LIFETIME ENGINEERING OF BUILDINGS AND CIVIL INFRASTRUCTURES AS A REALISATION OF SUSTAINABLE CONSTRUCTION

ΜΗΧΑΝΙΚΗ ΤΟΥ ΚΥΚΛΟΥ ΖΩΗΣ ΚΤΙΡΙΩΝ ΚΑΙ ΑΣΤΙΚΩΝ ΥΠΟΔΟΜΩΝ ΩΣ ΥΛΟΠΟΙΗΣΗ ΤΗΣ ΑΕΙΦΟΡΟΥ ΑΝΑΠΤΥΞΗΣ

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ABSTRACT
At the time being the design is mainly focused on the construction phase and the first use, and maintenance and repair are reactive. New and increased demands, e.g. health and environmental aspects are not enough included into these processes. The integrated lifetime engineering methodology concerns the development and use of technical performance parameters to guarantee, that the structures fulfil through the life cycle the requirements arising from human conditions, economy, cultural, social and ecological considerations. It includes: investment planning and decision making, integrated lifetime design, integrated lifetime management, maintenance, repair and rehabilitation (MR&R) planning, reuse, recycling and disposal.

ΠΕΡΙΛΗΨΗ
Μέχρι σήμερα ο σχεδιασμός είναι κυρίως επικεντρωμένος στη φάση της κατασκευής και της πρώτης χρήσης των κατασκευών, ενώ η συντήρηση και η επισκευή τους δε λαμβάνονται υπόψη στην αρχική αυτή φάση. Νέες απαιτήσεις, διαρκώς αυξανόμενες,
όπως η υγεία και οι περιβαλλοντικές απαιτήσεις δεν συμπεριλαμβάνονται επαρκώς στις διαδικασίες αυτές. Η ολοκληρωμένη μεθοδολογία της μηχανικής του κύκλου ζωής αφορά στην ανάπτυξη και τη χρήση τεχνικής απόδοσης των παραμέτρων που διασφαλίζουν το γεγονός ότι οι κτιριακές δομές εκπληρώνουν καθ’ όλη τη διάρκεια ζωής τους τις απαιτήσεις που ηγάζονται από ανθρώπινες, οικονομικές, πολιτιστικές, κοινωνικές, οικολογικές ανάγκες. Η μεθοδολογία αυτή περιλαμβάνει: σχεδιασμό επενδύσεων και λήψης αποφάσεων, ολοκληρωμένο σχεδιασμό βάσει του χρόνου ζωής, ολοκληρωμένη βάσει του χρόνου ζωής διαχείριση, σχεδιασμό των αποκαταστάσεων και των αναπλάσεων, επαναχρήση, ανακύκλωση, διάθεση.

1. BACKGROUND

Sustainable development is aimed to reach a stable social and economic development in harmony with nature and cultural heritage. Against all these aspects: social, economic, ecological and cultural, the construction branch is a major player. The construction branch includes building and civil engineering and all their life cycle phases: construction, operation, maintenance, repair, renewal, demolition and recycling. As an example, in Europe the construction branch share is: 11% of GNP, 15% of employment, and 40% of raw materials consumption, energy consumption and waste production. Building and civil engineering structures are responsible for a major share of all the influences mentioned above. Building and civil engineering structures are the longest lasting products in societies. Typically the real service life of structures lies between 50 years and several hundreds of years. We know, and this is especially known here in Greece, that some of the most valued historic structures currently, have even reached an age of several thousand years. This is the reason why sustainable engineering in the field of buildings and civil infrastructures is especially challenging in comparison to all other areas of technology.

In order to reach these objectives we have to make changes even into paradigm, and especially the frameworks, processes and methods of engineering in all phases of the life cycle: investment planning and decisions, design, construction, use and facility management, demolition, reuse, recycling and wasting. This is the reason for starting
to speak on life cycle engineering. The lifetime (also called: “whole life” or “life cycle”) principle has been started to introduce into design and management of structures during last years, and this development process is getting increasing interest in practice of structural engineers.

2. CONTENT OF THE LIFETIME ENGINEERING

2.1. Definition and general view of the content

Lifetime engineering is an innovative idea and a realisation of this idea for solving the dilemma that currently exists between infrastructures (buildings and civil infrastructures) as a very long-term product and short-term approach to design, management and maintenance planning.

Lifetime engineering includes:
- Lifetime investment planning and decision making
- Integrated lifetime design
- Integrated lifetime management and maintenance planning
- Modernisation, reuse, recycling and disposal, and
- Integrated lifetime environmental impact assessment and
- minimisation

The integrated lifetime engineering methodology concerns the development and use of technical performance parameters to guarantee, that the structures fulfil through the life cycle the requirements arising from human conditions, economy, cultural and ecological considerations. With the aid of lifetime engineering we thus can control and optimise the human conditions (safety, health and comfort), the monetary (financial) economy and the economy of the nature (ecology), and taking into account cultural and social needs.

For the life cycle design, the analysis and design are expanded into two economical levels: monetary economy and ecology, which means the economy of nature. The life cycle expenses are calculated into the present value or into annual costs by discounting the expenses from manufacture, construction, maintenance, repair, changes, modernisation, reuse, recycling and disposal. The monetary costs are treated as usual
in current value calculations. The expenses of nature are the use of non-renewable natural resources: materials and energy, the production pollutants into air, water or soil, and production of solid waste. Consequences of air pollution are health problems, inconvenience for people, ozone depletion and the global climatic change. The goal is to limit the natural expenses under the allowed values and to minimise them.

2.2. Integrated life cycle design

2.2.1. Framework

Fig. 1: Main viewpoints of the life cycle quality.

The objective of the integrated life cycle design is to make concrete the design methods
and methodologies for structural design in order to meet the requirements of sustainable
development during the entire life cycle of the structures (resources, transports,
manufacture, use, recycling and reuse, demolition, wasting). The objective is to design
for life cycle quality (Fig. 1.). The integrated life cycle design includes the mechanical,
physical, economical, energy, health and environment aspects. The integrated life cycle
design shall manage the multiple requirements in a systematic way.

2.2.2. Design process

The main phases in the model of integrated life cycle design process are: Analysis of
the actual requirements, interpretation of the requirements into technical performance
specifications of structures, creation of alternative structural solutions, life cycle analysis
and preliminary optimisation of the alternatives, selection of the optimal solution
between the alternatives and finally the detailed design of the selected structural
system and its modules and components. A summary of the integrated life cycle design
phases and the specific design methods are presented in Table 1.

The conceptual, creative design phase is very decisive in order to utilise the potential
benefits of integrated design process effectively. Controlled and rational decision making
when optimising multiple requirements with different metrics is possible through the
application of systematics of multiple attribute optimisation and decision making. In
detailed design phase, life cycle aspects rise needs for total performance over the life
cycle, including durability design and design for mechanical and hygro-thermal long
term performance.

At the life cycle planning, a modular systematic is preferred. This allows the systematic
allocation and optimisation of the target service life as well as life cycle economy and
ecology of different parts of the building. A suited modularisation at the highest level of
hierarchy is the following: Bearing frame, envelop, foundations, partitions, heating and
ventilating services, information, water and sewage system, control, data processing
and communication services and waste management system. All of these assemblies are
specified during the development or design process on continuously increasing precision
starting from general performance specifications and ending into detailed designs.
Table 1: Integrated life cycle design process and central methods for application.

<table>
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<tr>
<th>Design phase</th>
<th>Life Cycle Design Methods</th>
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<tbody>
<tr>
<td>1. Investment planning</td>
<td>Multiple criteria analysis, optimisation and decision making. Life cycle (monetary and natural) economy</td>
</tr>
<tr>
<td>2. Analysis of client’s and user’s needs</td>
<td>Modular design methodology. Quality Function Deployment Method (QFD)</td>
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<tr>
<td>5. Creation and sketching of alternative structural solutions</td>
<td>Modular design methodology.</td>
</tr>
<tr>
<td>7. Multiple criteria ranking and selection between alternative solutions and products</td>
<td>Modular design methodology. Quality Function Deployment Method (QFD). Multiple Criteria Analysis, optimisation and decision making</td>
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Ranking between design alternatives ends the sketch design phase resulting the draft designs. All classes of requirements are systematically taken into account at the ranking. Applying the Multiple Criteria Analysis method, the core properties are mainly calculated quantitatively with numerical equations, but some of added properties are evaluated qualitatively only. The selected alternative can fulfil some of the following criteria:
Best in all requirements
Best weighted properties with reasonable cost level
Best in preferred requirements, fulfilling accepted level in all requirements
Best in valuated multiple criteria benefit/cost ratio

At the phase of detailed design the durability design is a new approach, which is important for long life structures in a harsh environment. In durability design following methods can be applied:

durability design with structural detailing rules
design of the environmental conditions of the structures for durability
protection of the materials and structures against deterioration
lifetime safety factor method
reference factor method

2.2.4. Indicators of the lifetime quality

The central life cycle quality indicators of a structural system are adaptability in use, changeability during use, reliable safety, technical performance and durability, resistance against obsolescence, healthy and ecological efficiency. In buildings, the compatibility and easy changeability between load bearing structures, partition structures and building service systems is important. Regarding the life cycle ecology of buildings, the energy efficiency of the building is a dictating factor. Envelope structures are responsible for most of the energy consumption, and therefore the envelope must be durable and have an effective thermal insulation and safe static and hygrothermal behaviour. The internal walls have a more moderate length of service life length, but they have the requirement of coping with relatively high degrees of change, and must therefore possess good changeability and re-useability. In the production phase it is important to ensure the effective recycling of the production wastes in factories and on site. Finally, the requirement is to recycle the components and materials after demolition. Obsolescence of buildings is either technical or functional, sometimes even aesthetic in nature. Technical and functional obsolescence is usually related to the primary life time quality factors of structures. Aesthetic obsolescence is usually architectural in nature.
Civil engineering structures like harbours, bridges, dams, off shore structures, towers, cooling towers etc. are often very massive and their target service life is long. Their repair works under use are difficult. Therefore their life cycle quality is tied to high durability and easy maintainability during use, saving of materials and selection of environmentally friendly raw materials, minimising and recycling of construction wastes, and finally recycling of the materials and components after demolition. Some parts of the civil engineering structures like waterproof membranes and railings have a short or moderate service life and therefore the aspects of easy re-assembly and recycling are most important. Technical or performance related obsolescence is the dominant reason for demolition of civil engineering structures, which raise the need for careful planning of the whole civil engineering system, e. g. the traffic system, and for selection of relevant and future oriented design criteria.

2.3. Integrated life cycle management and maintenance

Analogously to life cycle design, the life cycle maintenance planning and management system also includes sustainability aspects: life cycle monetary economics, life cycle economics of nature (ecology) and life cycle performance. These indicators can be modelled and optimised applying the same basic methods as presented in the description of the life cycle design methods. The economic and performance models developed in the design stage are the first estimates for the life cycle maintenance planning. In course of use, the results of periodic condition assessments can be used for updating the forecasting models. Thus the models are serving as a basis for repair and renewal plans for each of the next planning periods, until the planning of demolition and recycling. Future long-term maintenance, repair and renewal plans can be optimised. These principles can be concretised in a predictive, life cycle oriented and integrated Life Cycle Management System (LMS).

Integration and Life Cycle principle means the implementation of all planning aspects: LCC (Life Cycle Cost), LCP (Life Cycle Performance), LCE (Life Cycle Ecology), functionality, safety, health and comfort.

As tools for concretising this approach can be applied the following methods of
system technology and mathematics: Multi-Attribute Optimisation and Decision Making, Performance systematics and mathematical modelling, Quality Function Deployment (QFD), risk analysis and statistical reliability theory, and modelling of performance and service life of structures. Both numerical calculations and qualitative descriptions (LCE / biodiversity, health, comfort, obsolescency) will be included in the optimisation and decision making.

At present state there is no quantitative classification of exposure environment or potential degradation factors in standards. The classification system of environmental degradation loads have to be developed taking into consideration the interaction between environment and structure. The classification has to be mainly quantitative, and it must be compatible with the predictive performance and service life models.

**CALCULATION MODELS**

1. Performance and service life calculation models
2. Performance and residual service life models of repaired structures
3. Environmental loading functions

**LIFECON LMS**

1. TERMS AND DEFINITIONS
2. FRAMEWORK OF LIFECON LMS
3. MANAGEMENT PROCESS
4. MODELS
5. METHODS

**IT PROTOTYPE**

**COMMERCIAL IT**

**PARTNER APPLICATIONS**

**PLANNING METHODS**

1. Modular and hierarchical systematics of structures
2. Limit state calculations with statistical method
3. Limit state calculations with deterministic lifetime safety factor method
4. Condition Assessment Protocol
5. Quality Function Deployment Method (QFD)
6. Risk analysis and optimisation
7. Markovian Chain method
8. Multiple Attribute Decision Making and

**Fig. 2:** A scheme of the “Lifecon” life cycle oriented maintenance and facility management system [12].

The quantitative classification of degradation loads have to be divided regionally, nationally and locally. Quantitative degradation loads will be defined at design and
maintenance planning on a structural level (structure as a whole) and on detail level (specific surfaces, joints etc.). A schedule of the “Lifecon” management system is presented in Fig.2 [12].

2.4. Reuse and recycling

Most of the wastes in the construction sector, up to 80 %, are produced in renovation and demolition, only about 20 % come from the construction of new facilities. The dominant waste materials are earth, concrete, masonry, gypsum and wood. The active reduction of wastes in renovation and demolition is possible through the selective dismantling for recycling of structural systems, components and materials.

Several civil engineering structures, like roads and streets, are major consumers of raw materials. In those structures, materials consumption can be reduced with the use of industrial by-products like fly ash and blast furnace slag, and construction and demolition waste materials like crushed concrete and masonry. Detailed quality specifications and an effective quality control are needed for the use of these secondary materials.

The recycling ability of the structural materials and components depends on the degree and/or the technical level of the desired re-use. It is important to recognise that the recycling possibilities of the building components, modules and even technical systems shall be reconsidered in connection with design. The higher the hierarchical level of recycling, the higher also the ecological and economical efficiency of recycling. Therefore the re-use of entire components, modules or systems has to be preferred, even if there are difficulties in quality requirements and quality control in re-use.

Special issues to be treated in the design of structures and materials for re-use and recycling are:

- separability of the structural components or materials during demolition of a structure, e.g. the use of demountable structural components using suitable connections and joints,
- structural separation of components, modules or systems with different service lives and different recycling techniques,
- reduction in the variety of materials,
- separation ability of materials, which cannot be recycled together,
- avoidance of insoluble composite substances and/or composite substances that are either only slightly soluble or soluble only with a high expenditure or energy input.

Selective dismantling includes the detailed planning of dismantling phases, optimising the work sequences and logistics of the dismantling and selection process. The main goal is to separate the different fractions of materials and different types of components already at the demolition phase in order to avoid multiple actions. The recycling ability of the building materials and structural components depends on the degree and/or the technical level of the desired re-use. In case of reuse of building components the main problem is to guarantee the quality of the reused products.

3. CONCLUSIONS

Incorporating life cycle principles into the practical design, construction, maintenance and recycling of structures is quite an extensive process. Application of life cycle principles is widening the scope of structural design to the extent that the entire working processes must be re-engineered. The tradition of structural engineers in applying mathematical and physical calculation methods in design will serve as a good basis for applying the additional multiple calculation methods that are needed in lifetime structural engineering.

Concerning materials and structures, new basic knowledge will be needed especially regarding environmental impacts, hygrothermal behaviour, durability and service life of materials and structures in varying environments. Structural design methods that are capable of life cycle design, multiple analysis decision-making and optimisation will have to be further developed. Recycling design and technology demand further research in design systematics, recycling materials and structural engineering. The knowledge obtained will have to be put into practice through standards and practical guides.

For practical application also IT software tools are needed. These tools shall include all process models, procedures and methods which belong to the lifetime design, maintenance, repair and rehabilitation planning, as well as to the planning of selective
demolition, reuse, recycling and wasting. Relevant databases of data which are needed for these calculations will support the use of the lifetime engineering software.

REFERENCES


Lausanne.


