HEURISTICS IN ENGINEERING EDUCATION. A CASE STUDY APPLICATION TO SUSTAINABLE BRIDGE MANAGEMENT SYSTEMS

I. Navarro Martínez[1], V. Yepes Piqueras[2], J.V. Martí Albiñana[2]

[1]Dept. of Construction Engineering, Universitat Politècnica de València (SPAIN)
[2]Institute of Concrete Science and Technology (ICITECH), Universitat Politècnica de València (SPAIN)

Abstract

This paper deals with the postgraduate course 'Predictive and optimisation models for concrete structures', offered at the Masters in Concrete Engineering of the Universitat Politècnica de València. Within this course, engineering students are introduced into different optimization algorithms, such as simulated annealing, neural networks, genetic algorithms, etc. of application in the automated design of concrete structures of any type. In recent times, such heuristic methods have turned out to be of great interest in the resolution of complex and actual engineering problems, such as the sustainable design and management of structures.

This communication presents a case study where the ongoing research of the teaching body is applied so as to find the most sustainable management strategy for a particular bridge system consisting of 7 bridges whose lengths vary between 380 m and 1980 m. The optimization problem here aims to minimize both the economic and environmental life cycle impacts derived from the maintenance of the concrete decks of a bridge network by selecting the adequate maintenance intervals for every deck considering annual budgetary restrictions. A multi-objective simulated annealing algorithm is applied to find the set of Pareto optimal solutions for the presented engineering problem. The environmentally preferable maintenance strategy results in life cycle costs 4.9% greater than those related to the cost-optimal strategy, which in turn results in environmental impacts 5.6% greater than those from the environmentally optimized management option. Results are then compared to the optimal strategies considering a single bridge deck, showing that the optimality at the bridge level does not necessarily lead to a sustainable optimum at the network level. From this it follows that, when optimizing maintenance under budgetary restrictions, the network shall be analysed as a whole, and not as an aggregation of optimal strategies for each individual bridge. The case study presented here shows in a nutshell the close connection between the course curricula of the MSc course and the ongoing research of the teaching and research group.

Keywords: Postgraduate education, applied research, heuristic algorithms, sustainable thinking, bridge management system.

1 INTRODUCTION

1.1 Postgraduate civil engineering studies

In recent times, higher engineering education has been in the spotlight of the European Union as a key factor for the future development of countries [1]. Traditionally, postgraduate engineering studies allowed students to deepen and widen the well-established knowledge taught at the undergraduate level. Recently, after the Bologna Declaration, postgraduate courses have changed their educational perspective, complementing the traditional approach with techniques and tools related to the latest research trends [2], to provide engineers with sufficient resources to address the new problems that are now emerging together with the progressive development of society [3]. The Concrete Engineering Master of the Universitat Politècnica de València, which started in 2007, may well be a good example of this new educational paradigm in the engineering field. The main objective of this paper is to present some of the topics taught in the course 'Predictive and optimization models for concrete structures' offered at the Master, which result to a great extent of the research work of the academics. This work shows how the contents of the course are applied in assessing a development gap recently detected in the usual practice in the field of bridge managing.

ISBN: 978-84-09-05948-5

1.2 Background on Bridge Management Systems

As countries reach higher levels of development, so do their networks of infrastructure and roads, with a consequent progressively less need for the construction of new structures. In such context, during the past recent years administrations of developed countries have started prioritizing the conservation of their infrastructure. As critical elements of the road networks, special attention has been paid to bridge structures. Under budgetary restrictions, the decision on the moment when the maintenance of a bridge shall be performed becomes of capital importance, due to the economic implications of such choice over time. As a response to this situation, and in order to guarantee the safety and adequate functionality of the existing bridge structures, Bridge Management Systems (BMS) emerged during the last decades of the 20th century, and have been implemented increasingly in different countries.

BMSs are tools that support the decision-making process associated to the conservation of road networks by providing helpful information to the authority responsible for making the decision. Given that these tools are developed by each country independently, all of the currently existing BMSs show particularities and different levels of development. However, they all are based on the same principles and share therefore similar aspects that allow us to classify them according to their scope and development level in four types of systems, as shown in Fig. 1.

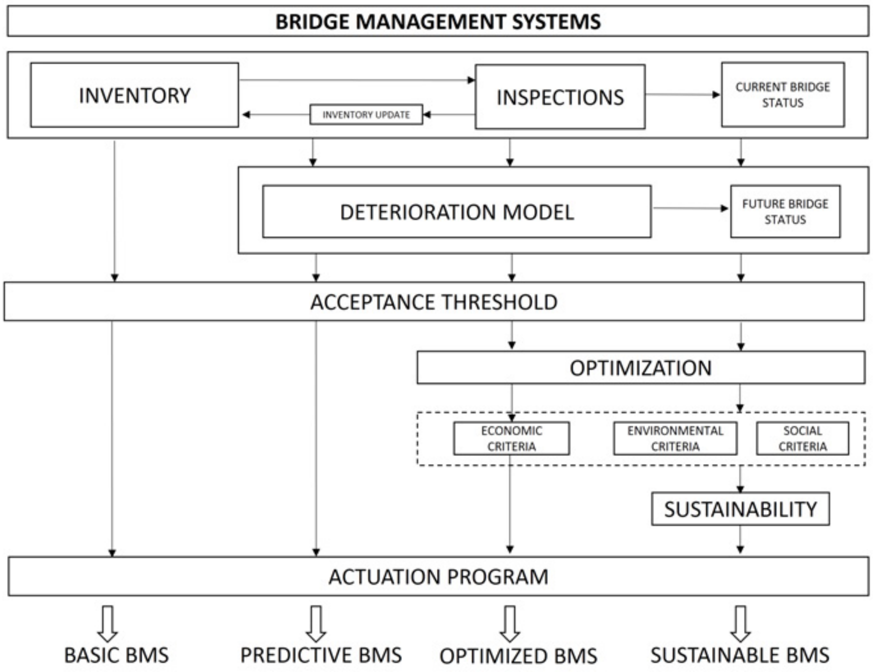

Figure 1.Development levels of existing Bridge Management Systems.

The most basic BMS consists of an inventory containing information on the current conservation status of all structures in the network under analysis. The different routine or main inspection tasks carried out over time enable the inventory information to be constantly updated, allowing the managing technician to know the history of each bridge, the pathologies detected and the conservation operations carried out in the past. As a result, basic BMSs assist decision-making by providing the decisors with a large, up-to-date database. However, it is left to the judgement and experience of the technician to identify the priority structures of the network and to decide when to undertake the maintenance operations. These systems are usually based on reactive maintenance strategies: acceptance thresholds are defined, so that maintenance is carried out if the structure status resulting after a particular inspection exceeds the mentioned threshold. The Netherlands, Ireland or Spain base the management of their bridges in such basic BMSs.

More developed BMSs are the so-called predictive systems. Such tools complement the inventory data of the basic management systems by incorporating models to predict the deterioration of the structures. The deterioration models used in predictive systems may be either deterministic, such as the Norwegian management system called BRUTUS, or probabilistic, such as the American AASHTOW are, which uses stochastic Markov chains to model deterioration. Regardless of the formulation of the model, all of them are usually calibrated based on the information gathered through the inspection activities held on the structures under analysis. Predictive BMSs let the technician know with a reasonable degree of certainty when the acceptance threshold of each network structure is expected to be reached, thus allowing for a more appropriate maintenance planning. Examples of predictive BMSs can be found in Australia, Denmark or Poland. However, in such systems it is still left to the technician's discretion to decide when to carry out maintenance and what strategy to adopt. Studies have shown the advantages of preventive versus reactive maintenance strategies for bridges in economic terms [4, 5] from a life cycle perspective. As a consequence, more refined BMSs are developed so as to find those maintenance intervals that lead to the minimum bridge life cycle costs and adapt therefore better to the usual budgetary restrictive contexts in which such decisions are made.

The most developed BMSs currently existing are the so-called intelligent or optimized systems. Countries such as USA, Japan, Canada or Switzerland have implemented such systems for the management of their road networks and bridges. These systems rely on the results provided by the deterioration models to provide decision-makers with information on when maintenance is most appropriate to be held to minimise the economic impacts of maintenance over a given period of analysis. In order to optimize the allocation of financial resources, complex optimization techniques are implemented in these management systems, such as Genetic Algorithms or Artificial Neural Networks.

Currently existing intelligent management systems only take into account the economic point of view when optimizing the maintenance activities on a bridge network. However, three are the pillars on which sustainability is based, namely economy, environment and society. Sustainable development was first defined in 1987 by the World Commission on Environment and Development as a way of guaranteeing the actual wellbeing without compromising the ability of future generations to satisfy their own needs. In recent years, efforts have been made to incorporate this concept into the manufacture and design of several types of products, from fertilizers [6] to supply chains [7] or automotive components [8]. Under the perspective of sustainability, bridges acquire relevant importance, as they are particular types of products designed to reach service lives of over 100 years. With so long service lives, it is of paramount importance to avoid an unsustainable management of such structures, as the repercussions of their maintenance during their serviceability phase will affect several generations and may be greater than the impacts derived directly from the construction of the structures [9].

For the reasons exposed, the new challenge in the development in BMSs is to incorporate sustainability criteria in the maintenance optimization process, shifting from economically optimized BMSs into sustainable BMSs. Sustainable systems shall allow the decision maker to know which is the most appropriate action interval to minimize not only the economic, but also the environmental and the social impacts throughout the life cycle of each bridge of the road network under study, thus finding the most sustainable solution. So far, such level of development has not yet been implemented in any of the countries using BMSs.

In the postgraduate course ‘Predictive and optimization models for concrete structures’, students are introduced in different optimization techniques and multi-criteria decision methodologies of application in the improvement of current bridge management systems, providing essential results for a proper decision assessment in the context of sustainability. The present paper shows, by means of a case study, how sustainability criteria shall be considered in the optimization process of the sustainable maintenance of a bridge both at the bridge and at the network level.

2 SUSTAINABLE BRIDGE MANAGEMENT SYSTEMS

2.1 Overall description of the course

The course aims to provide participants with enough knowledge and tools to apply optimization techniques and predictive modelling in the design of concrete structures. The first part of the lectures offers the participants an introduction to decision assessment techniques and to the optimization methods applied to structural design. The student is thus introduced to how to approach real problems in the field of concrete structures through different types of models, establishing the basics on which the rest of the course is based.

The second part of the course focuses on the in-depth analysis and discussion of the most commonly used heuristic optimization algorithms. This course deals with algorithms such as simulated annealing, threshold acceptance, genetic algorithms and others, in which the lecturers show a wide experience based on the research lines conducted in recent years [10-13]. The structures under study include prestressed bridge decks, retaining walls, culvert shaped road underpasses and bridge substructure elements, such as abutments and piers. Although the cost of the structure is usually the main objective function in optimization problems, multiobjective optimization techniques are explained in the course, including criteria such as environmental impacts, safety or constructability.

The third set of topics covered by this course develops predictive models commonly used for concrete structures, including everything from linear multiple regression models to the more complex artificial neuronal networks or fuzzy logic based approaches. The design of experiments as basic statistical techniques in the prediction of main effects is also addressed.

The last part of the course deals with multi-criteria decision assessment techniques, focusing on their application to concrete structures under a life cycle perspective. The students are explained how it is necessary to select the best structural typology based on criteria that are not always objective or easily quantifiable: economy, durability of the solution, aesthetics, environment, social aspects. The different techniques of multi-criteria decision making are introduced and discussed, including their use for obtaining objective weights of criteria that may even be subjective, or for the selection of the best option within a Pareto front after a multi-objective optimization.

2.2 Application to sustainable maintenance of bridge networks

The optimization of a bridge network is a complex problem, as it deals with a considerable amount of variables that shall be combined in a way that the resulting maintenance plan satisfies particular restrictions. The optimization problem here aims to minimize the sustainability objective functions E_i in Eq. (1) to a minimum while satisfying the specific restrictions represented in Eq. (2).

$$E_i = f_i(x_1, x_2, \dots\ x_n) \tag{1}$$

$$g_i(x_1, x_2, \dots\ x_n) \leq 0 \tag{2}$$

The objective functions E_i are the life cycle impacts of the structures under study in economic, environmental and social terms. The design variables x_k are the maintenance intervals to be selected for each bridge in the network to minimize the sustainability function. Multi-objective problems have no solution that simultaneously minimizes every objective, as they are usually in conflict. The problem is solved by finding the Pareto Front, namely the set of solutions for which there is no other feasible solution in the design space that improves any of the objectives without worsening the solution performance in at least one of the others.

2.2.1 Multi-objective simulated annealing procedure

The optimization algorithm chosen for this problem is a multi-objective heuristic called SMOSA, which is based on the single objective simulated annealing (SA). SMOSA algorithm was first defined by [14], and has been used since then by several authors in different multi-objective optimization problems [15, 16] with success. SMOSA algorithm works as follows. An initial set of feasible solutions is generated randomly. Then, an initial temperature is chosen for each of the objective functions following the method for SA presented in [17]. Once the initial temperatures are selected, a small modification in any of the solutions of the initial set is performed to obtain a new feasible solution in the neighbourhood of the initial one. This solution is then checked against the Pareto condition, which is met if the solution is not dominated by any of the ones contained in the initial set. A solution is said to be dominated by an element of the Pareto set when both objective results are greater than those of the Pareto element are. Therefore, if the solution is not dominated, it shall substitute the initial solution of it improves every objective, or added to the Pareto set otherwise. If dominated, the new solution shall be accepted as a starting point for the random modification to obtain the next solution with a probability given by Eq. (3):

$$\prod_{i=1}^{n} e^{-\frac{\Delta f_i}{T_i}} \tag{3}$$

where T_i is the value of the temperature for the objective function i, and Δf_i is the increment in the objective function i between the solutions under comparison. The process is repeated a number of iterations, called Markov chain, decreasing the temperature in each chain by a cooling coefficient α. The algorithm stops when the temperature is small enough or when the Pareto set has not been improved in a number of successive Markov chains.

2.2.2 *Reliability based maintenance*

The range of each variable x_k of the problem is limited by the expected service life of each of the bridges considered. This service life results from finding when a particular target reliability index β_{lim} is reached. β_{lim} is directly related to the risk that the decisor is willing to take so as to guarantee a proper condition of the bridge during its entire service life. Given a particular deterioration model, and once a failure criterion is established for the deterioration mechanism identified, the reliability of a structure β(t) at a specific time t is associated to the probability of failure p_f. Therefore, the available maintenance intervals for a particular bridge are to be found within the years where Eq. (4) is satisfied:

$$\beta(t) = -\phi^{-1}\left[p_f\,(t)\right] \leq \beta_{lim} \tag{4}$$

where Φ-1 is the inverse of the Gaussian cumulated distribution function of the probability of failure at time t. The probability of failure $p_f(t)$ is obtained by means of Monte Carlo simulations.

2.2.3 *Impact assessment*

The proposed sustainable optimisation of bridge networks relies on the evaluation of the life cycle impacts resulting from the different maintenance activities held during the maintenance phase of each structure. The impact assessment follows the four main steps suggested in the methodology proposed in ISO 14040 [18] standard for Life Cycle Assessments (LCA), namely the definition of goal and scope, the inventory description, the impact analysis and the interpretation of the results. For the sake of exposure simplicity, only the economic and environmental life cycle impacts are included in the present paper. In particular, environmental impact analysis is based on the Eco-Indicator 99 impact method, which allows for the aggregation of three different types of impact categories, namely damage to human health, deterioration of ecosystem quality and depletion of natural resources, in one single indicator. Such method has been widely used in the existing literature [19, 20]. On the other hand, the economic assessment is based on the well-known concept of the discount rate, which takes into consideration the influence that the time when future economic investments are done has on the decision now.

3 CASE STUDY

3.1 Problem definition

The presented methodology is applied for the sustainable optimization of deck maintenance at the bridge and network level of a particular case study. A simplified bridge network consisting of seven prestressed concrete bridges is considered here, with a bridge length variable between 380 m and 1980 m, and cross sections ranging between 5.9 m^2 and 7.78 m^2. Table 1 shows the concrete mixes assumed for each bridge deck.

Table 1. Geometrical parameters and Concrete mix proportions of the network bridge decks.

Bridge Deck Id.	Length (m)	Cross Section (m^2)	Cement (kg/m^3)	Water (l/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)	Fly Ash (kg/m^3)	Silica Fume (kg/m^3)	Plasticiser (kg/m^3)
B1	1400	7.78	400	172	927	828	0	0	0
B2	721	7.57	400	146	1010	1015	0	0	8
B3	1980	6.07	437	219	927	849	0	24	0
B4	820	7.78	358	172	980	941	80	0	0
B5	950	6.07	486	219	927	828	0	0	0
B6	380	5.9	500	175	977	883	0	0	10
B7	740	7.78	318	172	1018	980	0	32	0

3.1.1 Deterioration model

The present bridge network is assumed to be at the coastal region of Galicia (Spain). In such environments, where bridges are directly exposed to seawater, experience demonstrates that the most critical threat to concrete structures is the chloride-induced corrosion of the steel reinforcement. Corrosion of the steel bars occurs when the concentration of chloride ions at steel reaches a sufficiently high concentration, called the critical chloride threshold (C_{cr}), to trigger the deterioration process. The model proposed in Fib Bulletin 34 [21] is considered to predict the time needed by chloride ions to penetrate the concrete cover depending on the particular properties of the concrete. The model has been slightly modified to take into account that the most exposed bars are the ones located at the section edges, which are simultaneously exposed to two advancing chloride fronts. The resulting chloride concentration shall then be predicted at a particular time t and at a particular depth in both the x and y directions as:

$$C(x,y,t) = C_s \cdot \left(1 - erf\,\frac{x}{2\sqrt{D_{0,x}\cdot\left(\frac{t_0}{t}\right)^{\alpha}\cdot t}} \cdot erf\,\frac{y}{2\sqrt{D_{0,y}\cdot\left(\frac{t_0}{t}\right)^{\alpha}\cdot t}}\right) \quad (5)$$

where C(x,y,t) is the chloride concentration (wt.%/binder) at a particular position in the concrete depth [x, y] (mm) and time t (years); erf(.) is the error function; C_s is the chloride concentration at the surface of the concrete deck (wt.%/binder); D_0 is the chloride diffusion coefficient (mm^2/years), which is assumed to be the same in both x and y directions, given that the concrete cover is considered homogeneous. The age factor α has been assumed to be 0.5, as proposed in the Spanish concrete design code [22]. Table 2 shows the different durability parameters assumed for each bridge, depending on the particular concrete mix adopted for each structure, as well as the resulting expected service lives resulting from the application of the described prediction model. For each parameter, the mean and the standard deviation values assumed in the probabilistic analysis are provided. The service life has been predicted assuming a target reliability of $\beta_{lim} = 1.3$ [20].

Table 2. Durability parameters and service life of the network bridges.

Bridge Id.	C_s (wt.%/binder)		D_0 (x10^{-12} m^2/s)		C_{cr} (%)		r (mm)		Expected Service Life (years)	Ref
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.		
B1	3.1	0.3	9.56	1	0.6	0.15	50	2.5	11	[22]
B2	2.47	0.15	5.19	0.39	0.6	0.1	35	1.75	21	[23]
B3	2.86	0.24	3.31	0.25	0.38	0.06	30	1.5	15	[24]
B4	3.24	0.35	5	0.39	0.6	0.1	35	1.75	16	[25]
B5	2.6	0.18	10	1.1	0.6	0.1	45	2.25	11	[22]
B6	2.23	0.11	4.32	0.33	0.6	0.1	30	1.5	23	[23]
B7	3.4	0.4	1.88	0.19	0.28	0.04	35	1.75	39	[26]

3.1.2 System boundaries and inventory analysis

Based on the described deterioration mechanism, the maintenance of the bridge decks under analysis is assumed to consist in replacing the concrete cover up to the depth where the critical chloride content is reached. Therefore, depending on the advance of the chloride front at the time of maintenance, the amount of concrete to be replaced will vary and consequently so will the impacts derived from the operation. The repair concrete is assumed to have the same properties than the base concrete mix. The activities considered for the evaluation of both economic and environmental impacts comprise those related to the production of materials, their transport from the respective production facilities to the location of the structures and the maintenance activities themselves, considering that the damaged concrete cover is removed by means of hydrodemolition. Environmental data for the production of the different concrete types considered here were collected from the Ecoinvent database 3.2. Data on energy demand for the different production and construction activities where obtained from the existing literature and machinery manufacturers Table 3 shows the assumed values for the different concepts considered in the evaluation of environmental impacts.

Table 3. Life cycle inventory data for LCA.

Process	Value	Source
Concrete mixing – Performance	0.12 h/m^3	[27]
Hydrodemolition – Required power	750 W	Acc. to manufacturer's specifications
Hydrodemolition – Performance	0.6 m^3/h	Acc. to manufacturer's specifications
Sandblasting – Fuel consumption	0.038 l/min	[28]
Sandblasting – Performance	0.22 m^2/min	[28]
Shotcreting – Required power	26500 W	Acc. to manufacturer's specifications
Shotcreting – Performance	0.3 m^3/min	Acc. to manufacturer's specifications

The cost data was gathered from the construction cost database developed by CYPE and is shown in Table 4. A discount rate of 5% has been considered in the performed Life Cycle Cost Analysis (LCCA).

Table 4. Unit costs considered in LCCA.

Portland cement	87.77 €/t
Calcareous sand	13.98 €/t
Calcareous gravel	16.36 €/t
Water	0.91 €/m^3
Plasticiser	1.38 €/kg
Fly Ash	38 €/t
Silica Fume	1.14 €/kg
Truck mixer	30.51 €/h
Hydrodemolished concrete cover	923 €/m^3
Sandblasting	4.29 €/m^2
Reinforcement priming	11.73 €/m^2

3.2 Results at Network Level

Based on the multi-objective optimisation technique presented in Section 2, the Pareto front that optimizes both the economic and environmental life cycle results of the described bridge network is obtained. The calibration of the SMOSA parameters gave following results: an initial temperature for both criteria is adjusted following the method proposed by Medina [17], the length of the Markov chain is 2500, the cooling coefficient is 0.95 and as a stop criterion, it is considered three chains without improvements in the Pareto set. The annual budget spent on the maintenance of the network is restricted to $4x10^6$ €. The period of analysis is 100 years. The analysis results in a Pareto set consisting of 10 optimal maintenance strategies (P_i).Table 5 shows the economic and environmental life cycle impacts of the optimal solutions, as well as the maintenance intervals bridge (t_{Bi}) that lead to these results.

Table 5. Representative solutions of the Pareto Set.

Solution Id.	LCA results (EI99)	LCCA results (€)	t_{B1} (years)	t_{B2} (years)	t_{B3} (years)	t_{B4} (years)	t_{B5} (years)	t_{B6} (years)	t_{B7} (years)
P1	1.07E+06	6.91E+06	6	21	8	9	5	22	19
P2	1.08E+06	6.89E+06	8	14	7	5	6	23	19
P3	1.08E+06	6.74E+06	7	21	9	10	6	23	19
P4	1.08E+06	6.69E+06	8	21	10	10	6	23	19
P5	1.09E+06	6.68E+06	8	19	12	12	5	13	19
P6	1.09E+06	6.65E+06	8	21	11	11	7	22	19
P7	1.11E+06	6.63E+06	9	21	11	11	7	23	19
P8	1.11E+06	6.61E+06	10	21	12	13	7	21	19
P9	1.12E+06	6.60E+06	10	21	12	12	7	21	19
P10	1.13E+06	6.59E+06	10	21	12	11	9	23	19

The solutions conforming the Pareto front present very similar results, both in the economic and in the environmental analysis, with a dispersion of about 5%. It is interesting, however, that the solutions are conformed by very different intervention intervals. It can be observed that the network-optimized maintenance intervals do not coincide with the expected service life of any bridge, which would mean a reactive maintenance. Network optimization is thus based on prevention. Within the Pareto set, the cost-optimal solution is P10, and the environmentally preferable strategy is P1.

3.3 Results at Bridge Level

Here, special attention is paid to one of the bridges contained in the network, namely bridge B1. This is a 41+9x70+50 m prestressed concrete box girder deck whose great total length and significant concrete cover makes him be one of the most critical elements for the maintenance of the network. As observed in the presented results at network level, the optimal strategies imply maintenance intervals of B1 deck that range between 6 and 10 years. At the bridge level, a direct reliability-based maintenance optimization of the solution set is performed, as the expected service life of this deck is expected to be 11 years according to the results of the selected deterioration model and the maintenance interval options are thus reduced. The results of the analysis are presented in Table 6, where both the economic and the environmental life cycle impacts derived from an LCA, LCCA and a reactive maintenance strategy are presented.

Table 6. Strategic maintenance results for bridge deck B1.

	Maintenance interval t_{B1} (years)	LCA results (EI99)	LCCA results (€)
LCA-optimized	6	4.41 E+05	2.94 E+06
LCCA-optimized	10	4.58 E+05	2.64 E+06
Reactive maintenance	11	4.82 E+05	2.72 E+06

It can be observed that the optimal maintenance interval for the considered bridge deck depends on the objective to be minimized, ranging from a 55% to a 90% of the expected service life. When environmentally optimized, the LCA results are reduced up to an 8.5% when compared to the reactive maintenance. From the point of view of life cycle costs, optimization leads to a reduction of 2.9%. In this case, the Pareto front is composed by these two solutions.

When compared with the results of the network optimization, it is observed that both the cost and the environmental optimized solution of the Pareto set imply the bridge deck B1 being maintained at its individual optimal intervals. This is due to the importance of this deck, which implies a major proportion of the network impacts due to its characteristics. However, it can be seen that this is only true for a particular combination of maintenance intervals for the rest of the bridges, and that there are other Pareto-optimal solutions for which the deck B1 is maintained at intervals different from its optima.

4 CONCLUSIONS

This paper has presented the main elements of a postgraduate course which forms part of the curricula of the Master in Concrete Engineering at the Universitat Politècnica de València, and which is focused on the use of metaheuristics applied to the automatization of design of concrete structures and to the resolution of complex engineering problems. The present communication shows how the concepts taught in the course should be applied to the resolution of newly emerging challenges in the field of sustainability, such as the sustainable maintenance optimization of concrete bridge networks under budgetary restrictions. In particular, this work contains the optimization of a network in a coastal environment using a multi-objective simulated annealing technique. The results are compared to the ones derived from a maintenance-based optimization of a single bridge deck. Results have shown that the optimality at the bridge level does not necessarily lead to an optimum at the network level. From this, it follows that, when optimizing maintenance under budgetary restrictions, the network shall be analysed as a whole, and not as an aggregation of optimal strategies for each individual bridge.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the Spanish Ministry of Economy and Competitiveness, along with FEDER funding (Project: BIA2017-85098-R).

REFERENCES

[1] E. Pellicer; L. A. Sierra; V. Yepes. ‘Appraisal of infrastructure sustainability by graduate students using an active-learning method’, in *Journal of Cleaner Production*, vol. 113, pp. 884-896, 2016.

[2] V. Yepes; E. Pellicer; J.A. Ortega. ‘Designing a benchmark indicator for managerial competences in construction at the graduate level’, in *Journal of Professional Issues in Engineering Education and Practice*, vol. 138, pp. 48-54. ISSN: 1052-3928, 2012.

[3] C. Torres-Machí; A. Carrión; V. Yepes; E. Pellicer. ‘Employability of graduate students in construction management’, in *Journal of Professional Issues in Engineering Education and Practice*, vol. 139, pp. 163-170, 2013.

[4] N.M.Okasha; D.M. Frangopol. ’Novel approach for multicriteria optimization of life cycle preventive and essential maintenance of deteriorating structures’, in *Journal of Structural Engineering*, vol.136, pp. 1009 – 1022, 2010.

[5] J.O. Almeida; P. Teixeira; R.M. Delgado. ‘Life cycle optimisation in highway concrete bridges management’, in *Structure and Infrastructure Engineering*, vol. 11, no. 10, 2015.

[6] J. Martínez-Blanco; A. Lehmann; P. Muñoz; A. Antón; M. Traverso; J. Rieradevall; M. Finkbeiner. ‘Application challenges for the social LCA of fertilizers within life cycle sustainability assessment’, in *Journal of Cleaner Production*, vol. 69, p.p. 34-48, 2014.

[7] Y. Tsao; T. Vo-Van; J. Lu. ‘Designing sustainable supply chain networks under uncertain environments: Fuzzy multi-objective programming’, in *Journal of Cleaner Production*, vol. 174, p.p. 1550-1565, 2018.

[8] X. Sun; J. Liu; B. Lu. ‘Life cycle assessment-based selection of a sustainable lightweight automotive engine hood design’, in *International Journal of Life Cycle Assessment*, vol. 22, p.p. 1373-1383, 2017.

[9] I.J. Navarro; V. Yepes; J.V. Martí. ‘Life Cycle Cost Assessment of preventive strategies applied to prestressed concrete bridges exposed to chlorides’, in *Sustainability*, vol. 10, no. 3, p.p. 845, 2018.

[10] V. Yepes; J.V. Martí; T. García-Segura; F. González-Vidosa. ‘Heuristics in optimal detailed design of precast road bridges’, in *Archives of Civil and Mechanical Engineering*, vol. 17, no. 4, p.p. 738-749, 2017.

[11] T. García-Segura; V. Yepes. ‘Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety’ in *Engineering Structures*, vol. 125, pp. 325-336, 2016.

[12] J.V. Martí; T. García-Segura; V. Yepes. ‘Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy’, in *Journal of Cleaner Production*, vol. 120, p.p. 231-240, 2016.

[13] T. García-Segura; V. Yepes; J. Alcalá; E. Pérez-López. ‘Hybrid harmony search for sustainable design of post-tensioned concrete box-girder pedestrian bridges’, in *Engineering Structures*, vol. 92, p.p. 112-122, 2015.

[14] A. Suppapitnarm; K.A. Seffen; G. Parks; P.J. Clarkson. ‘A simulated annealing algorithm for multiobjective optimization’, in *Engineering Optimization*, vol. 33, p.p. 59–85, 2000.

[15] I. Paya; V. Yepes; F. González-Vidosa; A. Hospitaler. ‘Multiobjective optimization of concrete frames by simulated annealing’, in *Computer-aided Civil and Infrastructure Engineering*, vol. 23, p.p. 596-610, 2008.

[16] B. Suman; P. Kumar. ‘A survey of simulated annealing as a tool for single and multiobjective optimization’, in *Journal of the Operational Research Society*, vol. 57, no. 10, p.p. 1143–1160, 2006.

[17] J.R. Medina. ‘Estimation of incident and reflected waves using simulated annealing’ in *ASCE Journal of Waterway, Port, Coastal and Ocean Engineering*, vol. 127, no. 4, p.p. 213– 21, 2001.

[18] International Standards Organization. ‘Environmental Management:—Life Cycle Assessment—Principles and Framework’, International Standards Organization, Geneva ISO 14040: 2006, 2006.

[19] Y. Ribakov; I. Halperin; S. Pushkar. ‘Using Eco-indicator 99 and a two-stage nested analysis of variance test to evaluate building mitigation measures under hazard risks’, in *Advances in Structural Engineering*, vol. 19, p.p. 860 – 870, 2016.

[20] I.J. Navarro; V. Yepes; J.V. Martí; F. González-Vidosa. ‘Life cycle impact assessment of corrosion preventive designs applied to prestressed concrete bridge decks’, in *Journal of Cleaner Production*, vol. 196, p.p. 698-713, 2018.

[21] Fib. ‘Fib Bulletin 34,. Model Code for Service Life Design’, Fib, Lausanne, 2006.

[22] Ministerio de Fomento. ‘Instrucción de Hormigón Estructural EHE’, Madrid, 2008.

[23] T. Cheewaket; C. Jaturapitakkul; W. Chalee. ‘Concrete durability presented by acceptable chloride level and chloride diffusion coefficient in concrete: 10-year results in marine site’, in *Materials and Structures*, vol. 47, p.p. 1501–11, 2014.

[24] J.M. Frederiksen. ‘Chloride threshold values for service life design’, in *Second International RILEM Workshop on Testing and Modelling the Chloride Ingress into Concrete*, Paris, France, RILEM Publications, 11-12 September 2000.

[25] N. Otsuki; T. Nishida; C. Yi; T. Nagata. ‘Effect of blast furnace slag powder and fly ash on durability of concrete mixed with seawater’, in *4th International Conference on the durability of concrete structures*, Purdue University, West Lafayette, USA, 24-26 July 2014.

[26] M. Manera; Ø. Vennesland; L. Bertolini. ‘Chloride threshold for rebar corrosion in concrete with addition of silica fume’, in *Corrosion Science*, vol. 50, p.p. 554-560, 2008.

[27] P. Zastrow; F. Molina-Moreno; T. García-Segura; J.V. Martí; V. Yepes. ‘Life cycle assessment of cost-optimized buttress earth-retaining walls: a parametric study’, in *Journal of Cleaner* Production, vol. 140, p.p. 1037-1048, 2017.

[28] L.R. Millman; J.W. Giancaspro. ‘Environmental evaluation of abrasive blasting with sand, water, and dry ice’, in *International Journal of Architecture, Engineering and Construction*, vol. 1, no. 3, p.p. 174-182, 2012.