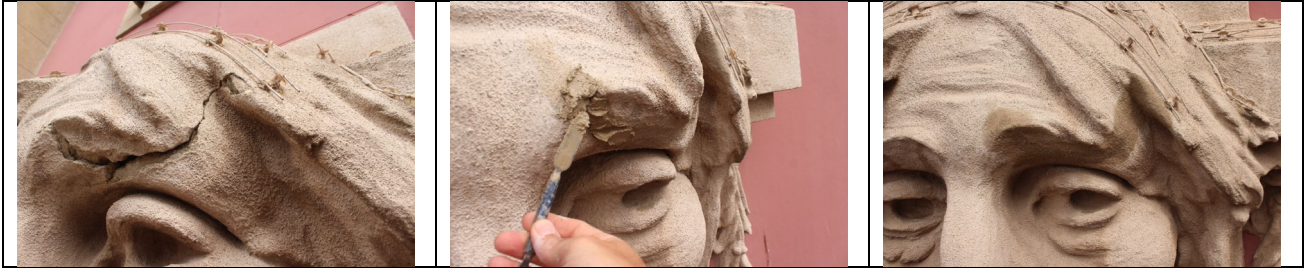


Fig. 3. Example of intervention type I2



Fig. 4. Example of intervention type I3

3 Case study: the São João National Theatre

The São João National Theatre is a National Monument located in the city of Porto, Portugal. The construction of the current theatre started in 1910 under the direction of architect Marques da Silva, the most important architect of Porto at the time, after the original building was destroyed by a fire in 1908. The style of L'Ecole des Beaux-Arts in Paris, where Marques da Silva studied, is found in the São João theatre's architecture.

The Beaux-Arts architecture expresses a neoclassical architectural style that involved sculptural decoration along conservative modern lines and employed French and Italian Baroque and Rococo formulas combined with an impressionistic finish and realism. An abundance of balustrades, statues, columns, garlands, pilasters between doors and windows, and grand staircases is typical of this architectural style. In the case of the São João National Theatre, these decorative elements exist in all the façades (with a total area of approximately 4800m²) and are made of reinforced concrete (Fig. 5 e Fig. 6). Some of the decorative elements having vegetal and geometrical patterns are seen to be repeated throughout the façades.



Fig. 5. Façade of the São João National Theatre



Fig. 6. Reinforced concrete architectural sculptures of the São João National Theatre

In 2006, the façades of the São João National Theatre began to exhibit severe signs of deterioration due to the long-term weathering of the concrete surfaces, the corrosion of steel reinforcement and the fall of pieces of mortar (the latter enforced the need to install façade nets to prevent such pieces to fall over the pedestrians). The development of a conservation project for the façades was therefore needed with some urgency. Considering the previously referred degradation issues related to steel corrosion and concrete spalling, the conservation and preservation of such a rich and dense array of decorative elements and sculptures presented numerous issues and several intervention options not easy to choose from.

Besides the severe cracking and spalling levels found in the concrete due to corrosion of the reinforcement, significant damages were also found to be related to bird-dropping deposits and the presence of black crusts. To illustrate the state of degradation of some of the reinforced concrete elements of the theatre façades, Fig. 7 presents some examples of damaged reinforced concrete decorative elements of the façades of the São João National Theatre.

To adequately plan and prepare these interventions that occurred in 2013/2014, a survey of the damages and degradation levels found on the façades and their decorative elements and sculptures was needed. A first assessment of their state of degradation was carried out before the cleaning operations of the façades took place, which resulted in an incomplete characterization of the elements' condition. A reliable assessment was only possible after the cleaning operations (Fig. 8). In addition to the damage survey, several concrete samples were taken from the façades for laboratory analysis and testing to determine the components and mix proportions of the original concrete, thus enabling the development of a repair mix with properties compatible with the original concrete.



Fig. 7. Examples of damaged reinforced concrete decorative elements of the façades of the São João National Theatre.

The cleaning operations also revealed that a conservation intervention had been previously carried out on the façades in the mid-20th century because some decorative elements exhibited additional layers of mortar over the original ones which altered their original volumetric proportions. In other cases, by visual observation and by comparing the several types of mortars, it was possible to conclude that some of the original decorative elements were replaced during that intervention. Given these aspects, the current intervention project foresees the possibility of making casts of original elements to replace similar ones previously intervened in the mid-20th century. These replaceable elements are those exhibiting a current state of degradation that implies a level of repair incompatible with the simultaneous upholding of their authenticity and of their safety against falling. Even though the fundamental purpose of the intervention is to replace as few elements as possible,

the main objective of the proposed index is thus to identify which elements exhibit the need for a more severe repair intervention along with a higher potential for replacement.

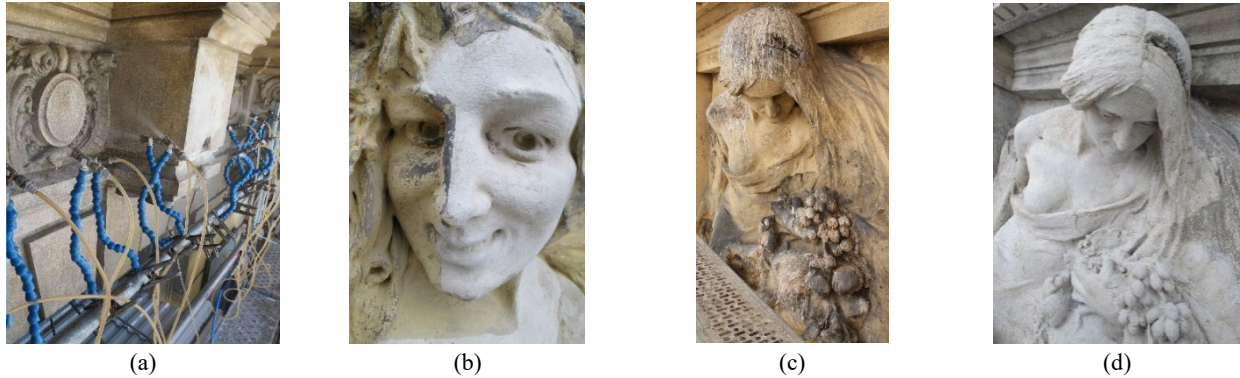


Fig. 8. Cleaning operations: (a) Cleaning operation to remove limewash, (b) cleaning operation by micro-abrasion, (c) example of a decorative element before cleaning; (b) after cleaning.

3.1 Application of the I_{π} to São João National Theatre

To apply the proposed methodology the identification of each element was not a simple operation due to the high level of interconnection between consecutive decorative forms (Fig. 9). In these cases, individual elements were selected based on symmetry and repetitiveness criteria.



Fig. 9. Example of the considerable interconnection of architectural sculptures.

Although the proposed index establishes a set of objective criteria to characterize a given element, the grading of some aspects sometimes involves a certain degree of subjectivity. Grading the difficulty of making a cast of the element to replicate it (P4) or defining with absolute certainty the authenticity of a decorative element (C4) are examples of factors that may involve some degree of subjectivity. The cleaning operations of the façades are also decisive in the results of the index. As previously mentioned, a reliable assessment of the state of degradation of the decorative elements is not possible before such operations expose the true state of the elements which is, many times, hidden below several layers of dirt, black crusts, or paint.

To illustrate some of the results obtained when applying the proposed methodology to the São João National Theatre, Fig. 10 presents the value of the obtained I_{π} for seven reinforced concrete decorative elements or sculptures from West facade. As can be seen, the replacement of elements 3, 6 and 7 is suggested by the results. For the case of element 6, and comparing with the result obtained for element 5 which is similar to element 6, the “replacement” result given the index is because this element exhibits a high level of degradation with severe steel corrosion and concrete spalling, and more than

75% of its volume requiring consolidation. On the other hand, element 5 presents no steel corrosion, no spalling, and less than 25% of its volume requires consolidation. Concerning element 7, the decisive characteristics for the “replacement” result are its level of steel corrosion and concrete cracking, the fact that it requires the consolidation of more than 50% of its volume and the fact that it is not an original element. In terms of element 3, aside from its high level of cracking and needed consolidation, the fact that it is a small element easy to replicate is also a decisive factor to obtain a “replacement” result.

1	2	3	4	5	6	7
						
1.21	1.71	2.48	1.47	1.77	2.52	2.34

Fig. 10. Sample results obtained by the proposed intervention index when grading different types of reinforced concrete decorative elements of the São João National Theatre.

3.2 Assessment of the maintenance plan indicators

Following the interventions carried out in 2014, the National Theatre São João was subjected to maintenance interventions in 2019 and 2022, so it was possible to implement the maintenance indicators in both years and analyse the evolution.

According to what was established in section 2.2, one of the first steps is to determine the importance of each façade. This was accomplished by quantifying the total area of decorative elements and sculptures and the total area of unique decorative elements and sculptures on each façade. As shown in Fig. 11, the North façade, where the main entrance of the theatre is located, is the one with the highest density of decorative elements and sculptures, as well as unique elements, which leads to the classification of high importance. On the opposite side, the South façade clearly has less importance in terms of architectural sculptures, and the East and West facades have equal importance probably due to their symmetry (Fig. 11).



Fig. 11. Determination of elements’ density per façade: (a) Density of the total amount of decorative elements and sculptures per façade; (b) Density of unique decorative elements and sculptures per total of elements and façade.

The next step concerns the analysis of the types of interventions carried out during the implementation of the maintenance plan and their evolution between 2019 and 2022. First, the interventions of 2019 and 2022 were classified using the levels presented in section 2.2., as shown in Fig. 12. Then, a verification was performed to determine if interventions carried out in 2022 occurred in the same location of the same element of 2019.

The total numbers of 170 and 193 interventions were carried out in 2019 and 2022, respectively. The increased number in 2022 is justified by the larger number of Type I1 interventions (preventive interventions) carried out (Fig. 13). Type I1 interventions carried out in 2022 had a higher weight on the total number of interventions when compared with the ones carried out in 2022. One considers that this might be due to the confirmed effectiveness of interventions carried out in

2019, which reduced the number of Type I2 and Type I3 interventions. This it is also related to the fact that each façade was scheduled for intervention in pre-allocated time intervals, and during those intervals, technicians would execute interventions from Type I3 to Type I1 and if additional time was left, they would carry out preventive Type I1 actions that were not detected during the inspection or did not qualify as mandatory. From 2019 to 2022, the weight of Type I2 and Type I3 interventions decreased, except for the Type I2 interventions on the East façade, while Type I1 actions increased in all façades.

It is necessary to clarify that the interventions were executed during a specific interval of time and not sporadically throughout the year, due to the cost associated with resource mobilization.

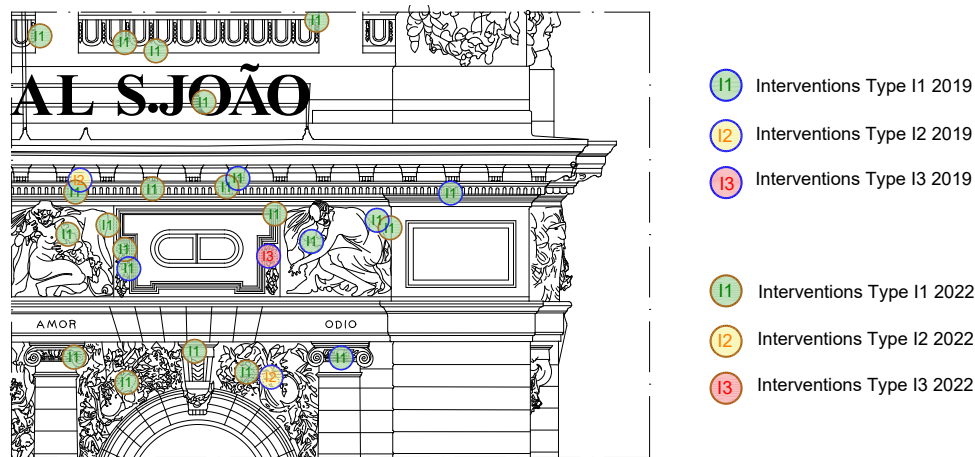


Fig. 12. Classification of type of intervention relative to one part of the North façade.

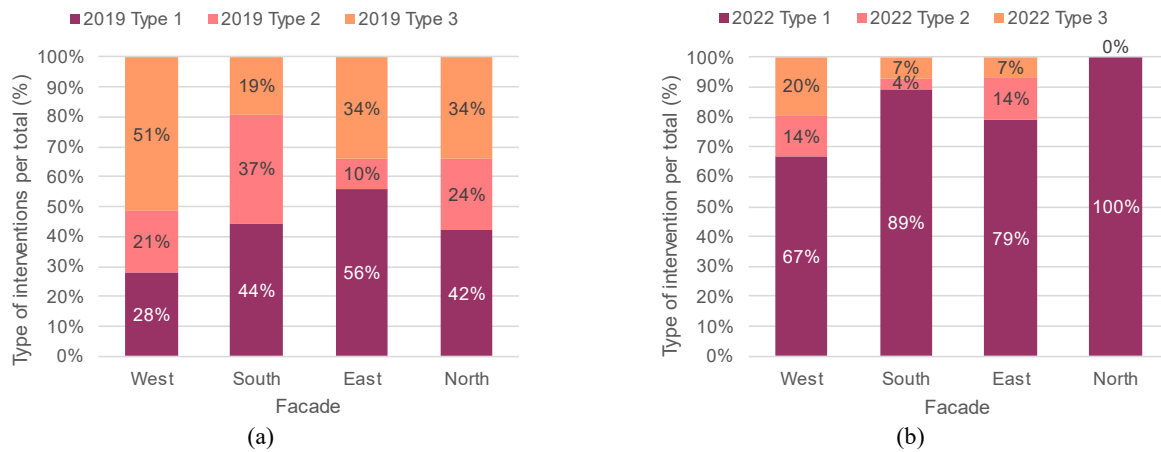


Fig. 13. Type of interventions on decorative elements and sculptures: (a) in 2019; (b) in 2022.

From Fig. 14, one can understand the evolution of the type of interventions in the same location of the same element, considering the interventions performed in 2019 and 2022. Interventions in coincident locations of the same element did not worsen since no cases are reporting an increase in severity (first two columns). In the West façade, there are two elements with the same type of intervention in 2019 and 2022 (I3-I3), which indicates that the previous intervention in 2019 did not result in an improvement in the situation.

Taking into consideration, the level of importance of each façade and the discussion performed regarding all interventions and interventions carried out on the same location of the same element, the North and West façades are the ones that require more attentive action and detailed analysis within the maintenance plan.

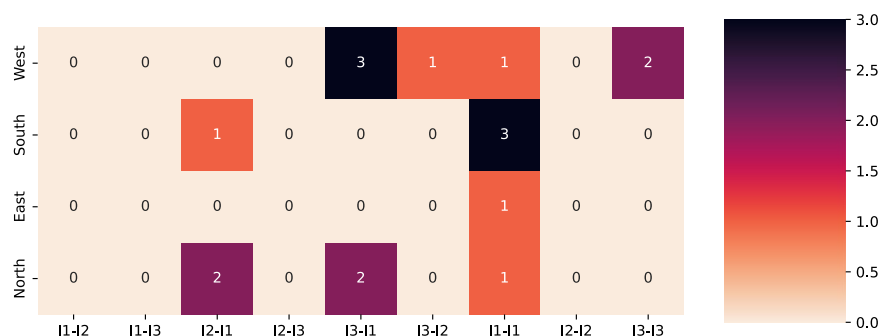


Fig. 14. Evolution of the type of interventions in the same location of the same element, from 2019 to 2022.

4 Conclusions

The conservation practice of reinforced concrete heritage from the late 19th and early 20th centuries has its specificities when compared to other historic constructions. The lack of professional experience and know-how in their repair is particularly important, namely when dealing with decorative elements in reinforced concrete. The fundamental purpose of an intervention is to maintain as many of the elements as possible, involving repair and consolidation operations that will safeguard as much as possible the elements' authenticity. Aside from the need to safeguard the cultural value and significance of the heritage, other important issues must also be weighed, namely those related to safety and durability, as well as to the intervention's duration and budget constraints.

Given the difficulty of balancing all the factors that influence the type of intervention to be carried out in each element under analysis, an intervention index was developed to help in this decision-making process. Although the proposed index involves a set of objective criteria to characterize a given element, the grading of some aspects is sometimes subjective. Furthermore, a reliable assessment of the state of degradation of the decorative elements is not possible before cleaning operations expose the true state of the elements which is, many times, hidden below several layers of dirt, black crusts, or paint.

A preliminary analysis of the maintenance indicators confirms the adequacy of the interventions carried out in 2019, with a clear decrease in Type I2 and Type I3 interventions in 2022. Particularly, when analysing interventions in the same location of the same element, one can verify that the intensity of the interventions did not escalate. The North and West facades are the ones that require more attentive action and detailed analysis within the maintenance plan.

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