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Integrovaný environmentální návrh a optimalizace konstrukcí budov

Integrated environmental design and optimization of building structures

Summary

Integrated environmental design represents a new approach integrating material, structural and environmental aspects in one complex design and optimization process. This approach integrates material, component, and structure design and considers selected relevant criterions from a wide range of criterions sorted in four basic groups of sustainability: environmental, economic, technical and socio-cultural. The ultimate goal is the reduction of negative environmental impacts, while increasing the structure's serviceability, durability and reliability throughout its expected life. This should be achieved while keeping the cost on a reasonable (minimum) level and performance on a feasible (maximum) level.

The required balance in the consumption of natural materials can be achieved in the form of closed material cycles, based on recycling of wastes which originate from previous use. Using recycled municipal waste in construction it is possible to keep once used primary material in a many times longer life cycle, and therefore save natural sources.

The application of principles of integrated environmental design and optimization is shown on development of three types of RC floor slabs with fillers from recycled municipal waste plastics for the use in construction of buildings. The alternatives of floor structures have been proved by theoretical, as well as experimental and in situ results. The shape of fillers has been determined as a result of integrated environmental design and optimization, considering selected environmental, structural and economic criterions.

The in situ use of the two types of optimized RC slabs lightened by fillers from recycled waste plastics is presented and discussed. The LCA analysis and comparison with other standard types of RC floor structures have showed that using recycled waste materials and the optimized shape of fillers, it is possible to reduce environmental impacts such as consumption of non-renewable silicate materials, the resulting level of embodied CO_2, embodied SO_2 and embodied energy while the performance quality remains on a high level or is even higher (e.g. using installation fillers).

Souhrn

Integrovaný environmentální návrh představuje nový přístup v navrhování a optimalizaci konstrukcí, který integruje materiálové, konstrukční a environmentální aspekty do jednoho komplexního návrhového procesu. Takový komplexní návrhový proces se zabývá současně návrhem skladby materiálu, návrhem konstrukčních prvků a celé konstrukce a uvažuje odpovídající vybraná a relevantní kritéria ze široké škály kritérií udržitelného rozvoje: environmentální, ekonomická, technická a socio-kulturní kritéria. Rozhodujícím cílem je redukce negativních environmentálních dopadů při současném zvýšení užitných vlastností, trvanlivosti a spolehlivosti konstrukce v průběhu celé předpokládané existence. Dosažení těchto parametrů by mělo být podmíněno udržením ceny realizace na přijatelné (minimální) úrovni a funkčních parametrů na přiměřené (maximální) úrovni.

Požadovaná rovnováha v čerpání přírodních zdrojů materiálů může být dosažena ve formě uzavřených materiálových cyklů, založených na recyklaci odpadů, které pocházejí z předchozího využití. Zabudováním prvků z recyklovaných komunálních odpadů do stavebních konstrukcí lze dosáhnout udržení již jednou krátkodobě využitých primárních materiálových zdrojů v mnohokrát delším materiálovém cyklu stavební konstrukce. Tímto přístupem lze významně šetřit přírodní zdroje materiálů.

Na třech příkladech železobetonových stropních konstrukcí vylehčených vložkami z recyklovaného komunálního odpadu jsou ukázány principy environmentálního návrhu a optimalizace konstrukcí budov. Navržené alternativy stropních konstrukcí byly ověřeny v rámci teoretického a experimentálního výzkumu a následnými realizacemi ve stavební praxi. Tvar vložek je výsledkem integrovaného environmentálního návrhu a optimalizace při uvažování vybraných environmentálních, technických a ekonomických kritérií.

V práci jsou prezentovány a zhodnoceny dva příklady použití optimalizovaných železobetonových stropních desek vylehčených vložkami z recyklovaného odpadového plastu ve stavební praxi. Z hodnocení životního cyklu (LCA) a porovnání s jinými běžnými typy železobetonových stropů je zřejmé, že užitím recyklovaných odpadových materiálů a optimalizovaného tvaru vložek je možné dosáhnout snížení environmentálních dopadů jako je spotřeba neobnovitelných silikátových materiálů, množství emisí CO_2, SO_2 a svázaná spotřeba energie, přičemž funkční kvalita zůstává na vysoké úrovni nebo je dokonce vyšší (např. při použití instalačních vložek).

Keywords: integrated design, sustainable construction, environmental impact, optimization, LCA – life cycle assessment, recycled waste, embodied emissions, embodied energy

Klíčová slova: integrovaný návrh, environmentální dopady, optimalizace, LCA – hodnocení životního cyklu, recyklované odpady, svázané emise, svázaná energie

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Contents

1. Introduction

On the global scale, the construction industry and its products (buildings, bridges, dams, roads, etc.) consume a crucial amount of material and energy sources, and are responsible for a very significant portion of pollution by harmful and damaging emissions and wastes. It is estimated that the building industry and its products – buildings are in Europe responsible for approx. 40% of energy consumption, 30% of CO_2 emissions and 40% of the total waste. This proportion is going to be similar in other parts of the World. Essential is thus the need for minimization of negative impacts of construction on the environment including reduction of non-renewable natural resources consumption.

With respect to such a significant influence of the construction industry, the *sustainable construction* approach has a high potential to make a valuable contribution to the general target - sustainable development. In the global context sustainable development incorporates various issues: environmental quality, economic constraints, technical quality, and social equity and cultural issues. Consequently, based on these general issues, the following target demands on construction can be defined as: *reduction of environmental impact, minimization of cost, maximization of technical performance (serviceability, reliability, durability etc.)* and *improvement of social and cultural quality* throughout the whole life of the civil engineering structure.

The problem of sustainability of structures is thus a very complex issue and includes a large number of parameters and criterions from different areas of technical as well as non-technical sciences. Sustainable construction should be based on the effort to (i) decrease exhausting of primary raw materials and energy, (ii) regulate consumption of renewable resources, (iii) decrease the amount of harmful emissions and wastes, while (iv) increasing the structure's serviceability, durability and reliability throughout its entire life. These goals should be achieved while keeping the total cost at a reasonable (minimum) level and social and cultural aspects in a feasible (maximum) quality. The complex optimization problem can be expressed in a multiobjective form:

$$\textit{sustainable construction}: f\,(\min \mathbf{E}_{tot}, \min \mathbf{C}_{tot}, \max \mathbf{T}_{tot}, \max \mathbf{S}_{tot}) \qquad (1)$$

where $\mathbf{E}_{tot}$ is the total environmental impact, $\mathbf{C}_{tot}$ is the total cost, $\mathbf{T}_{tot}$ is total technical performance and $\mathbf{S}_{tot}$ is the total social and cultural quality.

The first objective component - environmental impact - has a crucial importance. However, it is not often considered in the general design approach. A complex optimization of material and energy flows within the whole life cycle of the structure should become a necessary part of the quality design approach and should become the basic criterion for the evaluation of its sustainability.

2. Context and Principles

The goal and scope of environmental impact evaluation and optimization shall be consistent with the intended application in the design process. The recognition level of the evaluation and optimization model should be sufficiently well defined to ensure that the results of the study are compatible, relevant and sufficient to address the pre-defined goals.

The global character of the problem, significant by the complexity of relations among the elements of the analyzed system, requires consideration of its multicriterial character. The use of multicriterion evaluation methodology and multicriterion optimization techniques, respecting the significance of the system's interrelationships, is thus essential and necessary.

The evaluation and optimization methodologies have to be complex, considering all the relevant flows (material, energy and other), and thus covering the corresponding essential environmental criteria. However, the admissible simplifications of the model are usually needed.

Taking into account the relatively high variance of available environmental data used in environmental impact evaluation and optimization, the implementation of the stochastic approach, including sensitivity and reliability analysis can be suitable and/or even necessary.

The evaluation and optimization methods and models should be preferably based on the following characteristics and essential qualities:

- complexity – the methods and models should be complex and should cover the most important environmental criterions; a multicriterion approach incorporating the weighting method and corresponding sensitivity analysis is in many cases desirable or necessary,

- time dependency – the methods and models should consider the whole life (from "cradle to grave") of a product (element, structure, etc.). The typical life

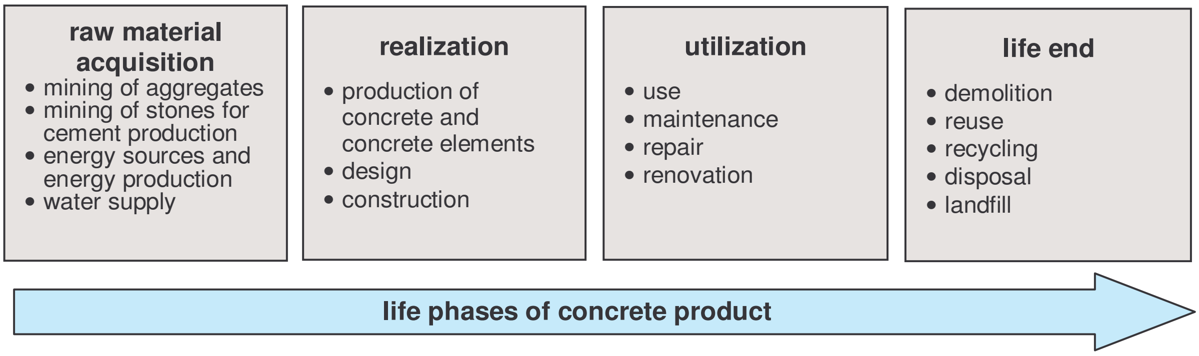

Fig. 1 *Life cycle of a concrete structure with essential life stages*

cycle of a structural element should cover the following stages: raw material acquisition, production of structural components, design and construction, operation and maintenance, repair, renovation, demolition, recycling and waste disposal (Fig. 1).

• probability - the evaluation methods and models should respect the probability feature of the time dependent problem; the implementation of stochastic approaches including reliability analysis is valuable and/or necessary.

The structure performance quality throughout its life is essentially determined in the initial conceptual design stage. Correspondingly the best opportunity to influence the total value of the environmental impact of the structure arises in the initial phase of the structural design – in the conceptual design stage (Fig. 2). The second opportunity comes at the beginning of the construction phase – when the technology concept is being adjusted and detailed.

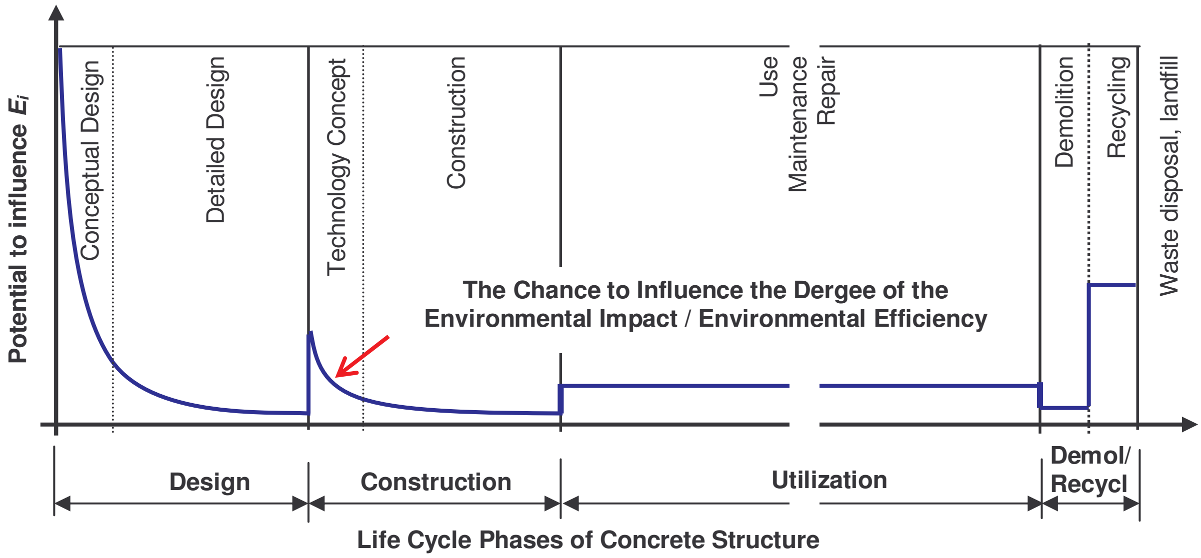

Fig. 2 *The potential chance to influence the degree of the environmental impact throughout the life of the building*

The level of environmental impact of a building structure in the utilization phase is strongly pre-determined by the design and construction concepts and can be influenced, during the utilization phase, only to a relatively small extent – particularly during maintenance or repair of a building structure. There is a relatively high chance to influence the degree of the environmental impact at the very end of the life cycle – in the recycling phase – when elements, parts and materials can be converted and prepared for the new use in another material cycle.

Considering the above described features of the life cycle, it is extremely important to concentrate the optimization efforts on the starting conceptual steps of both the design and construction phases.

3. Evaluation Criteria and Data

A varying number of various behaviour aspects and parameters of a building structure have to be considered when the design, optimization and evaluation respecting environmental issues are carried out. In general, the parameters can have both technical and non-technical features, respectively.

The important environmental aspects are: (i) non-renewable raw materials exhaustion, (ii) non-renewable energy sources exhaustion, (iii) non-controlled water consumption and contamination, (iv) renewable resources use at a rate faster than their regeneration ability, (v) harmful emissions, (vi) harmful waste, (vii) nuisance and health risk, (viii) durability, (ix) repairability, (x) reuseability and (xi) recycleability.

The main environmental impact categories essential and frequently used for evaluation of environmental performance of structures and corresponding criteria are listed in Table 1. However, also other environmental criteria can be important in specific evaluation tasks of building structures.

Tab. 1 *Environmental impact categories*

impact category	**criteria**	**impact level**
GWP – global warming potential	greenhouse gas emissions, mainly CO_2	global
ODP – ozone depletion potential	HCFC emissions	global
AP – acidification potential	SO_2 emissions	regional
EP – eutrophication potential	PO_4^{3-} equivalent	regional
water use and contamination	water consumption	regional
raw material depletion	non-renewable material and energy sources depletion	global and regional
waste disposal	disposal of non-recyclable and hazardous waste	regional and global
air pollution	POCP potential	regional and global
toxicity of indoor and outdoor environment		local
land use	use of natural land, built area	local, regional

4. Environmental Impact Evaluation and Optimization

4.1 Methodology

Environmental impact evaluation is an essential part of Life Cycle Assessment (LCA). The general methodology of LCA is defined in the International Standard ISO 14040:1997 Environmental management – Life cycle assessment – Principles and framework and in the complementary International Standards ISO 14041, ISO 14042 and ISO 14043 concerning various phases of LCA. The LCA includes a technique for assessing environmental aspects and potential impacts associated with existence of a product – a building or another civil engineering structure. With respect to the general principles of LCA, environmentally based optimization represents a process targeting the reduction of negative environmental impact of products – civil engineering structures and should cover their entire life.

The goal and scope of environmental impact evaluation and optimization shall be consistent with the intended application in the design process. The recognition level of the evaluation and optimization model should be sufficiently well defined to ensure that the results of the study are compatible, relevant and sufficient to address the pre-defined goals.

The global character of the problem and complexity of relations among the elements of the analyzed system require the use of multicriterion evaluation methodology and optimization techniques, which respect the significance of the system's interrelationships.

4.2 Environment-Based System Model

Building structures are in general composed of a huge number of structural parts and elements. The elements are connected in joints and bonds, and the whole structure exists in the state of interaction with the surrounding environment. The definition and solution of the exact model is practically impossible, and it is necessary to search for an acceptable approximation in the form of the *simplified environmentally based system model*.

The process of creating the simplified environmentally based structural model covers:

- *decomposition* of the system into subsystems or elements with a definition of mutual interfaces;
- *detachment* of subsystems or elements with an admissible low mutual influence (only in cases where it is relevant to consider independent behaviour from the viewpoint of environmental impact);

- *selection* of parameters and criterions essential for environmental impact assessment.

All elements of the system are characterized by a set of parameters that are more or less important for the specific behaviour assessment. Using a homogenization process, it is possible to define a simplified, environmentally based system model on a reasonable recognition level, covering the most important environmental criterions. Various parameters of a structure (technical as well as non-technical features) can be significant for the evaluation of its sustainability within the specific target behaviour (e.g., cost, self-weight, thermal resistance, acoustic characteristics, cultural aspects, etc.), Fig. 3.

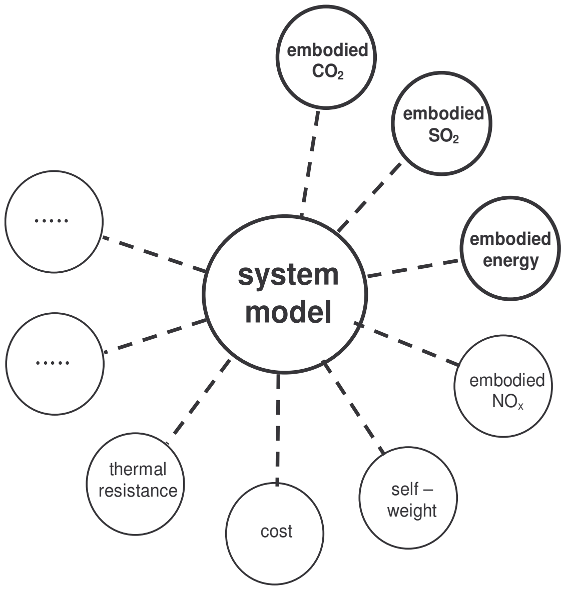

Fig. 3 *Environmentally based system model*

4.3 Principles of Environmental Impact Evaluation

4.3.1 Life Cycle Concept

The total environmental impact of a building structure should be considered throughout its entire life, from raw material acquisition, through production, use and disposal. A characteristic life cycle of a concrete structure with its typical material and energy flows and consequent environmental impacts is presented in Fig. 4. It is essential that the goal of optimization efforts should be to keep structural materials in the closed material cycle (the gray area) as long as possible and to minimize inputs (non-renewable material and energy sources) and outputs (negative environmental impacts – emissions, nuisance, and wastes). The high importance of maintenance and repair processes, which can increase the durability of a building structure, is thus evident. Equally, the significance of renovation and recycling phases on the total environmental impact of a building structure is considerable.

The environmental impact of the entire structure can be expressed in two principal forms:

- environmental profile – environmental profile is composed of a set of values of different criterions
- environmental impact expressed by a single characteristic value (weighted sum of values of different criterions)

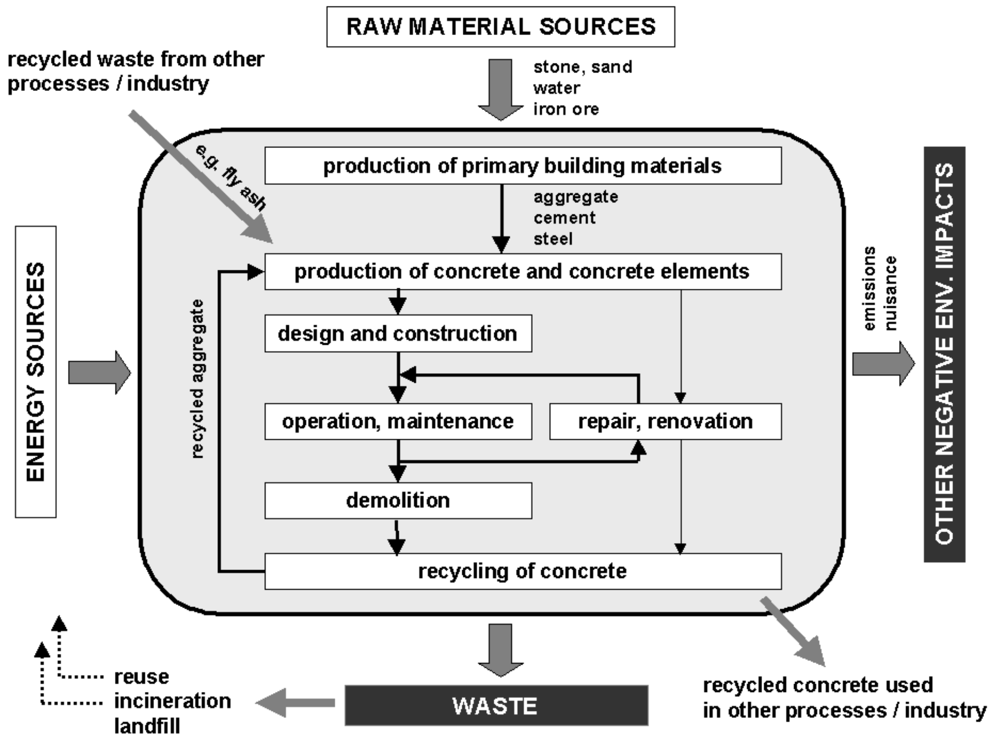

Fig. 4 *Life cycle of concrete structure – material and energy flows and consequent environmental impacts*

Taking into account the whole life cycle of a building structure, the environmental impact associated with a particular criterion can be expressed as a sum of partial environmental impacts $\mathbf{E}_i$ as follows:

$$\mathbf{E}_{tot} = \sum \mathbf{E}_i \quad . \qquad (2)$$

The value of environmental impact of the product and/or process can be expressed as an environmental cost – eco-cost or in normalized numbers of points.

For most cases of concrete structures the general equation can be expressed in this more detailed form as:

$$\mathbf{E}_{tot} = \mathbf{E}_{ini} + \mathbf{E}_{oper} + \mathbf{E}_m + \sum \mathbf{E}_{repair} + \sum \mathbf{E}_{renov} + \mathbf{E}_{demol} + \mathbf{E}_{recycl} \;, \qquad (3)$$

where $\mathbf{E}_{ini}$ represents the initial environmental impact covering production, design and construction phases defined as

$$\mathbf{E}_{ini} = \mathbf{E}_{pbm} + \mathbf{E}_{pc} + \mathbf{E}_{constr} \quad . \tag{4}$$

Specific environmental impacts within definite life-cycle steps include:
$\mathbf{E}_{oper}$ ... environmental impact associated with operation of the structure,
$\mathbf{E}_{m}$ environmental impact associated with the maintenance,
$\mathbf{E}_{repair}$ ... environmental impact associated with the repair of the failure,
$\mathbf{E}_{renov}$ ... environmental impact associated with renovation,
$\mathbf{E}_{demol}$ ... environmental impact associated with demolition,
$\mathbf{E}_{recycl}$ ... environmental impact associated with recycling and waste disposal,
$\mathbf{E}_{pbm}$ ... environmental impact associated with the production of primary building materials,
$\mathbf{E}_{pc}$ .. environmental impact associated with the production of elements,
$\mathbf{E}_{constr}$ environmental impact associated with the design and construction of the structure.

Partial environmental impact $\mathbf{E}_i$, related to a particular step of the life cycle should incorporate the entire environmental damage, which corresponds to all the essential environmental criterions:

$$\mathbf{E}_i = \sum w_j \; Q_j \,, \tag{5}$$

where $\{w_j\} = (w_1 \ldots w_m)^{\mathrm{T}}$ is the vector of weighting coefficients representing the importance of the individual criteria, m is the number of the essential environmental criteria and $\{Q_j\} = (Q_1 \ldots Q_m)^{\mathrm{T}}$ is the vector of the embodied values of the environmental criteria.

Considering the particular environmental criteria, the environmental impact in each phase of the life cycle can be written in the form:

$$\mathbf{E}_i = w_1 Q_{CO2} + w_2 Q_{SO2} + w_3 Q_{en} + \ldots + w_m Q_m \,, \tag{6}$$

where Q_{CO2}, Q_{SO2} and Q_{en} are values of embodied CO_2, SO_2 and energy, respectively.

This equation should be determined for every particular phase of the life cycle in order to analyze environmental impact of the structure within the entire life cycle.

Applying the weighting statement (5) makes it possible to rewrite the general equation for evaluation of the total environmental impact (2) as

$$\mathbf{E}_{tot} = \sum \sum w_j \, Q_j \quad . \tag{7}$$

In some cases the independent evaluation of the environmental impact of the single criterion can be important and useful:

$$\mathbf{E}_i = Q_{CO2} \quad \text{… for Life Cycle } CO_2 \text{ (LCCO2) evaluation,} \tag{8}$$

$$\mathbf{E}_i = Q_{en} \quad \text{… for Life Cycle Energy (LCE) evaluation} \tag{9}$$

4.3.2 Probability of Environmental Impact

The evaluation methods should consider the random character of the time dependent problem. The implementation of a stochastic approach including reliability analysis is in many cases valuable and/or needed. Pre-setting various probable life-cycle strategies is one of the useful approaches.

Risk of environmental damage caused by a product and/or process can be commonly expressed as

$$\mathrm{R} = p\ C_{env}\ , \tag{10}$$

where p is the probability of environmental damage caused by particular impact and C_{env} is the corresponding environmental damage.

With respect to the probability of the environmental impact caused in individual phases of the life cycle of the structure, the total environmental impact can be expressed as follows:

$$\mathbf{E}_{tot} = \sum p_i\ \mathbf{E}_i \tag{11}$$

For most concrete structures the equation (11) can be rewritten into the form:

$$\mathbf{E}_{tot} = \mathbf{E}_{ini} + \mathbf{E}_{oper} + \mathbf{E}_m + \sum p_f\ \mathbf{E}_{repair} + \sum p_{renov} \mathbf{E}_{renov} + \mathbf{E}_{demol} + \mathbf{E}_{recycl}, \tag{12}$$

where p_f is the failure probability and p_{mod} is the probability of modernization/reconstruction.

Using the weighting expression (5) we finally arise at the following general equation for evaluation of the total environmental impact (11)

$$\mathbf{E}_{tot} = \sum p_i \sum w_j\, Q_j\ \ . \tag{13}$$

The environmental impact evaluation of building structures is in some modifications included in several computer program packages, e.g. the GB Tool, BREEAM, ECOTECH, BEES, Eco-Quantum, and similar other computer codes, respectively.

4.4 Concept of Environmental-Based Optimization

Environmentally based optimization is a process targeting the reduction of negative environmental impact. In general, environmentally based optimization of structures is dependent on many different criterions: physical, chemical, biological, economic and others. The complex formulation of this multicriterion and muliparametric problem is, anyhow, very complicated.

The complex optimization model of the building structure can be simplified by splitting it into three optimization steps:

- 1st step: material optimization,
- 2nd step: shape optimization,
- 3rd step: life cycle optimization.

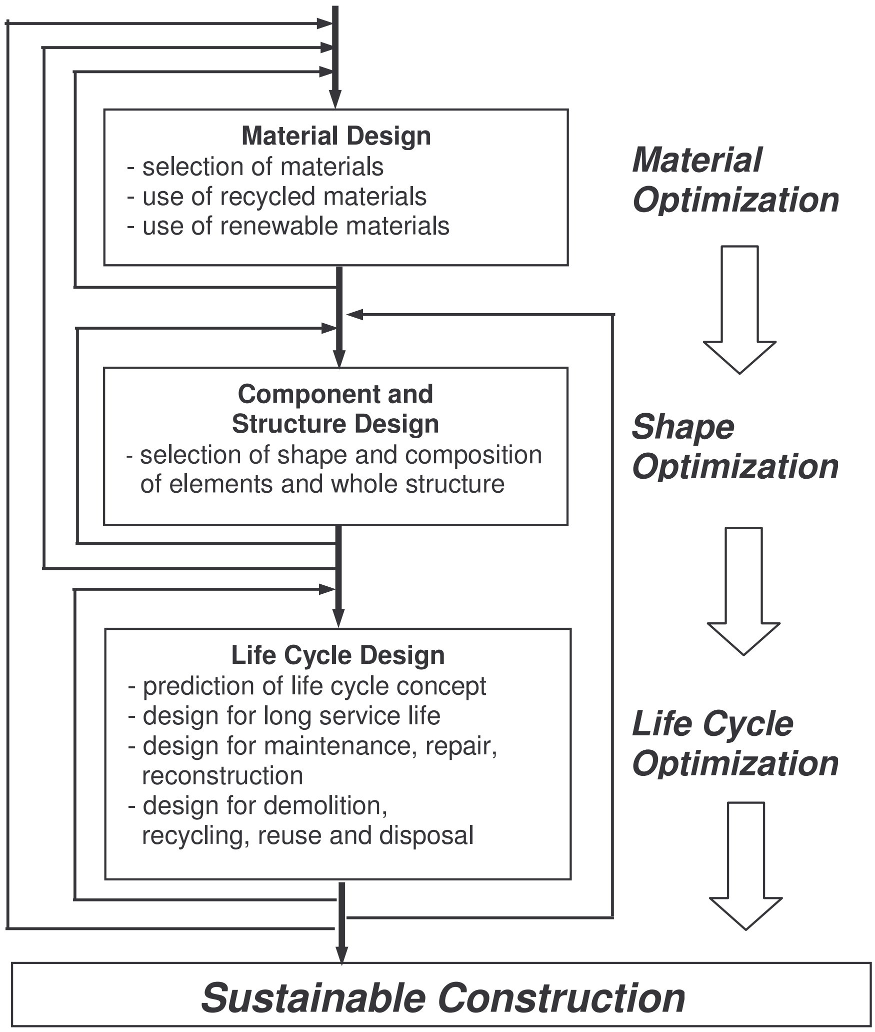

Fig. 5 *Concept of Environment Based Optimization*

The optimization process has a complex and iterative character and should thus cover all relevant interactions and repeated iterations within all the above specified optimization steps. The basic concept of the environment-based optimization of a concrete structure is displayed in the flow chart in Fig. 5.

Formulation of Environment-Based Optimization

Minimization of the negative environmental impact can be formulated as follows:

$$\min \mathbf{E}_{tot} (\{x_k\}) \quad \text{such that} \quad \beta > \beta_0 \tag{14}$$

where $\mathbf{E}_{tot}$ is the total environmental impact (it can be expressed as eco-cost), β is reliability of the structure and β_0 is the value of design reliability, and $\{x_k\}= (x_1 \ldots x_p)^{\mathrm{T}}$ is the vector of design variables.

The objective function E_{tot} is, in general a multicriterion function and can be derived from equations specified in chapter 4.3.

The independent single-criterion optimization using formulations like: min Q_{CO2} ($\{x_k\}$), min Q_{SO2} ($\{x_k\}$), min Q_{em} ($\{x_k\}$), or other can be in some specific target studies valuable and effective.

The optimization process according to the general flow chart shown in Fig. 5 may be performed using common models for environmental impact evaluation in successive iterative steps. This discrete optimization approach is in many cases effective – especially when feasible structural alternatives are varying in a significant manner.

4.5 Weighting and Sensitivity Analysis

The evaluation of multicriterion assessment can be performed by determining the environmental profile (a set of values of different criterions) or by the use of the weighting approach. The determination of weighting vector $\{w_j\}$ representing significance of particular criterions is very complex and should cover specific conditions, boundary constraints and preferences associated with the particular case. However, this process is very often subjective due to a variety of criterions with different characteristic features (the problem of "mixing apples and oranges"). The quality and reliability of evaluation results is highly dependent on the quality of determination of weighting coefficients. Sensitivity analysis of the multicriterion problem could be thus essential.

Usually it is necessary to set specific weighting coefficients for different countries and/or regions, because natural, climatic and industrial conditions and the resulting preferences of environmental criteria can be significantly different and each country can have different environmental targets in their government policy. It is possible to work with weighting coefficients decided at the national level, regional level or local level (within a group of the concerned people - experts).

The sensitivity analysis of the weighting coefficients is one of the approaches that can help the designer to decrease a level of subjectivity in the decision process based on multicriterion assessment. Nevertheless, it cannot rule out the risk of the assessment conflict due to impropriate weighting of different criterions. However, the results of the sensitivity analysis can significantly support the quality of the final decision.

It is recommended to reduce the number of environmental aspects to be weighted in order to keep the specific evaluation task in manageable and transparent form. The recommended number of the weighted aspects in one group is about 4 to 7. This requires sorting of criterions into groups – Categories and/or Issues groups. In some cases the number of the weighted aspects can be reduced using aggregated indicators obtained by the following transformation: one environmental aggregated indicator covers more particular criterions (e.g., environmental aspect: GWP, aggregated indicator: CO_2 equivalent, criterions: CO_2 emission, CH_4 emission, N_2O emission, etc.).

The weighting coefficients can be determined using different weighting approaches and methods such as the EPS method (Environmental Priority Strategies in Product Design), the Panel method (Expert-based determination of weighting factors), the NEL method (No-Effect Level method), the Combined Panel-NEL method, etc.

The dominant weighting method represents a weighting method with the implemented sensitivity analysis. The method is based on the sequential increasing or decreasing of the pre-determined weights (e.g. using the panel method) by means of multiplication by the factor of dominance. This is done by the step by step procedure for all the environmental impacts considered in the evaluation process. The sensitivity analysis using dominant weighting simulation can be used as a tool for decreasing of a level of subjectivity and increasing validity and reliability of final assessment in the decision process based on multicriterion assessment.

4.6 Multicriterion Assessment and Sensitivity Analysis Using Dominant Weighting Method

A multicriterion assessment model MSA was developed as a tool for a relative comparison of several structural alternatives using more evaluation criterions. The *dominant weighting method* used for sensitivity analysis represents an essential part of this model. The method is based on a sequential step by step increasing or decreasing of weights of particular criterions by means of multiplication by *factor of dominance D*. Although numbers of structural alternatives and criterions are in general unlimited their selection should respect the efficiency of the assessment or optimization process in the current task.

Structural alternatives are characterized by values of particular evaluation criterions. These values can be ordered into a matrix $[c_{ij}]$ (size m x n), where the number of rows is equal to the number of structural alternatives m and the number of columns corresponds to the number of particular evaluation criterions n. The matrix of criterion values can be written in the form

$$[c_{ij}] = [\{c_{i1}\}, \{c_{i2}\} \dots . \{c_{in}\}] , \qquad (15)$$

where $\{c_{ij}\}$, $i = 1 \dots m$ is the column vector with m values of j-th criterion associated with the corresponding structural alternatives 1 ... m.

The column vectors of matrix (15) representing the respective j-th criterion (j = 1 ... n) can be conducted in a calibrated form with respect to the *best values* (≈ recommended or required values) using transformation

$$\{c_{cal,ij}\} = \{c_{ij}\}/B_{Vj} \quad , \quad \text{for } i = 1 \dots m \text{ , fix } j \text{ ,} \qquad (16)$$

where B_{Vj} is the *best value* of the corresponding j-th criterion.

The elements of calibrated matrix $[c_{cal,ij}]$ express the relative values of particular criterions related to the theoretically best case represented by the $c_{cal,ij}$ value equal to 1.

A multicriterion characteristic value of a particular structural alternative is defined as a sum of calibrated values of the matrix entries multiplied by the corresponding weighting coefficients as follows

$$V_{char,i} = \sum_{j=1}^{n} c_{cal,ij} w_j \quad \text{, where} \quad \sum_{j=1}^{n} w_j = 1 \qquad (17)$$

The resulting level of environmental impact (and/or environmental quality) of a particular structural alternative follows from the comparison of the corresponding characteristic values. It is evident that the reliability of such a multicriterion assessment result is dependent on the quality of determination of both the weighting coefficients wj and best values B_{Vj} associated with the corresponding criterions.

Characteristic values of specific structural alternatives V_{char} considering particular dominant states can be obtained by multiplication of the calibrated criterion matrix $[c_{cal,ij}]$ by the matrix of dominant weights $[w_{d,jk}]$

$$[V_{char,ik}] = [c_{cal,ij}]\,[w_{d,jk}]\ , \tag{18}$$

where $[w_{d,jk}] = [\{w_{d,j1}\}, \{w_{d,j2}\} \ldots\ \{w_{d,jn}\}]$ and $\{w_{d,jk}\}$, $j = 1 \ldots n,$ is a vector of dominant weights related to the k-th dominant state of the corresponding criterion.

Elements of column vectors of the matrix of dominant weights should satisfy the condition $\sum w_{d,jk} = 1$ (k is fixed). Thus, the following transformation of weights is applied

$$w_{d,jk} = \frac{w_j d_{jk}}{1 + (D_k - 1) w_k} \tag{19}$$

for $j = 1 \ldots n$ and $k = 1 \ldots n$

where D_k are dominant factors of the corresponding criteria and d_{jk} are elements of the matrix of dominant factors in the form

$$[d_{jk}] = \begin{bmatrix} D_1 & 1 & \cdots & 1 \\ 1 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 1 \\ 1 & \cdots & 1 & D_n \end{bmatrix} \tag{20}$$

The resulting characteristic values $V_{char,ik}$ express relative values related to the theoretically best case represented by the value equal to 1. The smaller is the absolute value of difference $|V_{char,ik} - 1|$, the better is the corresponding alternative.

The model can be used for simulation of different dominant states, including super-dominant state $D >> 1$ or sub-dominant state $D << 1$ in which weights of particular criterions are sequentially increased or decreased in a significant manner.

A computer program, MSA 02, (Multicriterion and Sensitivity Analysis) for relative multicriterion assessment and sensitivity analysis has been developed based on the described theory. The graphic presentation of both the multicriterion assessment and dominant weighting results is expressed in the form of net-graphics (Fig. 6).

The left graph in the figure represents the relative comparison of five independent criterions (relative cost, embodied CO_2, embodied SO_2, embodied energy and self-weight) and the right graph shows results of the sensitivity analysis using the dominant weighting method.

MSA 02 MULTCRITERION ASSESSMENT AND SENSITIVITY ANALYSIS © Petr Hájek 2002

Criterions
(Number of criterons n = 5)

	Criterion	Dominance factor vector d	Weighting vector w
1	relative cost	3	0,25
2	embodied CO2	4	0,30
3	embodied SO2	4	0,25
4	embodied energy	4	0,15
5	self weight	2	0,05
	sum of weights		1,00

Matrix of Dominant Factors (n x n)

3	1	1	1	1
1	4	1	1	1
1	1	4	1	1
1	1	1	4	1
1	1	1	1	2

Extended Matrix of Dominant Weights (n x n+1)

11111	D1111	1D111	11D11	111D1	1111D
0,25	0,50	0,13	0,14	0,17	0,24
0,30	0,20	0,63	0,17	0,21	0,29
0,25	0,17	0,13	0,57	0,17	0,24
0,15	0,10	0,08	0,09	0,41	0,14
0,05	0,03	0,03	0,03	0,03	0,10
1,00	1,00	1,00	1,00	1,00	1,00

Alternatives of evaluated subject
(Number of alternatives m = 6)

- A RC slab
- B RC ribbed slab with hollow ceramic brick fillers
- C RC hollow core panels
- D Lightweight concrete panels
- E Composite steel+concrete slab
- F Composite RC "filigran slab with fillers from recycled plastics
- *best values*

Matrix of Criterion Values (m x n)

	1	2	3	4	5
A	34	65	0,24	470	440
B	38	57	0,22	550	290
C	32	53	0,20	410	320
D	62	77	0,25	770	170
E	52	53	0,24	560	175
F	41	51	0,19	410	340
Bv	30	40	0,15	350	250

Calibrated Matrix of Criterion Values (m x n)

	1	2	3	4	5
A	1,14	1,63	1,60	1,34	1,76
B	1,26	1,43	1,47	1,57	1,16
C	1,06	1,33	1,31	1,17	1,28
D	2,06	1,93	1,67	2,20	0,68
E	1,73	1,33	1,60	1,60	0,70
F	1,37	1,28	1,27	1,17	1,36

Extended Matrix of Dominant Characteristic Values

	11111	D1111	1D111	11D11	111D1	1111D
A	1,46	1,35	1,54	1,52	1,42	1,48
B	1,40	1,36	1,41	1,43	1,46	1,39
C	1,23	1,17	1,27	1,26	1,21	1,23
D	1,88	1,94	1,90	1,79	1,98	1,82
E	1,51	1,58	1,42	1,55	1,54	1,47
F	1,28	1,31	1,28	1,28	1,25	1,29

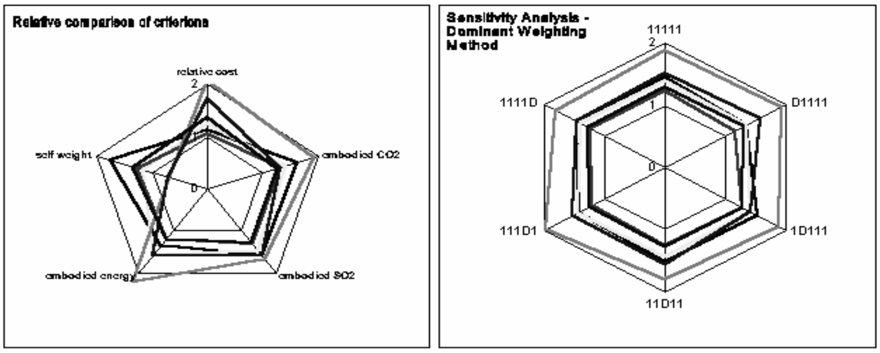

Fig. 6 *Example of output from programme MSA 02 used for multicriterion assessment and comparison of six structural alternatives of floor slabs and five criterions.*

5. Framework of Integrated Environmental Design and Optimization

Integrated design is a new approach implementing relevant and significant criterions into one single design process. This approach integrates material, component, and structure design and considers selected relevant criterions from a wide range of criterions sorted in four basic groups of sustainability: environmental, economic, technical and socio-cultural.

The target instruments have a multicriterial nature and involve many different criterions like functional quality, costs, environmental impact, durability, reliability and others. The decisive methodological approaches of integrated design include multicriterial optimization of function parameters, and sensitivity and risk analysis. The requirement that behaviour should be predicted for the whole life cycle leads to application of the probability approach.

The new conceptual 3D model of an integrated design, representing time dependent multi-parametric design has been proposed by Hajek (2004) and its application to concrete structure design is being developed within the work of fib Commission C3 – Task Group C3.7 Integrated Life Cycle Assessment of Concrete Structure. This approach considers:

- different performance criteria (environmental, economic, technical quality and socio-cultural criteria)
- sequential life phases of the structure throughout the entire life cycle
- various definition (recognition) levels (material, components, building, surrounding)

The principle of the three dimensional complex model is shown in Fig. 7. The horizontal x-axis shows the selected groups of performance criterions, the horizontal y-axis shows the life cycle phases and the vertical z-axis shows different definition levels.

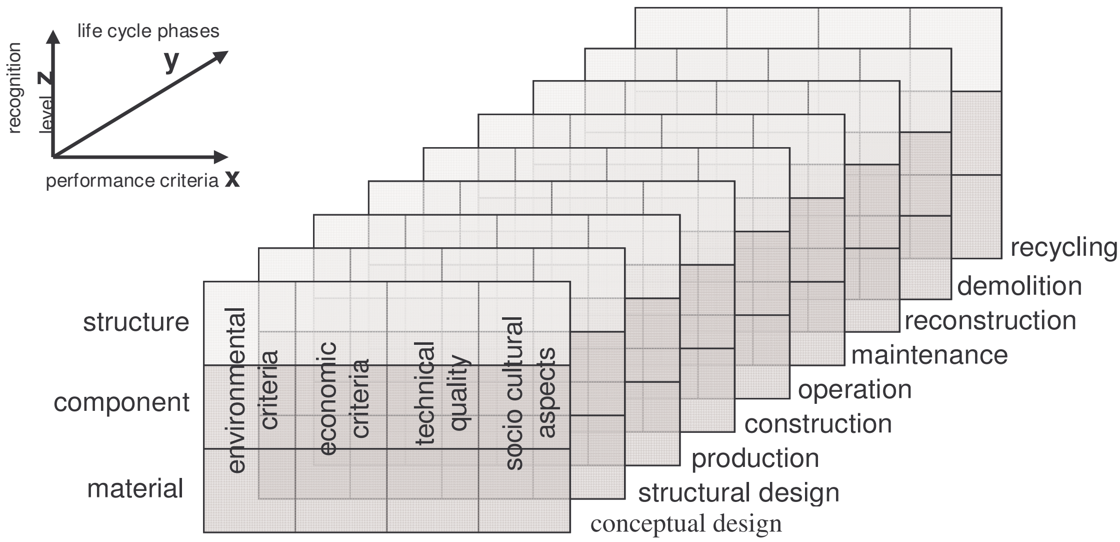

Fig. 7 *Conceptual 3D model of integrated design*

Life Cycle Phases Integration (y – axis): The conceptual model for integrated life cycle design is based on LCA principles (according to EN ISO 14040). The total impact value I_{tot} associated with a specific criterion can be expressed as a sum of partial impacts I_i as follows

$$I_{tot} = \sum I_i \tag{21}$$

where I_{tot} represents the total impact of a criterion within the life cycle and I_i is a partial impact corresponding to a particular life phase.

Performance criterions integration (x – axis) is based on a complex consideration of a set of relevant and significant criterions. This needs application of multiparametric assessment tools usually based on the weighting procedure.

$$I_i = \sum w_j \; Q_j \qquad (22)$$

where $\{w_j\} = (w_1 \ldots w_m)^T$ is the vector of weights representing importance of individual criteria, m is the number of essential criteria and $\{Q_j\} = (Q_1 \ldots Q_m)^T$ is the vector of embodied values of criteria.

The assessment and/or optimization process on one definition level can be formalized by following equation:

$$I_{tot}^{R} = \sum\sum w_j \; Q_j \qquad (23)$$

The definition (recognition) levels integration (z – axis) is based on parallel application of multicriterion LCA design tools to corresponding definition levels. The permanent interaction in the interface between parallel levels is considered. The complex 3D model can be expressed by the formal scheme shown in Fig. 8.

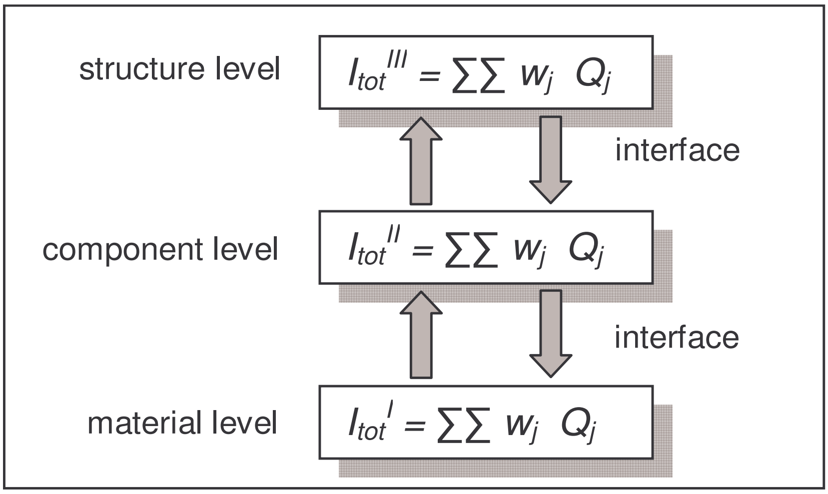

Fig. 8 *Scheme representing complex 3D analysis procedure on integrated design model*

6. Integrated Environmental Design of Concrete Slabs – Application in Practice

The application of principles of the integrated environmental design and optimization is shown on development of the three types of RC floor slabs with fillers from recycled waste plastics for the use in the construction of buildings.

6.1 Process of Design and Optimization

Material level

One of the basic principles of sustainable development is a need for significant reduction of primary non-renewable materials. The required balance in the consumption of natural materials can be searched in the form of closed material cycles, based on recycling of wastes which originate from previous cycles. There is a high potential for the use of secondary materials obtained from recycling of waste generated by other industrial processes and from municipal waste.

Most plastic waste is still a part of mixed municipal waste incinerated with all consequential negative environmental impacts. However, separated plastic municipal waste (collected in yellow collecting containers) can be recycled in a relatively simple way. The pre-sorted plastic waste is processed by crushing and grinding and the resulting fractions then serve for preparation of mixtures in proportions ensuring good workability guarantying high quality of products. The mixture is subsequently homogenized, melted and squeezed into iron moulds where products receive their final shape. Elaborateness and energetic demands are not high. Processing of 1kg of plastic material needs only approximately 0.6 kW of electric energy. There are no danger environmental outputs from production - no hazardous waste material, waste water or harmful emissions of such a kind as to endanger the surrounding environment.

Both the developed alternatives of RC floor slabs utilized shell lightening filler elements from recycled non sorted plastics from municipal waste. The possibility of the production of filler elements has been proved by experimental production of fillers in the recycling company Transform Lazne Bohdanec in 1999 – 2000.

Component level

The shapes of fillers were determined as a result of integrated environmental design and optimization considering environmental criterions as well as structural parameters of the resulting composite structure. The optimized shapes of both alternatives are shown in Fig. 9. The initial optimization steps, covering the use of the ribbed or waffle shape and use of recycled materials, resulted in the reduction of embodied values (CO_2, SO_2, energy). The cut in consumption of natural (non-renewable) sources (limestone, granite, oil, etc.) is evident. The integrated performance approach is also presented by light shell elements from recycled waste plastics which create installation space for wiring and other building services inside "filigran" composite RC slabs.

Structure level

Three types of optimized RC composite slabs lightened by the above described two types of fillers from recycled waste plastics have been developed and used in practice. The first practical application was construction of the Senior Centre in Moravany in 2000, where RC floor slabs with installation shell fillers were used. The second in situ application was reconstruction of the floor structure in the two storey factory hall in 2004. The third application is development of prefab panels with installation fillers from recycled waste plastics.

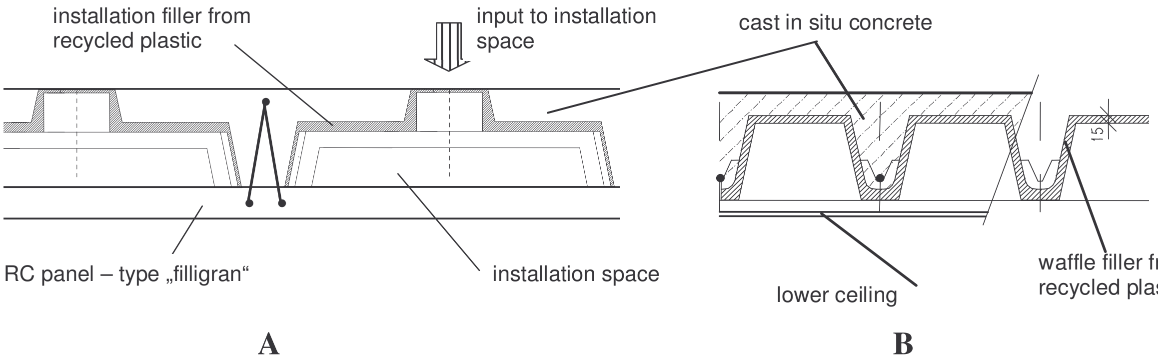

Fig. 9 *Two types of optimized RC floor structures with lightening fillers from recycled waste plastics – A – composite RC floor slab with installation shell fillers; B - RC waffle structure with permanent shell fillers*

6.2 Construction of Senior Centre in Moravany

The experimental production of installation shell fillers from recycled waste plastics sorted from municipal waste started in spring 2000 in the recycling company TRANSORM Lazne Bohdanec. These installation fillers were used within the construction of the two storey building of the Senior Centre in Moravany near Pardubice in the Czech Republic.

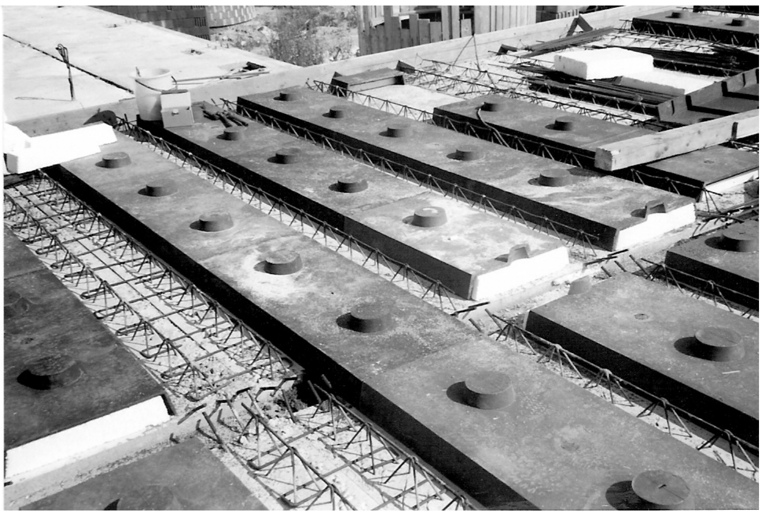

Fig. 10 *Construction of Senior Centre Moravany - composition of installation shell elements on filligran precast panels*

The original design of the floor structure employed a composite RC slab. The use of shell installation fillers resulted in the reduction of concrete consumption up to 0.08 m^3 per m^2 , i.e. 34%. The self weight of the floor structure was reduced about 2.0 kN/m^2. The installation space inside the floor structure was used for the wiring and for the heating system in plastic tubes. This brought additional cost savings compared to the originally assumed installation system placed in upper layers of flooring.

6.3 Reconstruction of the Floor Structure in the two Storey Factory Hall

The reconstruction of the two storey RC factory hall in Skoda Factory, Mlada Boleslav into a storage hall required an increase of the load bearing capacity of the intermediate floor structure so that the new structure would facilitate a new function with a higher live load of 5 kN/m^2. The existing cast-in-place RC slab with a thickness of 120 mm did not meet such requirements; moreover, there were a lot of openings unsuitable for the new way of use. The removal of the inconvenient RC floor slab was, due to the time limits, technological demands and total costs, unfavorable. In principle this alternative would represent almost complete demolition of the existing structure. The optimization analysis showed that construction of a new load bearing floor structure dimensioned to the required load and covering the old openings would be a more favorable solution.

With respect to the limited load bearing capacity of the existing vertical load bearing RC structure, the originally expected alternative (solid full RC slab) would require strengthening of RC columns and footings. Thus, a specific solution was requested to lighten the floor slab compared to a solid one.

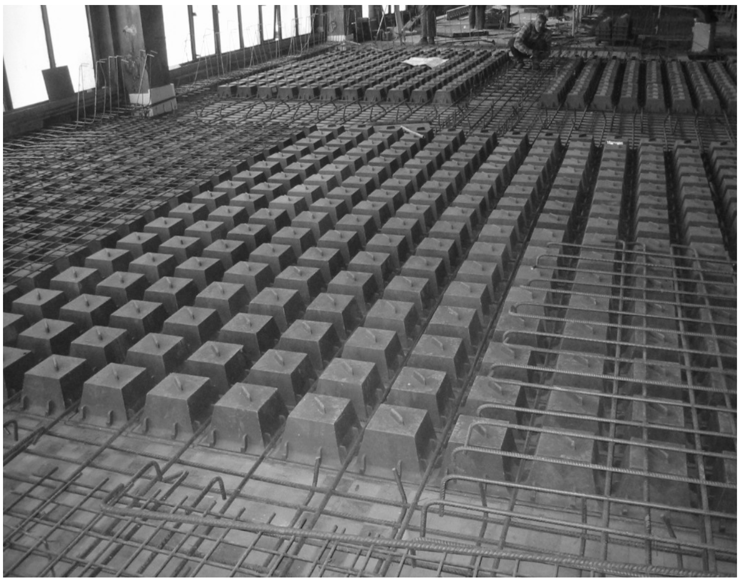

Fig. 11 Reconstruction of Skoda factory hall in Mlada Boleslav – composition of waffle fillers on existing floor structure

The new RC waffle floor slab was placed directly on the existing floor structure (Figure 11). Plastic fillers were placed on the floor so that the existing RC floor structure provides sufficient fire safety. Plastic formwork fillers were made as a custom manufacturing in the Transform Lazne Bohdanec Company in a total amount of 650 m^2 of the fillers. The construction was erected between December 2003 and January 2004 without any technological problems.

6.4 Precast Floor Panels Lightened by Installation Fillers from Recycled Plastics

A new type of an RC precast floor panel with installation fillers from recycled plastic from municipal waste has been developed. The installation fillers are of the same type as those used in the construction of Senior Centre. The test production of panels started in March 2006 in the Company ZPSV Uhersky Ostroh – prefab plant Borohradek, Czech Republic. The width of the panels is 2.4 m, length 4.5 m and the total thickness 200 mm. The lower part of the panel with thickness 50 mm is reinforced by "filligran" space reinforcement girders.

Fig. 12 *Precast filligran panel with installation shell elements – during experimental manufacturing*

Installation fillers from recycled plastic are placed between "filligran" reinforcements (Figure 12). The top covering RC slab is 50 mm thick. The panel has two border ribs and three internal ribs 80 mm wide. The internal installation space can be accessed from the top of the panel through installation holes in distances 600 x 580 mm. In comparison to a full RC slab, the reduction of the self weight is 38% and the reduction of concrete consumption is 43%. This type of precast panels will be used in the construction of Old Age Pensioners Home near Brno, CZ.

6.5 Evaluation of Environmental Impact

Some previously performed LCA analyses showed that using recycled materials and the optimized shape of the floor structure it was possible to reduce environmental impacts, such as consumption of non-renewable silicate materials, the resulting level of embodied CO_2, embodied SO_2 and embodied energy.

The goal of the current analysis is to show how the use of recycled materials from municipal waste for the formwork of an optimized shape of an RC floor slab can contribute to reduction of environmental impacts. The analysis was performed for structural alternatives described in Chapter 4 and for two structural cases which differ by the vertical support (one- or two-way slab). The two-way slabs were considered for spans 6 x 6 m, one-way alternatives were designed for a span 4.5 m. All alternatives were designed for the use in living areas of buildings with an identical live load and a final flat ceiling finish. The overview of all the analyzed alternatives, i.e. three alternatives of RC slabs with lightening fillers from recycled waste materials and two reference structures (RC full slabs), is presented in Table 1. The same table shows associated values of embodied CO_2, embodied SO_2 and embodied energy calculated using a data set based on UCPTE electricity mix (SIA 1995 and Waltjen 1999). The graph in Figure 13 shows the resulting relative comparison of the 3 analyzed alternatives of RC slabs with fillers from recycled MSW with the reference level represented by a corresponding RC full slab (100 %). The reduction of embodied CO_2 is 32 – 45%, the reduction of embodied SO_2 24 – 40%, the reduction of embodied energy 15 - 24%. The factor of reduction of corresponding environmental impacts varies in the range 1.2 – 1.8 x.

In Figure 14 there is a comparison of input material flows (during construction) and output flows (during demolition). It shows that the optimized alternatives use less primary material on one hand and more recycled materials on the other. However, the amount of primary materials and materials with an expected down-cycling process after demolition is still very high. This is due to the fact that concrete is nowadays mainly produced from primary materials and demolished concrete is usually used just for products with lowered quality/performance. These proportions should be changed in the future with respect to the current fast development of recycling techniques. Tamura et al. (2002) show the importance and possibilities of complete recycling of concrete in the future.

Tab. 1 *Embodied values of 3 alternatives of floor structures with fillers from recycled waste materials, and of 2 reference RC floor slabs*

Alternative of floor structure	**Self weight** kg/m^2	**Thickness** m	**Embodied energy** MJ/m^2	**Embodied** CO_2 kg/m^2	**Embodied** SO_2 kg/m^2
two-way floor slab 6 x 6 m					
Waffle RC slab with fillers from recycled waste plastic and gypsum board lower ceiling on timbre frame	341	0,28	481	51	0,22
Reference structure: RC two-way full slab	534	0,22	561	78	0,29
one-way floor slab 4.5 m span					
Composite RC slab with installation fillers from recycled waste plastic	325	0,20	419	50	0,20
Ribbed RC slab with permanent formwork made from boards from recycled laminated drink cartons	244	0,24	380	40	0,17
Reference structure: RC one-way full slab	508	0,21	515	73	0,28

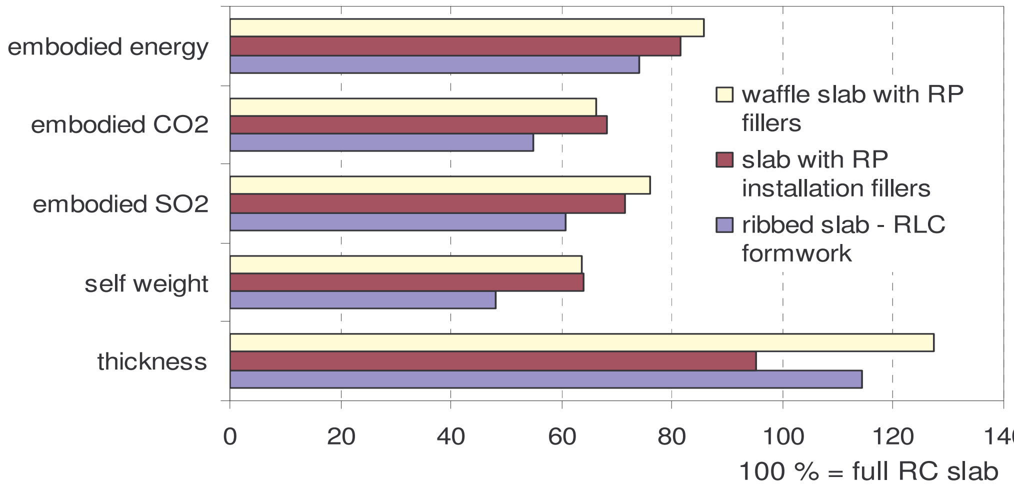

Fig. 13 *Relative comparison of embodied values of 3 alternatives of RC floor structures with lightening fillers from recycled MSW (RP = recycled plastic; RLC = recycled boards from laminated carton) with reference level RC full slabs (100%)*

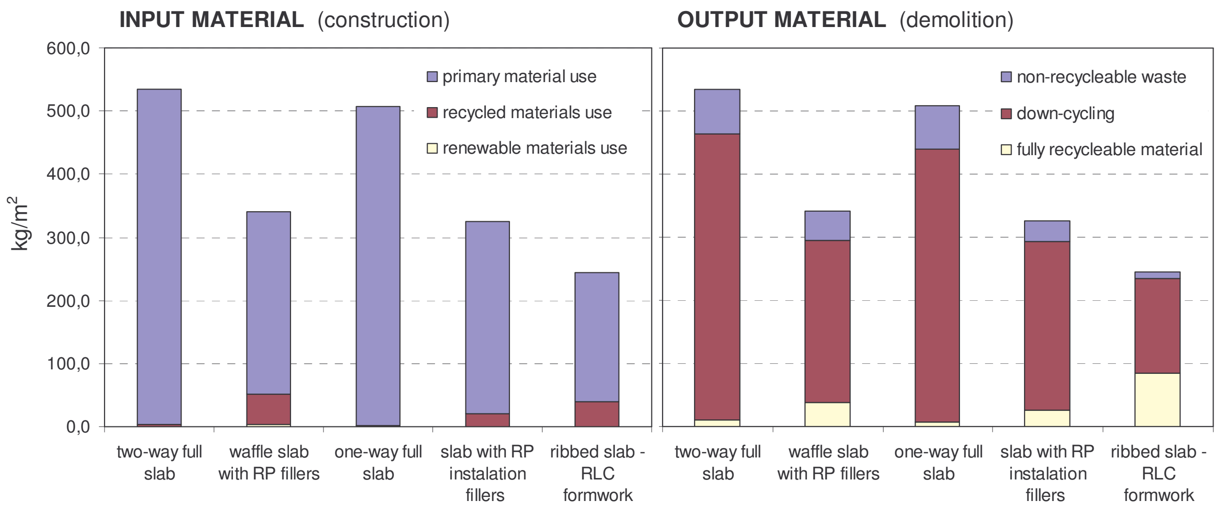

Fig. 14 *Balance of input and output materials at the beginning and at the end of life cycle of 5 alternatives of RC floor structures*

7. Conclusion

The undisputed need for a significant reduction of consumption of primary non-renewable materials is evident. The use of recycled waste materials in building construction represents an approach leading to the required reduction of environmental impacts including reduction of GHG emissions. Especially the use of those waste materials which are produced in large amounts but only a low percentage is recycled, is very important. Mixed plastic municipal waste collected in yellow collecting containers or waste laminated drink cartons represent such typical waste materials.

The theoretical analysis, optimization and performed case studies have supported preliminary assumptions about the undisputed significance of the selection of materials, including recycled materials and optimization of the shape of the structure. The performed case studies - LCA analyses and comparisons with other standard types of RC floor structures have showed that using recycled waste materials and the optimized shape of the floor structure, it is possible to reduce environmental impacts, such as consumption of non-renewable silicate materials, the resulting level of GHG emissions (embodied CO_2, embodied SO_2 , etc.) and embodied primary energy. The evaluated factor of environmental impact reduction in the range 1.2 – 1.8 can be considered insufficient, compared with the range of the needed improvements (factor 4 and more). However, these improvements are in a load bearing system where the main criterion is structural reliability and reduction of the use of structural materials is thus limited by safety reasons.

However, there is a big potential for the use of high performance silicate materials (UHPC, HPFRC etc.) to form ultra thin shell (ribbed, waffle, etc.) structures with higher reduction of the use of primary raw materials, and correspondent reduction of associated environmental impacts. Consequently, there are other possibilities how to reuse waste materials, preferably from municipal waste. Preliminary studies made by the author support the expectation that it will be possible to reach factor 3 or even more while keeping structural reliability on the needed high level. Integrated environmental design represents an advanced approach integrating different aspects in one complex design and optimization procedure. There is a good chance to achieve a significant reduction of environmental impact and, simultaneously, an increase in structural reliability and safety by the complex consideration of different sets of performance criterions within the whole life cycle of the structure and on parallel definition levels (material, component, structure) while considering interaction in interfaces among them.

Acknowledgemets

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Curriculum Vitae

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Education

1993	Doc (Assoc.Professor) - thesis "Combined Structural Systems and their Optimization“
1981 – 1984	CSc. (PhD) Czech Technical University in Prague, Faculty of Civil Engineering
1974 – 1979	Ing. (MSc.) Czech Technical University in Prague (CTU), Faculty of Civil Engineering

Professional Positions

2005 – ff	deputy head of research centre CIDEAS – Centre for Integrated Design of Advanced Structures
2003 – ff	Vice Dean for Research, Faculty of Civil Engineering CTU Prague
2003 – ff	member of Scientific Board of FSv CTU in Prague and of FBI TU Ostrava
1991 – 1998	design praxis in RedeS s.r.o. design office – head designer of more than 30 designs
1986 – ff	Authorized expert – specialization structural behaviour (in total more than 250 reports)
1983 – 1993	Assistant Professor, Dept. of Building Structures, CTU in Prague, Faculty of Civil Engineering

Teaching activities

Lectures – since 1990:
Building Structures 1 – Load Bearing Structures (in Czech and English)
Building Structures 2 – Load Bearing Structures (in Czech)
Optimization and Multicriterion Evaluation of Functional Performance of Building Structures

Practical training and seminars:
Building Structures 1, 2 – Load Bearing Structures (in Czech and English)
Design Project
Diploma projects: in total 105 diploma students since 1993

Activities in International and National Associations and Editorial Boards

2005 – ff	chairman of Czech Sustainable Building Society iiSBE Czech
2005 – ff	member of iiSBE – International Initiative for Sustainable Built Environment
2002 – ff	head of *fib* C3 TG C3.7 – Integrated life cycle assessment of concrete structures
1999 – ff	IABSE – member of International Association for Bridge and Structural Engineering
1999 – ff	IASS – member of International Association for Shell and Spatial Structures (IASS), WG18, Environmentally compatible structures and structural materials
1999 – ff	member of *fib* (International Federation for Structural Concrete) Commission 3 – Environmental Aspects in Design and Construction of Concrete Structures,
1996 – ff	member of board of the Czech Concrete Society
1996 – ff	chairman of editorial board of the journal Concrete TKS

Visiting positions

1993	DTU Lyngby, DK (1,5 months)
1992	City University London, UK (2 months)
1989 – 1990	USA – 6 months: Brown University RI, Colorado University Boulder CO, University of California CA

Research projects

head of research teams of 9 research projects (3 international), co-researcher of other 14 research projects. Selected research projects:

2006 – ff	6FP EU – LEnSE 022718 Methodology Development towards a Label for Environmental Social and Economic Buildings
2005 – ff	CIDEAS – Centre for Integrated DEsign of Advanced Structures, (deputy director)
2005 - ff	GACR 103/05/0292 Design Optimization of Progressive Concrete Structures
2003 - ff	GACR 103/03/H089 Sustainable Construction of Buildings and Sustainable Development of Urban Space (head of the research team)
2002 - 2004	SUREURO-NAS: Sustainable Refurbishment Europe, 5FP EU (EVK4-2002-00525)
2002 - 2004	GACR 103/02/1161 Sustainable Development and Concrete Structures
2000 - 2002	Research project MPO CR Building Construction and Sustainable Development (head of the research team)
2000 - 2004	MSM 210000001 Functional Efficiency and Optimisation of Structures
2001 - 2004	MSM 211100005 Environmental Aspects in Building Construction
1998 - 2000	GACR 103/98/0091 Composite Structures with Fillers from Recycled Materials (head of the research team)
1998 - 2000	GACR 103/98/1480 Optimization of Composite Waffle Slabs (head of the team)

Selected publications – in total more than 120 professional publications.

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