Integrated life cycle design of materials and structures

Asko Sarja
Technical Research Centre of Finland (VTT), Espoo, Finland

Abstract
Integrated life cycle design is an important tool for sustainable civil engineering. It aims to concretise the multiple requirements of functionality, economy, resistance, aesthetics and ecology into technical specifications and further into designs of materials and structures. With this objective in mind we have to extend the scope of structural design and develop the design process. The extended design must also include multiple calculation methods in which calculations of life cycle monetary economy are added to those of life-cycle natural economy — in other words ecology. Safety and mechanical serviceability are guaranteed by traditional mechanical design with statistical and dynamics methods. Controlled technical serviceability throughout the target service life is guaranteed by durability design. Health is protected by methods of building physics, including hygrothermal physical and chemical methods. Design for recycling is a special area with its own considerations and methods. The selection of final solutions between alternative structural ideas, materials and products can be done by applying the methods of multiple requirements decision-making. Modular product and performance systematics can be applied at several of the design phases.

The methodology of integrated life cycle design can be used at the design of individual buildings or other structural facilities, as well as in the development of new materials and structures or structural systems.

Many research results exist which allow the introduction of new design methods into praxis. However, new basic knowledge is needed especially in regard to hygrothermal behaviour, durability and service life of materials and structures in varying environments. This knowledge will then have to be put into practice through standards and practical guides. The creation of new types of materials and structures in which the properties can be tailored to each specific need is of vital importance.

Before integrated life cycle design can be introduced into practice, many new guides and standards will be needed. Some such guidelines already exist as international and national standards, but do not yet suffice. Extensive education will also be needed to give practising engineers the required skills in the expanded design process and its methods.

Keywords: Design, life cycle, requirements, environment, integrated design, ecology, service life, durability.
1. Introduction

Our societies are living in a time of rapid change in which old values and traditions are being increasingly challenged. Clearly recognisable in the building sector are pivotal changes in the goals and requirements of construction. The main trend is an increase in the basic requirements of buildings and building facilities. Traditionally the four groups of requirements have been functionality, resistance, aesthetics and economy. To these we now add ecology and general sustainability, and increasingly health aspects.

Sustainability must always be treated according to the life cycle principle — in other words with the application of life cycle methodology to design, manufacture, construction, maintenance, and the management of building projects, companies and other organisations in building. Referring to Fig. 1 we could give a technical definition for sustainable building as follows (Sarja, 1997):

"Sustainable building is a technology and practice which meets the multiple requirements of the people and society in an optimal way during the life cycle of the building facility."

![Fig. 1. Multiple requirements for sustainable buildings](image)

2. Principles of integrated life cycle design

2.1 Interpretation of requirements in economical and technical terms

Sustainability is related to ecology and economy. The ecological aspects include the quantitative goals regarding the consumption of non-renewable natural resources, the production of pollutants into air, soil and water and the qualitative goals regarding non-calculative effects like biodiversity and noise. Ecology can be interpreted as the economy of the nature (Sarja, 1995). The term gives us a quite concrete starting point for the application of this aspect to materials and structural engineering and it can be concretised in the life cycle methodology in design, manufacturing, construction and management.
Through the principle of sustainability, resistance design will be expanded into durability design to include time as a new dimension in the design calculations. Health aspects are generally related to the control of moisture and thermal conditions and to special subjects like hazardous emissions from materials.

Design for recycling is an important tool for saving natural non-renewable resources and for reducing the environmental impact.

2.2 General framework and design process
The overall scheme of the integrated structural design (fig.2) includes the following main phases of the design process (fig.3): 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.

Fig. 2. Framework of integrated structural design (Sarja, 1996) /2, 6, 7/. 
The conceptual, creative design phase is very decisive for utilising the potential benefits of the integrated life cycle design process effectively. This is the phase at which the design is done at system level. Modular systematics help rational design, because the structural system typically has different parts, here called modules, with different requirements e.g. regarding durability and service life requirements.

Controlled and rational decision making when optimising between multiple requirements with different metrics is possible through the application of systematics of multiple requirements decision making. All these aspects are widening the scope of structural design and construction to the extent that the entire working processes must be re-engineered. Close co-operation with clients and architects is therefore needed. In design, we can start to establish a new design process, or so-called integrated structural design, which is scheduled and described below.

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<tr>
<th>ANALYSIS OF FUNCTIONAL REQUIREMENTS</th>
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<td>- definition of performance parameters</td>
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<td>- multiple criteria selection between the design alternatives</td>
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| MECHANICAL DESIGN PHYSICAL DESIGN DURABILITY DESIGN |

| FINAL INTEGRATING DETAILED DESIGN |

Fig. 3. The process of integrated structural design (Sarja, 1995) /4, 5, 7/. 
2.3 Methods of the integrated life cycle design

The key issues from an environmental viewpoint are the life cycle monetary and natural economy, and the service life design.

The conceptual, creative design phase plays a decisive role in the effective exploitation of the potential benefits of integrated design. At that stage, the design works on a system level. Modular systematics greatly help rational design, because the technical systems typically comprise different parts, here called modules, each with different requirements as to e.g. durability and service life.

For life cycle design the analysis and design has expanded to two economical levels: monetary economy and ecology, which means the economy of nature /3, 4, 7/. Life cycle expenses are calculated at present value or in yearly costs by deducting the expenses of manufacture, construction, maintenance, repair, changes, modernisation, reuse, recycling and disposal. Monetary expenses are treated as usual in current value calculations. Those relating to nature are the use of non-renewable natural resources, the emission of pollutants into air, water or soil, and global warming. These impacts dictate the environmental profiles of the structural and building service systems. The environmental impact profile generally includes the consumption of globally and locally critical raw materials like energy and water and the production of CO₂, CO, SO₂, NO₃, dust, solid wastes and noise. The aim is to limit and minimise natural expenses below the allowed values. Some ecological impacts, like noise and reduction of biodiversity, cannot be calculated, but must be considered separately during the decision-making process.

Safety and mechanical serviceability is guaranteed through traditional mechanical design with the use of statics and dynamics. Controlled technical serviceability throughout the target service life is guaranteed by durability design /9/. Health is protected through building physics including hygrothermal physical and chemical methods. The final choice between alternative structural ideas, materials and products can be made by applying the methods of multiple requirements decision-making.

The active reduction of wastes in construction and renovation is possible through designing for selective dismantling in renovation and for recycling of new structural systems, components and materials.

Currently, monetary and natural economies may stand in contradiction to each other because of e.g. differences in pricing and taxes between work and natural resources. Such instances lead to valuation problems, which must be resolved by the clients using their defined valuation within the framework of a society’s norms. Besides the calculated expenses are factors which cannot be numerically defined, such as the impact of construction on biodiversity and noise emissions. These must be evaluated and valued separately by society’s general rules for individual design cases.

Introducing integrated design principles into practical design is quite an extensive process. Not only is the work of structural engineers changing, but the form of their co-operation with other partners of construction and use will have to be developed — particularly if the structural engineers’ expertise is to be maximally effective at the decisive creative and conceptual phases of design. This kind of co-operation also helps clients realise the benefits of investing slightly more in the structural design.
2.4 Factors of sustainability

Much sustainability analysis and assessment work has been done during the last decade. In most cases life cycle methodology has been applied. The results of comparisons regarding all types of main sustainability requirements, generally speaking, lead to the conclusion that differences between different materials and structural solutions of the construction phase are quite small. On the contrary, quite large differences can be found between life cycle sustainability factors of existing entire buildings or other facilities. The differences are caused by differences in the basic factors of sustainability, which are flexibility in design, changeability during use, durability by comparison with the design service life, and the recyclability of components which have quite a short service life. In order to focus on these factors it is necessary take a separate look at the different types of facilities.

In buildings the energy consumption is economically important and dictates mostly the environmental properties in the life cycle, the differences in environmental economy between different structural systems being otherwise quite small. For this reason, besides well-controlled heating, ventilation and heat recovery, the thermal insulation of the envelope is important. The bearing frame is the most massive and long lasting part of the building, and the durability and flexibility in view of functional changes, spaces and service systems are very important. The envelope must be durable and, as mentioned above, have an effective thermal insulation and a safe static and hygrothermal behaviour. The internal walls have a more moderate length of service life, but they have a requirement of coping with relatively high degrees of change, and must therefore possess good changeability and recyclability. An additional property of an environmentally effective structural system is a good and flexible compatibility with the building service system, as the latter is the most frequently changed part of the building. 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.

Engineering structures like bridges, dams, towers, cooling towers etc. often are very massive and their target service life is long. Therefore environmental efficiency is tied to selection of environmentally friendly local raw materials, high durability and easy maintainability of the structures during use, minimising and recycling of construction wastes, and finally recycling of the components and materials after demolition. Some parts of the engineering structures like water proofing membranes and railings have a short or moderate service life and therefore the aspects of easy reassemble and recycling are most important.

All factors mentioned above are related to the properties connected to the function and performance of the facilities. We know that the decisive factor in our society is financial economy. The budget must always stay within the agreed limits and plays a major role when decisions between design alternatives are made.

Conclusively, the most important sustainability factors in performance for structures with long target service life can therefore generally be defined as flexibility towards functional changes of the facility and high durability, while in the case of the structures with moderate or short target service life changeability and recyclability are dominating. The competitiveness in sustainability between materials and structures
focuses on the question of which materials and structures are able to be produced, designed and manufactured with skill and at the same cost, for the best sustainability of the building facility.

2.5 Modular systematics in design
In advanced building we can apply so-called modular systematics /10/. Modulation involves division of the whole into sub-entities, which to a significant extent are compatible and independent. Compatibility makes it possible to use interchangeable products and designs that can be joined together according to connection rules to form a functional whole of the building or another structural system. Typical modules of a building are the bearing frame, facades, roofing system, partition walls and building service systems.

Modular product systematics is firmly tied to the performance systematics of the building. For example, the main performance requirements of floors can be classified as follows:
1. Mechanical requirements, including
   - static load bearing capacity,
   - serviceability behaviour: deflection limits, cracking limits and damping of vibrations
2. Physical requirements, including
   - air tightness
   - acoustics: airborne sound insulation, impact sound insulation, emission
   - moisture tightness (in wet parts of the floor)
   - thermal insulation between cold and warm spaces
   - fire resistance and fire insulation
3. Flexible compatibility with connecting structures and installations
   - partitions
   - services: piping, wiring, heating and ventilation installations
4. Other requirements: buildability, changeability during use, easy demolition, reuse, recycling and wasting.

2.6 Recycling aspects in design
The consumption of building materials can be considerably limited with effective recycling and use of by-products like blast furnace slag, fly ash and recycled concrete. The components of the environmental profile of the basic materials already include the recycling efficiency, which means the environmental expenses in recycling. It is important to realise that the recycling possibilities of building components, modules and even technical systems must be reconsidered in connection with design. The higher the hierarchical level of recycling, the higher also the ecological and economical efficiency of recycling /3, 7/.

3. Research needs
Concerning materials and structures, new basic knowledge will be needed especially regarding hygrothermal behaviour, durability and service life of materials and
structures in varying environments. Structural design methods will have to be
developed that are capable of life cycle design, multiple analysis decision-making and
optimisation. 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. The creation of
new types of materials and structures, in which the properties can be tailored separately
for each specific need, is of vital importance. Both strong and soft solutions must be
sought, depending on the specific life cycle requirements. New creative innovations for
applications of by-products and recycling materials from industry and general
consumption are still needed..

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