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REVIEW

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Sustainability of steel structures: towards an integrated approach to life-time engineering design

Abstract Nowadays, the construction sector is more and more oriented toward the promotion of sustainability in all its activities. The goal to achieve is the optimization of performances, over the whole life-cycle, with respect to environmental, economic and social requirements. According to the latest advances, the concept of sustainability applied to constructions covers a number of branches such as life-cycle costing, ecology, durability and even structural design. Several procedures and design tools have been implemented in the framework of international research. Indeed the current trend in civil engineering research is moving towards life-time engineering, with the aim to implement integrated methodologies to consider as a whole all the sustainability requirements according to time-dependent multi-performance-based design approaches. Following a general introduction of the concept of sustainability applied to constructions, this paper presents an overview of life-time engineering methodologies according to the current state-of-the-art. In particular the methods currently received by International Standards are discussed. A special focus is devoted to the durability design of metal structures with respect to the degradation phenomena able to impair the structural capacity over time. Finally a proposal towards an integrated approach to life-time engineering design of steel structures and needs for further advances are presented.

Keywords sustainability, life-time engineering, performance based design, durability, metal structures

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1 Introduction

The concept of "Sustainable Development" was defined in 1987, by the World Commission on Environment and Development, as the "development that meets the needs of the present, without compromising the ability of future generations to meet their own needs" [1]. Starting from the principles of environmental protection, the concept of sustainability has greatly enlarged and nowadays it concerns all the human activities and the related impacts produced on the environment, the economy and the society.

The first European Sustainable Development strategy, launched in 2012, was aimed at "dovetailing policies for economically, socially and ecologically sustainable development" [2] and according to periodical monitoring reports of the Community's strategy [3–9], the Construction Sector has been responsible of considerable environmental impacts, consuming a significant proportion of limited resources of the planet, including energy, raw materials, water and land.

In particular the European Construction Industry consumes much of raw materials (i.e. sand, gravel and other nonmetallic minerals) extracted from the domestic territory, greatly influencing the domestic material consumption, the resource productivity and the overall material flow [10]. Besides, the Construction Sector generates about 40% of all greenhouse emissions and, according to the Eurostat database [10], the waste arising from activities such as the construction and demolition of buildings and civil infrastructure, the road planning and maintenance etc., consists of a third of the total waste, 970 million tones, produced in EU.

In addition to the problem of environmental degradation, the Construction Sector generates significant impacts on the economic growth, as shown in Fig.1. Indeed, the construction industry accounts for about the 10% of the GDP, is the largest industrial sector in EU, represents a quarter of the total output, involves 2.5 million of enterprises and 13 million employees [3]. [1]

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[1] Data source: Eurostat statistics database (free access at http://epp.eurostat.ec.europa.eur)

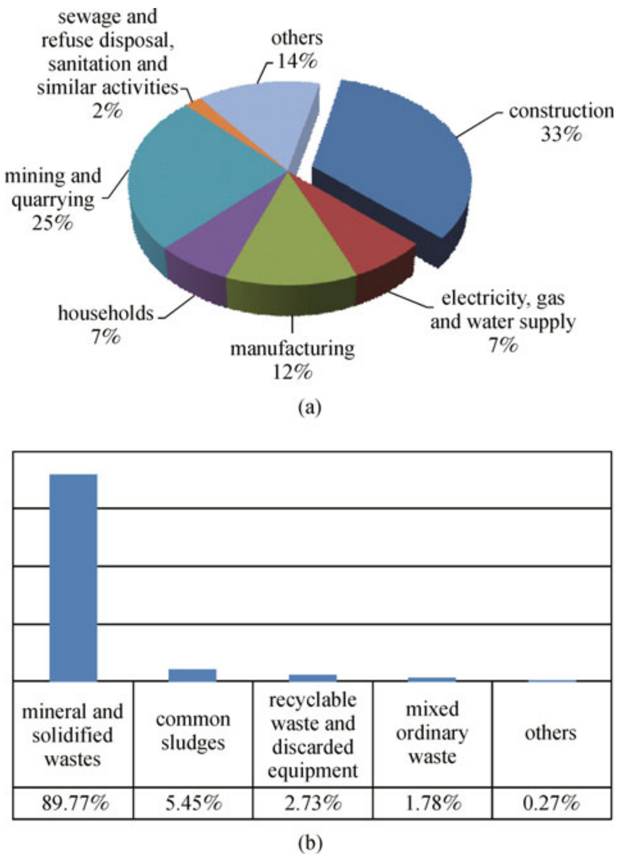

Fig. 1 Percentage of the total waste generated in the EU-27 by Economic Sector (a); construction waste sorted by type (b)

Following this brief outline, it is clear that nowadays, the enhancement of sustainability of the built environment has become a pressing issue touching all the construction industry and related activities. In this framework, the role of steel structures towards sustainable development has been widely recognized [11], due to several advantages such as the offsite prefabrication and the consequent reduction of site wastes and impacts, the easy dismantling process, the high recycling rates of the material and components, etc. Indeed, the steel construction industry has been giving more attention to the questions related to life-cycle costing, ecology, durability and sustainability of steel products and components.

In line with that, this paper presents an overview of the methodologies developed in the framework of international research on sustainability of structures, addressing the basic principles of life-time engineering, that is an innovative design philosophy based on time-dependent multi-performance-based design approaches for the sustainable design and management of structures.

A special focus is devoted to the durability design of metal structures with respect to the degradation phenomena able to impair the structural capacity over time and a proposal towards an integrated approach to life-time engineering design of steel structures is presented.

2 Life-time engineering: basic principles

Life-time engineering is a new methodological approach for the structural design which integrates the basic requirements of ordinary mechanical design with additional basic requirements related to sustainability [12–16].

According to Sarja et al. [17] it is a “theory and practice of predictive, optimizing, and integrated long-term investment planning, design, construction, management in use, maintenance, repair rehabilitation and end of life management of asset”.

The main goal of life-time engineering is to maximize the mechanical, durability, economic and environmental performance of a structure, during the whole life-cycle, reducing, at the same time, the adverse impacts played on planet, people and economy. Indeed, according to life-time engineering, besides safety and serviceability requirements, each structure shall achieve additional performance requirements, as reported in Table 1.

Life-time engineering consists of evaluating the structural performances, the environmental performances and the economic performances of a structure during the whole life-cycle (Fig. 2) when subjected to foreseeable design scenario. The method is characterized by three key attributes:

1) It is a multi-performance based design approach: several requirements are defined such as enhanced safety and reliability, reduced environmental impacts, optimized life-cycle costs.

2) It is a life-cycle oriented methodology: the time unit, adopted for the verification of life-time engineering requirements, goes beyond the ordinary design working life set in EN1990 [18]. According to the so-called cradle-to-grave-to cradle approach, the life-cycle may include all the stages of the construction’s life: from the extraction of raw materials, to the end of life of the construction work, also considering the manufacturing of products, design, construction and operational stages, the maintenance operations, the dismantling and/or demolition, the disposal and recycling of materials.

3) It envisages the use of quantitative design procedure, based on performance levels, for the evaluation of mechanical safety and serviceability, durability, ecology and economy of the structures.

With respect to this last items, several design and/or assessment methodologies have been developed in the framework of international research, for the quantitative evaluation of specific performance requirements. In the following section a brief overview of methods liable for life-time engineering is presented, focusing on the

Table 1 An overview of life-time engineering requirements

society	environment	economy
mechanical resistance and stability①	energy economy and heat retention①	reduced operational costs,
safety in case of fire①	improved air and water quality,	reduced maintenance costs and increase revenue
safety in use①	reduced water consumption	life-cycle economy
protection against noise①	reduced waste disposal	….
structural resistance②	energy efficiency	
serviceability②	reduced environmental impacts	
durability②	optimization in the use of raw materials	
robustness②		
enhanced safety and reliability		
aesthetic		
hygiene, health and environment①		

Notes: The list in intended to be indicative but not exhaustive
① The six essential requirements for construction work defined in the Construction Product Directive [19]
② Basic requirements according to EN 1990 (2002)

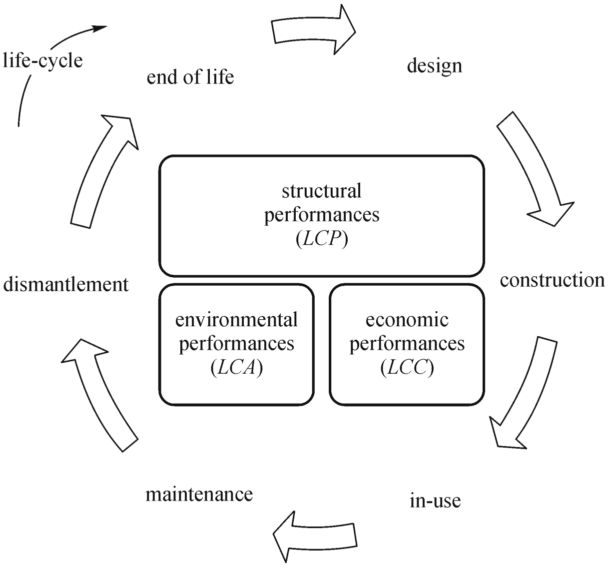

Fig. 2 A sketch of life-time engineering concept

methodologies currently received by International Standard Organization (ISO).

3 Life-cycle assessment

The environmental performance of building materials, products and process can be assessed according to different procedures and tools, i.e., the mandatory environmental labels and eco-management schemes to be adopted by manufacturers, distributors etc., the declaration of conformity with EU energy regulations (i.e. the Directive 2006/32/EC [20]) and so on. As for calculation methods of environmental impacts liable for life-time engineering applications, the life-cycle assessment methodology (*LCA*), outlined in the International Standards ISO 14040 [21] and ISO 14044 [22], is of great interest. *LCA* is aimed at evaluating the environmental burdens associated with a product process or activity by identifying energy and materials used and wastes released to the environment throughout the life-cycle (Fig. 3).

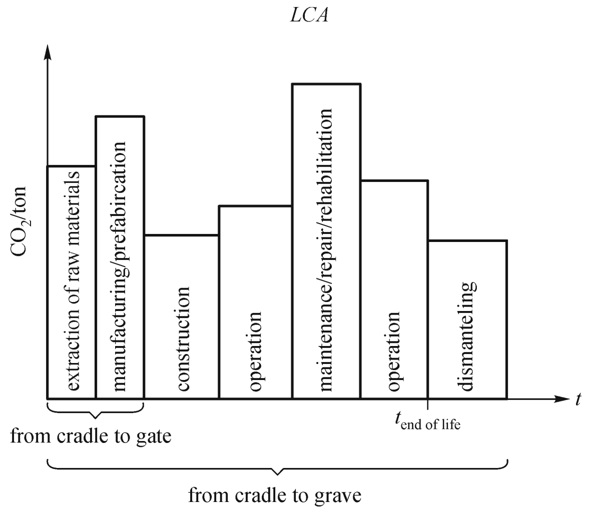

Fig. 3 A schematic representation of the result of an *LCA* analysis. The environmental impacts can be represented as CO_2 emitted per each stage of the life-cycle

LCA consists of four main stages, which include: the goal and scope definition, which describes the overall objectives, the boundaries of the system under study, the sources of data and the functional unit under investigation; the life-cycle inventory (*LCI*), a detailed compilation of all the environmental inputs (material and energy) and outputs (air, water and solid emissions) at each stage of the life-cycle; the life-cycle impact analysis, aimed at quantifying the relative importance of all environmental burdens obtained in the *LCI* by analyzing the relative influence on the selected environmental effects; the life-cycle interpretation which provide the final results and suggestions for improvement.

LCA requires advanced skills and comprehensive database concerning environmental impacts related to construction materials and processes, which are seldom on hand. Although specific *LCA* software tools are currently available, the practical application of *LCA* to constructions requires further research effort. In line with that several studies have been carrying out and further details can be found in [23–28].

4 Life-cycle costing

Life-cycle costing (*LCC*) is a calculation methodology concerned with the estimation of the costs, in monetary terms, over the whole life-cycle of a construction [29]. According to the guidelines for *LCC* provided by the ISO Standards 15686-5 [30], *LCC* is a methodology for the systematic economic evaluation of costs arising from construction, maintenance, operation, occupancy and end of life activities. Whether the analysis include also the evaluation of non-construction costs and benefits (i.e. incomes and externalities), it is called whole life-cycle costing (*WLC*).

LCC "enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational and asset replacement costs, through to end of life (…) also taking into account any other non construction costs and income" [31]. A *LCC* process usually includes steps such as planning of *LCC* analysis (e.g. definition of objectives), selection and development of *LCC* model (e.g. designing cost breakdown structure, identifying data sources and uncertainties), application of *LCC* model, and documentation and review of *LCC* results. According to Langdon [31] although extensive research and reports on *LCC* have been carried out, this methodology is not commonly applied in Europe.

Compared to the current approach, which estimates only the direct costs for construction and maintenance, *LCC* extends the analysis over the whole life of the project, showing the real value of the investment.

Advanced applications in the field of *LCC* [32,33] evaluate the costs related to the entire life-cycle in combination with the assessment of structural performances over time. Initial cost, maintenance costs, inspection and repair costs, and cost of failure (which comprises costs associated with structural failure multiplied by their probability of occurrence) are evaluated as a function of the reliability of the structure under investigation, according to a reliability-based approach (Fig. 4). In such a way, once the costs have been computed and included, the optimum solution is defined as the one which produces the lowest total life-cycle cost. Further details can be found in Ref. [29,34,35]

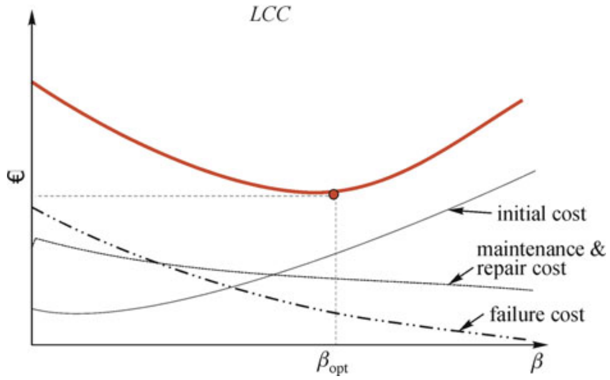

Fig. 4 A representation of reliability-based life-cycle costing (adapted by Frangopol & Estes [29])

5 Life-cycle performance

The assessment of structural performances during the life-cycle involves different questions related to the evaluation of durability against the effects of deterioration phenomena, the effectiveness of planned maintenance operations, the inspection and monitoring of the structure, etc.

A review of the design rules and recommendation provided by the structural codes, which are currently adopted for the design and verification of structures [18,36,37], highlights that 1) durability is listed among the basic requirements that each construction shall meet during service life, 2) no mandatory design procedure is defined for the evaluation of the durability performances over time under different deterioration mechanisms, and 3) only conceptual guidance, based on simplified criteria and indirect evaluation and qualitative and common provisions are furnished.

Besides, the current trend is moving towards life-cycle performance design (*LCP*) that is a performance based approach for the verification of durability. According to ISO 13823 [38] durability is "the capability of a structure or any component to satisfy, with planned maintenance, the design performance requirements over a specified period under the influence of the environmental actions, or as a result of a self-aging process" and it shall be checked according to a limit state format, defining durability failure events, which correspond to the maximum allowable decrease in the structural capacity.

LCP methods are based on the prediction of the deterioration that will likely act on the structure and the corresponding effect over time, and they can be considered as mathematical interpretation of the durability of a structure as a function of different design parameters [39].

On the basis of the quality of input information (mainly concerning with the available degradation models), it is possible to distinguish among deterministic *LCP* analysis, usually based on building science principles, expert judgment and past experience, which provide a simple estimation of durability, and probabilistic *LCP* calculations [40].

The objective of *LCP* (Fig. 5) is to evaluate the period of time during which a structure or any component is able to achieve the basic performance requirements considering the effect of the deterioration on the structural capacity [40,41].

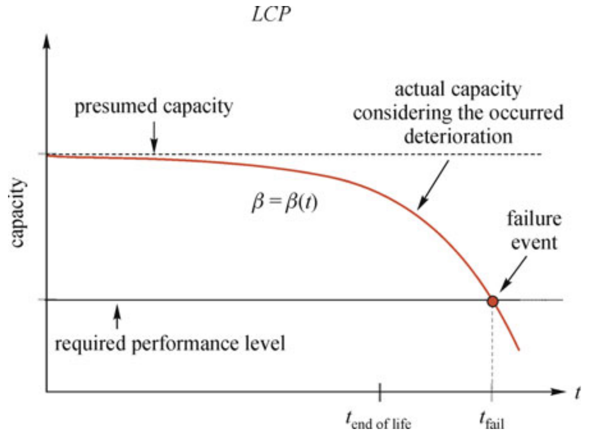

Fig. 5 Formal representation of the deterioration of structural capacity over time

LCP analysis usually consists of different steps, such as the characterization of the structure environment, the definition and of relevant degradation mechanisms, the identification of the transfer mechanism and environmental actions that will likely act onto the structure, the formulation of durability limit state and the final verification.

Several design methodologies have been developed in the framework of scientific research, mainly for reinforced concrete structures [35,39,42–45]. As for durability design of metal structures, few references can be found in the scientific literature considering the different sources of deterioration. Some of the available studies focus on the problem of corrosion rate modeling of structural material [46,47], some others on the effect of simplified corrosion models on the structural capacity [48,49]. As a matter of fact, a general framework for the durability design of metal structure, which combines the quantitative evaluation of material degradation together with the evaluation of structural capacity over time, is still lacking. In line with that, in the following section it is briefly presented a proposal for the life-cycle performance design of metal structures, with respect to the degradation of materials induced by atmospheric corrosion.

6 Life-cycle performance design of metal structures

The durability performances of metal structures are strongly influenced by damage due to fatigue and atmospheric corrosion whose control is a key aspect for design and maintenance of both new constructions and existing buildings. As for fatigue, several design procedures have been developed in the framework of both scientific literature [50] and normative references. At code level, the Eurocode EN 1993-1-9 [51] gives methods for the assessment of fatigue resistance of steel members, connections and joints subjected to fatigue loading, under the assumption of structures operating under normal atmospheric conditions, with sufficient corrosion protection and regular maintenance (EN 1993-1-9, par. 1.1.7 [51]).

With regard to durability against atmospheric corrosion, the European codes [36,51–53] provide only qualitative and common provisions, conceptual guidance based on simplified criteria and indirect evaluations (i.e. the use of coating protective systems, the choice of corrosion resistant materials and structural redundancy) to prevent the effects of corrosion during lifetime of metal structures. In particular, design guidelines such as EN1993, do not provide models for the evaluation of corrosion depth which are able to predict the rate of thickness loss as a function of different influencing parameters.

From the structural point of view, the thickness loss of the cross section due to corrosion attack leads to a smaller resistant area, producing a decrease of the structural performances in terms of strength, stiffness and ductility. In some cases, the local failure of a member or joint could affect the stability of the whole structure. In addition, in case of cyclic loads, the corrosion phenomenon can produce a significant reduction in the fatigue strength, mainly in zones with high stress concentrations [49,54].

Following the general framework provided for r.c. structures [38,39,42], the following methodology is proposed to evaluate the life-cycle performance of metal construction subjected to the atmospheric corrosion [15,55–57].

The methodology consists of six steps, as reported in Fig. 6 and briefly described in the following:

1) Definition and characterization of structure environment

To define the potential damage due to atmospheric corrosion, the first step of the durability design procedure consists in defining the macro-environment where the structure is located in. The analysis of the environmental condition is performed and it provides the project background. With regard to atmospheric corrosion of metal structures the identification of both the climatic conditions (such as temperature, rain, condensation of moisture, freezing, solar radiation and air pollution), and the

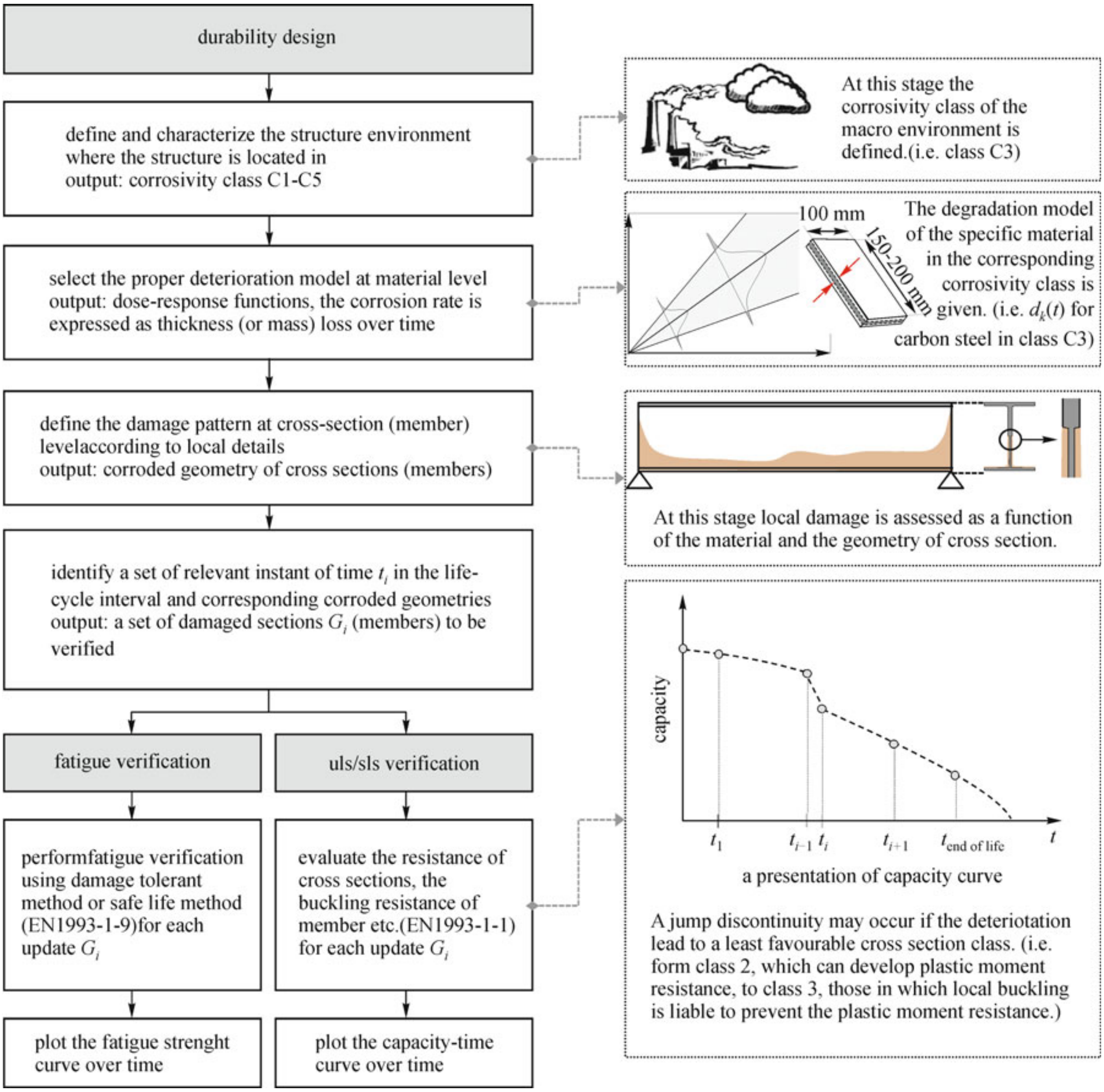

Fig. 6 The flowchart for the proposed approach to the durability design of metal structures

geological conditions (such as the location of ground water, possible contact with sea water, contamination of the soil by aggressive agents like sulphates and chlorides) has to be provided. Once a qualitative analysis has been performed, it is possible to classify the structure environment according to the ISO Standard series ISO 9223-6 [58–61], currently under revision. The output of this phase is the classification of the structure environment by means of corrosivity class (C1-C5).

2) Deterioration model for structural material

Atmospheric corrosion is mainly an electrochemical process that occurs in the presence of thin film electrolytes formed on the metal surface. The attack proceeds by balancing anodic oxidation reaction, which involves the dissolution of the metal in the electrolytic film, and cathodic reactions, involving the oxygen reduction reaction. The overall rate of the metal dissolution process is strongly influenced by the formation of corrosion products, their solubility in the water film and the formation of passive coatings as well as by the corrosiveness of the environment. As for the assessment of corrosion rates, deterioration models shall be also derived from in situ measurements, otherwise the indicative value reported in the International standard ISO 9224 [59] (currently under revision for updating) and/or dose–response functions developed in the framework of scientific researches [46,47,62] shall be adopted. Further detail can be found in Landolfo et al. [56].

3) Damage models at component level

At this stage, starting from the corrosion rate of materials, the damage pattern of cross section and the development of deterioration along the structural components is defined. The deterioration at component level is strongly influenced by local exposure condition, details etc. The damage pattern shall be defined according to visual inspection, past experience and observation of similar structures as well as on the basis of the literature. As an example, for steel bridges Czarnecki and Nowak [54] found that "field survey results indicate that corrosion is most likely to occur along the top surface of the bottom flange, due to traffic spray accumulation, and over the entire web near the support, due to deck leakage. At midspan, corrosion of the web is usually reaching 1/4 of the web height.".

4) Discretization of life-cycle interval

A set of instant of time t_i is identified according the assumed design scenario (i.e. making assumption about the maintenance of the structure). For each point of time, an updated geometry of the element under investigation is defined following the damage model defined in the previous steps.

5) Identification of relevant failure modes for the corroded members

The evaluation of structural capacity over time is verified considering reduction of fatigue, bearing and buckling capacity of corroded member at the selected instants of time. On the basis of the quality of input information, it is possible to carry out a deterministic and/or probabilistic analysis. Due to the inherent randomness of deterioration models and the epistemic uncertainties related with imperfect knowledge, a probabilistic approach is envisaged.

6) Design and verification for durability

Three durability limit states shall be checked (ISO13823 [38]), namely ultimate limit state (*ULS*) as the condition beyond which the capacity of the component or structure become equal to or less then the demand, serviceability limit state (*SLS*) when local damage and/or relative displacement affect the functionality and/or the appearance of the construction and initiation limit state (*ILS*) corresponding to the initiation of significant deterioration. For each failure mode the verification of durability is performed with respect to the set of instant of time identified before. Also in this case, the verification shall be performed at different levels by means of partial safety factors, reliability indexes and/or probability of failure.

7 A proposed approach towards an integrated to life-time structural design

As discussed in previous sections, life-time engineering design should be carried out considering the three dimensions of sustainability by means of *LCA*, *LCC* and *LCP*, as depicted in Fig. 7. Following the general principles for the integration of life-time engineering

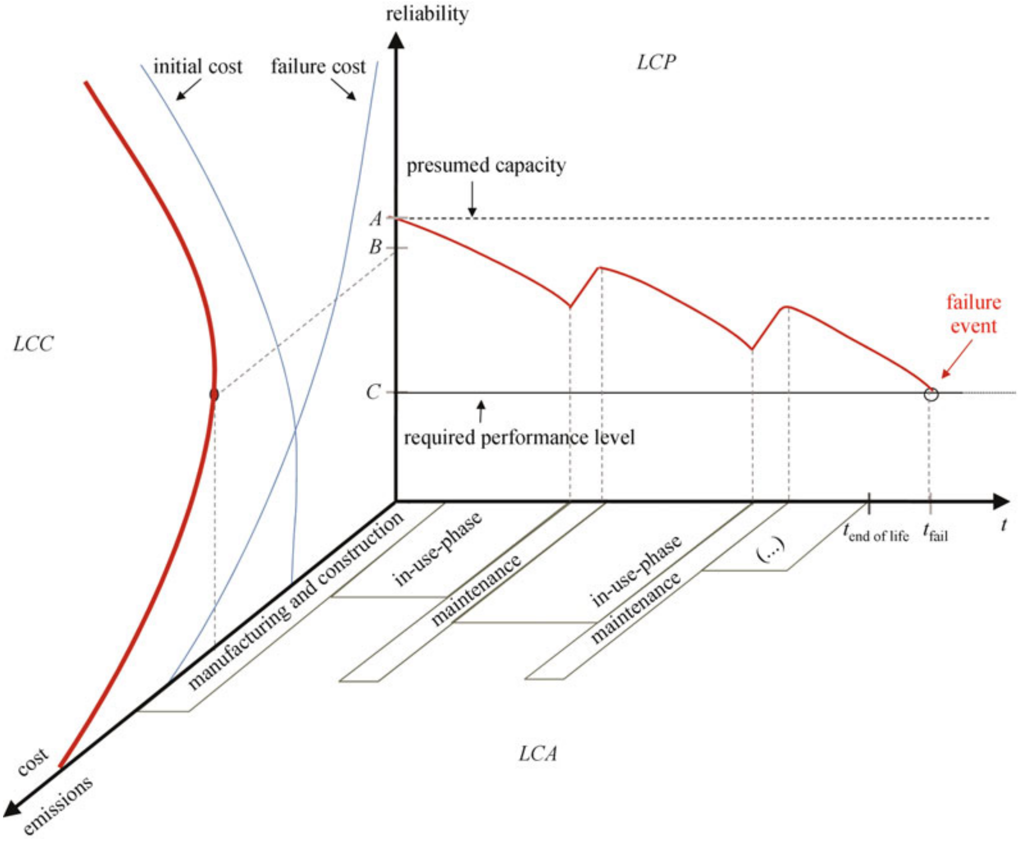

Fig. 7 The three dimension of life-time engineering according to an integrated approach

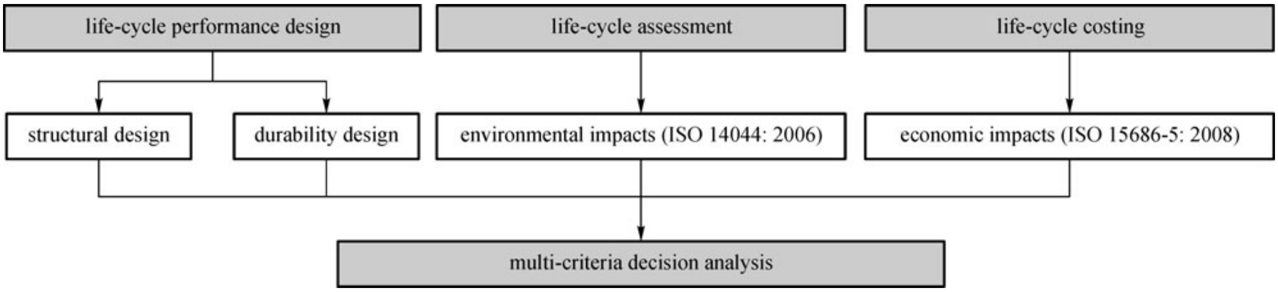

Fig. 8 The flowchart for the proposed approach to the durability design of metal structures

design given by Sarja [17], it is proposed to apply Multi-Criteria Decision Making (MCDM) methods for the integration of *LCA*, *LCC*, *LCP* (Fig. 8).

MCDM methods are techniques aimed at identifying and choosing alternatives starting from several criteria. The existing literature offer many different approaches to the optimization problem, that is the problem of selecting the best among different alternatives (or actions) given a set of selection criteria (or constraints).

As for the applications of MCDM to structural problem, several application of the TOPSIS method to the problem of retrofit and rehabilitation of buildings can be found in the scientific literature, resulting in a very suitable tool for structural design [63], as it is discussed in Caterino et al. [64].

TOPSIS method is based on the assumption that the best alternative should have the shortest distance from an ideal solution and the farthest distance from the negative-ideal solution (Fig. 9). It is assumed that each criterion has a tendency of monotonically increasing or decreasing utility. The preference order of the alternatives is obtained on the basis of these relative distances.

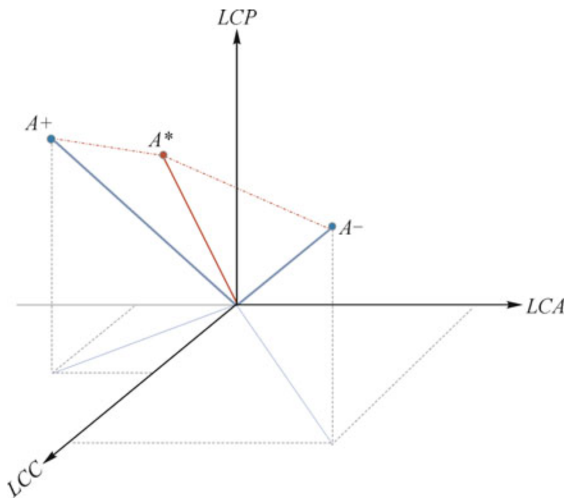

Fig. 9 A formal representation of ideal positive and negative solutions and the relative distances according to the TOPSIS method

8 Conclusions

At present sustainability of construction is a very present-day topic due to the huge impacts that constructions exercise on planet, people and economy.

The challenge of sustainability of constructions is to optimize the environmental, economical and social performances of a construction during the whole life-cycle, reducing, at the same time, the adverse impacts played on planet, people and economy.

To achieve the goal of sustainable constructions it is required to apply integrated design methodology, according to life-time engineering principles. In line with that, several methodologies have been developed in the framework of scientific research as briefly discussed in the paper.

As for further development of sustainable design, currently the challenge is to cope the gap between research and common practice even at standard level. To this end, the ISO Technical Committee TC59/SC 17 “sustainability in building construction” recognized that to achieve real progress in sustainable buildings it is necessary to create a common framework which should include common terminology, general principles, indicators for sustainable building construction, assessment and monitoring methods for production, design, construction and maintenance processes. Moreover, the Construction Sector Network (CSN) of the European Committee for Standardization (CEN), according to the Action plan developed by CSN in 2009, has planned to develop a second generation of Eurocodes, widening of the scope from the current structural design to other design criteria related to sustainability. Besides, the European Construction Technology Platform (ECTP), according to the implementation of the Strategic Research Agenda in the period 2007–2013, recognizes as a priority the development of new integrated processes for the Construction Sector through methods, the implementation of both software tools based on Building Information Models and Information and Communications Technology (ICT) applications for design and life-cycle analysis.

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References

1. Bruntlan G, ed. Our Common Future: the World Commission on Environment and Development. Report of the World Commission on Environment and Development. UN Document Symbol. A/42/427. 1987
2. European Commission. Communication from the Commission "A Sustainable Europe for a Better World: a European Union Strategy for Sustainable Development (Commission's proposal to the Gothenburg European Council)". Communication reference number: /* COM/2001/0264 final */. 2001
3. European Commission. Towards a Thematic Strategy on the Urban Environment. Communication reference number: /* COM/2004/060 final */. 2004
4. European Commission. Mainstreaming Sustainable Development into EU Policies: 2009 Review of the European Union Strategy for Sustainable Development. Communication reference number: /* COM/2009/0400 final */. 2009
5. European Commission. A Strategy for Smart, Sustainable and Inclusive Growth. Communication reference number: /* COM/2010/2020 final */. 2010
6. Council of the European Union. Renewed EU Sustainable Development Strategy. Official Journal of the European Union C 300 E/487. 2006
7. Ledoux L, Lock G , Wolf P, Hauschil W, eds. Measuring Progress towards a More Sustainable Europe, 2007 Monitoring Report of the EU Sustainable Development Strategy, Eurostat Statistical Books. Luxembourg: Office for Official Publications of the European Communities, 2007
8. Bolla V, Hauschild W, Hoffmeister O, Jung D, Lock G, Pavlovic A, Scheller A, Tronet V. Sustainable Development in the European Union, 2009 Monitoring Report of the EU Sustainable Development Strategy. Luxembourg: Office for Official Publications of the European Communities, 2009
9. European Commission. Europe in Figures–Eurostat Yearbook 2010. Luxembourg: Publications Office of the European Union, 2010
10. Eurostat. Environmental Statistics and Accounts in Europe. Luxembourg: Publications Office of the European Union, 2010
11. Burgan B A, Sansom M R. Sustainable steel construction. Journal of Constructional Steel Research, 2006, 62(11): 1178–1183
12. Landolfo R. Introduction to life-time engineering. In: Bragança L, Koukkari H, Blok R, Gervásio H, Veljkovic M, Plewako Z, Landolfo R, Ungureanu V, Silva L S. Sustainability of Constructions. In: Proceedings of the 1st Workshop on Sustainability of Constructions. Lisbon: Multicomp, Ldaa, 2007
13. Landolfo R, Ungureanu V. Life-time structural engineering. In: Bragança L, Koukkari H, Blok R, Gervásio H, Veljkovic M, Plewako Z, Landolfo R, Ungureanu V, Silva L S, Haller P. Sustainability of Constructions. In: Proceedings of the 1st Seminar on Sustainability of Constructions. Dresden, 2008
14. Landolfo R. Durability Design of Metal Structures. In: Bragança L, Koukkari H, Veljkovic M, Borg R P. Sustainable Construction—a Life Cycle Approach in Engineering International Training School. Malta, 2010
15. Cascini L. Atmospheric corrosion and durability design of metal structures. Dissertation for the Doctoral Degree. Naples: University of Naples Federico II, 2009
16. Landolfo R. Life-time Structural Engineering: Design for Durability, Life-cycle Performance, Maintenance and Deconstruction. Malta, 2011 (In press)
17. Sarja A, Bamforth P, Caccavelli D, Chevalier J, Durucan S. Lifetime Thematic Network: Lifetime Engineering of Buildings and Civil Infrastructures. Project number: G1RT-CT-2002-05082-Deliverable 3.1 Generic Description of Lifetime Engineering. 2005, available at: http://lifetime.vtt.fi/lifetime_deliverable_3_1.pdf
18. EN 1990. Eurocode: Basis of Structural Design. Brussels: CEN, 2002
19. European Union. Council Directive 89/106/EEC of 21 December 1988 on the Approximation of Laws, Regulations and Administrative Provisions of the Member States Relating to Construction Products. Official Journal of the European Union L 040, 11/02/1989 P. 0012–0026. CELEX number: 31989L0106. Brussels: European Union, 1998
20. European Union. Council Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on Energy End-use Efficiency and Energy Services and Repealing Council Directive 93/76/EEC (Text with EEA relevance). Official Journal of the European Union L 114. Brussels: European Union, 2006, 64–85
21. ISO 14040:2006. Environmental Management. Life Cycle Assessment. Principles and Framework. Genève, Switzerland: International Organization for Standardization, 2006
22. ISO 14044:2006. Environmental Management. Life Cycle Assessment. Requirements and Guidelines. Genève, Switzerland: International Organization for Standardization, 2006
23. Blok R, Bikad D, Kontoleon K, Giarma C, Gervasio H. Life Cycle Assessment-general Methodology. In: Bragança L, Koukkari H, Blok R, Gervásio H, Veljkovic M, Plewako Z, Landolfo R, Ungureanu V, Silva L S. Sustainability of Constructions. In: Proceedings of the 1st Workshop on Sustainability of Constructions. Lisbon: Multicomp, Ldaa, 2007
24. Blok R, van Egmond E, Glaumann M, Gervasio H. General Framework for Sustainability Evaluation of The Built Environment. In: Summary Report of the Cooperative Activities Integrated Approach towards Sustainable Constructions. Volume: 1. Malta, 2011 (In press)
25. Dattilo C A. Sustainable construction: life cycle analysis as a supporting tool for structural design. Dissertation for the Doctoral Degree. Naples: University of Naples Federico II, 2011
26. Gervasio H, Da Silva L. State-of-the-art on LCA. In: Bragança L, Koukkari H, Blok R, Gervásio H, Veljkovic M, Plewako Z, Landolfo R, Ungureanu V, Silva L S. Sustainability of Constructions. In: Proceedings of the 1st Workshop on Sustainability of Constructions. Lisbon: Multicomp, Ldaa, 2007
27. Gervásio H. Sustainable design and integral life-cycle analysis of bridges. Dissertation for the Doctoral Degree. Coimbra: Universi-

dade de Coimbra, 2010

28. Khasreen M M, Banfill P F G, Menzies G F. Life-Cycle Assessment and the Environmental Impact of Buildings: a Review. Sustainability, 2009, 1(3): 674–701
29. Frangopol D M, Estes A C. Life-Cycle Evaluation and Condition Assessment of Structures, Chapter 36 in Structural Engineering Handbook, Second Edition. CRC Press, 2005, 36–1–36–51
30. ISO 15686–5:2008. Buildings and Constructed Assets. Service-life Planning. Part 5: Life-cycle Costing. Genève, Switzerland: International Organization for Standardization, 2008
31. Langdon D. Towards a Common European Methodology for Life Cycle Costing (LCC)–Literature Review, 2007.
32. Frangopol D M, Lin K Y, Estes A C. Life cycle cost design of deteriorating structures. Journal of Structural Engineering, 1997, 123(10): 1390–1401
33. Frangopol, D M, Kong J S, Gharaibeh S. Reliability-based life-cycle management of highway bridges. Journal of Computing in Civil Engineering, 2001, 15(1): 27–34
34. Cho H N, Frangopol D M, Ang A H S, eds. Life-Cycle Cost and Performance of Civil Infrastructure Systems. London: Taylor & Francis Group. 2007
35. Biondini F, Frangopol D M, eds. Life-Cycle Civil Engineering, Set of Book and CD-ROM. London: CRC Press. 2008
36. EN 1993–1-1. Eurocode 3: Design of Steel Structures—Part 1–1: General Rules and Rules for Buildings, 2005, Brussels: CEN
37. JCSS-Joint Committee on Structural Safety. Probabilistic Model Code. Part 1: Basis of Design. 12th draft. JCCS, 2000. Available online at: www.jcss.ethz.ch
38. ISO 13823:2008. General Principles on the Design of Structures for Durability. Genève: International Organization for Standardization, 2008
39. Sarja A, Vesikari E, eds. Durability Design of Concrete Structures. RILEM Report of TC. 130-CSL. RILEM Report Series 14. E&FN Spon, Chapman & Hall. 1996, 165
40. Vesikari E, Landolfo R. Service Life Prediction Methods Referred to by Eurocode 0. In: Bragança L, Koukkari H, Landolfo R, Ungureanu V, Vesikari E, Hechler O. Life-time Structural Engineering: Design for Durability, Life-cycle Performance, Maintenance and Deconstruction. Malta 2011 (In press)
41. Landolfo R, Vesikari E. Service Life Design Methods for Civil Engineering Structures. In: Bragança L, Koukkari H, Landolfo R, Ungureanu V, Vesikari E, Hechler O. Life-time Structural Engineering: Design for Durability, Life-cycle Performance, Maintenance and Deconstruction. Malta, 2011 (In press)
42. Sarja A. Lifecon Deliverable D2.1. Reliability Based Methodology for Lifetime Management of Structures. Finland, 2004
43. Sarja A. Predictive and Optimised Life Cycle Management. Buildings and Infrastructures. London and New York: Taylor and Francis, 2006
44. Biondini F, Bontempi F, Frangopol D M, Malerba P G. Probabilistic service life assessment and maintenance planning of concrete structures. Journal of Structural Engineering, 2006, 132(5): 810
45. Fib- Fédération Internationale du Béton. Model Code for Service Life Design Bulletin 34. Stuttgard: fib, 2006
46. Albrecht P, Hall T T. Atmospheric corrosion resistance of structural steels. Journal of Materials in Civil Engineering, 2003, 15(1): 2–24
47. Klinesmith D E, McCuen R, Albrecht P. Effect of environmental condition on corrosion rate. Journal of Materials in Civil Engineering, 2007, 19(2): 121–129
48. Park C H, Nowak A S. Lifetime reliability model for steel girder bridges. In: Safety of Bridges. London: Thomas Telford Publishing, 1997
49. Kaiser J R, Nowak A S. Capacity loss due to corrosion in steel-girder bridges. Journal of Structural Engineering, 1989, 115(6): 1525–1537
50. Kühn B, Lukić M, Nussbaumer A, Günther H P, Helmerich R, Herion S, Kolstein M H, Walbridge S, Androic B, Dijkstra O, Bucak Ö. Assessment of Existing Steel Structures: Recommendations for Estimation of Remaining Fatigue Life. EUR Scientific and Technical Research Series. Luxemburg: Office for Official Publication of the European Committee, 2008, 89
51. EN 1993–1-9. Eurocode 3: Design of Steel Structures. Part 1–9: Fatigue. Brussels: CEN, 2005,
52. ENV 1993–1-4. Eurocode 3: Design of Steel Structures. Part 1–4: General Rules–Supplementary Rules for Stainless Steel. Brussels: CEN, 1996,
53. EN 1993–1-5. Eurocode 3: Design of Steel Structures. Part 1–5: Plated Structural Elements. Brussels: CEN 2004,
54. Czarnecki A A, Nowak A S. Time variant reliability profiles for steel girder bridges. Structural Safety, 2008, 30(1): 49–64
55. Cascini L R, Portioli F. An integrated approach to durability design of steel structures against atmospheric corrosion. Key Engineering Materials, 2008, 385–387: 657–660
56. Landolfo R, Cascini L, Portioli F. Modeling of Metal Structure Corrosion Damage: a State of the Art Report. Sustainability 2010. 2010, 2: 2163–2175
57. Landolfo R, Cascini L, D'Aniello M, Portioli F. On the effects of fatigue and corrosion degradation of metal railway bridges: an integrated approach for the assessment of the residual life. Costruzioni Metalliche, 2011, 6: 37–46 (in Italian)
58. ISO 9223:1992. Corrosion of Metals and Alloys. Corrosivity of Atmospheres. Classification. Brussels: CEN, 1992
59. ISO 9224:1992. Corrosion of Metals and Alloys. Corrosivity of Atmospheres. Guiding Values for the Corrosivity Categories. Brussels: CEN, 1992
60. ISO 9225:1992. Corrosion of Metals and Alloys. Corrosivity of Atmospheres. Measurement of pollution. Brussels: CEN, 1992
61. ISO 9226:1992. Corrosion of Metals and Alloys. Corrosivity of Atmospheres. Determination of corrosion rate of standard specimens for the evaluation of corrosivity. Brussels: CEN, 1992
62. Kucera V. Mapping effects on materials in Manual mapping critical load. ICP Materials Coordination Centre, Sweden, 2004. Available online at: http://icpmapping.org
63. Portioli F, Cascini L, Ungureanu V. Multi-criteria decision making methods in refurbishment, deconstruction and demolition of existing structures. In: Proceeding of International Symposium on Sustainable Construction. A Life-cycle Approach in Engineering. COST Action C25, Malta, 23–25 July, 2010, 177–184
64. Caterino N, Iervolino I, Manfredi G, Cosenza E, Iervolino I, Manfredi G, Cosenza E. Comparative analysis of multi-criteria decision-making methods for seismic structural retrofitting. Com-

puter-Aided Civil and Infrastructure Engineering, 2009, 24(6): 432–445

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