Life Cycle Assessment Optimization of a Shotcrete Tunnel Lining

P Stepanek, I Lanikova and J Venclovsky
Brno University of Technology, Faculty of Civil Engineering, Czech Republic
E-mail: stepanek.p@fce.vutbr.cz

Abstract. The proposed contribution describes the formulation of the optimization design of a utility tunnel lining. The objective function is defined as a multicriteria problem and includes economic and environmental aspects associated not only with concrete member production but also with maintenance during utilization (life cycle assessment). The constraining conditions expressed by relations derived from equations of equilibrium (the solution of optimization calculations for a structure with a Winkler foundation using the Finite Element Method), the reliability conditions of a reinforced concrete structure and the continuity of deformations define the range of allowable solutions from the mathematical viewpoint. The thickness of the tunnel lining and areas of the top and bottom reinforcement in cross-sections are optimized. A method (algorithm) for obtaining a serviceable reinforcement design (via the implementation of reinforcement types) from an optimal solution is described. The obtained results are compared and analysed.

Keywords: optimization, life time assessment, concrete, reinforcement, tunnel lining

1. Introduction
The aim of the “sizing” optimization of reinforced concrete load-bearing structures is a design that considers the cross-sectional dimensions of individual parts of the structure, as well as its reinforcement (i.e. optimized variables). The objective function in optimization tasks (dependent on these variables) usually expresses the cost of materials or cost of the whole building structure (i.e. including the cost of materials, formwork, fabrication, transportation, substructure, cladding, and erection, respectively). It means that typically one-criterion optimization task is solved to minimize construction costs [1][2][3][4][5][6]. However, nowadays it is also necessary to assess the quality of the design, in addition to the price, with regard to other aspects such as sustainability (from the environmental viewpoint), constructability, structural stiffness, etc. Therefore it is possible to solve each optimization task separately [7] and to consequently compare the obtained solutions manually (according to designer’s opinion), or - and i t is better variant - to formulate and solve multicriterial optimization task and gain the Pareto set of solutions. In addition, multi-objective optimization algorithms offer a range of possibilities for the study of distinct objectives; see [8][9][10].

The former tasks of optimization of reinforced concrete structures concerned in particular to the optimization of sub-elements, i.e. beams (simply supported or continuous), columns, floor slabs, and only few publications dealt with an optimization of frame structures [1][2]. The scope of tasks, i.e. dimensions of optimized variables space, was limited by used optimization algorithm (mostly classical exact methods or iterative gradient based algorithms). With the development of metaheuristic
algorithms (since the 70s of the last century), which has also been reflected in the field of engineering tasks, the scope of solved optimization tasks has expanded. These methods are often based on concept found in nature and they are characterized by the search techniques for the valid solution in design space. In particular, genetic algorithms [3][4][5][6], simulated annealing method [8][9], colliding bodies optimization [10], big bang-big crunch approach [7], harmony search [11], etc. were used to optimize framework structures.

Our research is focused on the complex evaluation of structures according to Integrated Life Cycle Assessment (ILCA) [12], which represents the multi-parametric evaluation of a structure over its whole life cycle. It integrates the main aspects of sustainability such as the total environmental impact, the total cost and the total sociocultural quality. The determination of the cost is easy, whereas the calculation of the environmental impact is complicated. Commonly, we have to take into account the following aspects: primary energy consumption (PE), global warming potential (GWP), acidification potential (AP), photochemical ozone creation potential (POCP), consumption of primary raw materials, water consumption, the amount of recyclable (reusable) materials and/or members (at the end of the lifetime of the analysed structure), and the amount of un-recyclable/un-reusable materials/members (amount of waste). The sociocultural quality is often neglected.

In order for the optimization task to be applicable not only to rectangular frames (what is usual) but also to frames which are irregular, the cross-sections for ULS assessment will need to be defined by a knowledgeable user when entering the data for a task. Therefore, the assessed cross-sections will not be automatically determined only for the frame span and joints, as is practised by authors of similar research works. The user defines the cross-sections for the individual members of the analysed structures; based on these, the structures will be discretized into finite elements. The proposed process can achieve suitable reinforcement along the length of individual members of the frame structure, i.e. it is possible to determine the lengths of the reinforced bars so that the reliability conditions are fulfilled even in places where the reinforcement area has changed, and not only in cross-sections with extreme moments.

The response structure model (which uses the FEM) considers the influence of physical non-linearity caused by the non-linear stress-strain diagram of concrete and reinforcement and by cracking in the tensile zone of concrete with consideration of the tension stiffening effect. Above mentioned approach allows the checking of deflection via calculation (not only by limiting the span/effective depth ratio [2][5][7]).

2. Formulation of optimization

In the investigated case, the objective function describes the cost and environmental impacts expressed in terms of the first four above-mentioned aspects, which are assessed for the whole lifetime of the structure. The problem is a multicriterial one, and all the aspects should be minimized. The method of weighted sums was applied. The terms of the objective function have different units and thus must be normalized by the chosen reference values. The objective function \( f(x) \) can be expressed in the form

\[
f(x) = w_{GWP} \frac{GWP_{\text{tot}}(x)}{GWP_{\text{best}}^{\text{tot}}} + w_{AP} \frac{AP_{\text{tot}}(x)}{AP_{\text{best}}^{\text{tot}}} + w_{POCP} \frac{POCP_{\text{tot}}(x)}{POCP_{\text{best}}^{\text{tot}}} + \\
+ w_{PE} \frac{PE_{\text{tot}}(x)}{PE_{\text{best}}^{\text{tot}}} + w_{C} \frac{C_{\text{tot}}(x)}{C_{\text{best}}^{\text{tot}}}
\]

where \( x \) is the vector of optimized design variables, \( GWP_{\text{tot}} \) is the total impact of equivalent global warming potential, \( AP_{\text{tot}} \) is the total impact of acidification potential, \( POCP_{\text{tot}} \) is the total impact of photochemical ozone creation potential, \( PE_{\text{tot}} \) is the total energy consumption and \( C_{\text{tot}} \) is the total acquisition costs for the whole lifetime of the optimized structure; \( w_{GWP}, w_{AP}, w_{POCP}, w_{PE} \) and \( w_{C} \)
are weighting coefficients in the objective function. The quantity $GWP_{\text{lot}}^{\text{best}}$ is the impact of GWP related to a structure which has minimized GWP, i.e. the value of the monocriterial objective function:

$$f(x) = GWP_{\text{lot}}(x).$$

Similarly, $A_{\text{lot}}^{\text{best}}, P_{\text{OC}}^{\text{best}}, P_{\text{E}}^{\text{best}}$ and $C_{\text{tot}}^{\text{best}}$ are the results of monocriterial optimizations with corresponding objectives. These quantities represent reference values of individual terms of objective function (1). All quantities are calculated for the whole lifetime defined by the problem designer. The other environmental aspects are not included in the objective function.

The range of allowable solutions is bounded via constraining conditions. A reinforced concrete structure must be safe and reliable, i.e. it has to fulfill the following requirements:

- reliability conditions defined in the relevant standards with regard to ultimate limit states (ULS) and serviceability limit states (SLS);
- equations of equilibrium (the solution of optimization calculations for a structure with a Winkler foundation using the Finite Element Method);
- structural provisions according to the standards;
- other requirements and limits set by the user.

ULS reliability conditions will be evaluated for a cross-section stressed with a combination of bending moment and normal force. During the calculation of deformations (i.e. displacements and rotations) of the structure for the evaluation of SLS reliability conditions, physical nonlinearity is considered (i.e. the weakening of the cross section due to the effect of cracks occurring in concrete). Constraints are more precisely described in [13].

The optimization task itself is nonlinear and we use the CONOPT solver [14], which is provided in GAMS modelling software. The task is composed of many situations where the usage of non-smooth functions is necessary (e.g. the approximation of stress-strain diagrams, and the calculation of stiffness for cross-sections, including the impact of cracks in the concrete). However, the usage of such functions is precluded by the reduced gradient algorithm. Such situations are then resolved via Hermit’s interpolation of these functions in their non-smooth parts. This is achieved in the Pascal programming language with the aid of a DLL library. The solver then calls the function values and their derivations with the aid of so-called external equations implemented in an algorithm written in the GAMS language.

However, the Winkler soil model only represents a one-way binding between the soil and the mentioned frame. It is ‘one-way’ in the sense that when the frame deflects into the soil, it causes a reaction, while when the frame deflects away from the soil, the reaction is non-existent. This problem is solved by repeating the optimization cycle in such a way that at first the deflections are calculated and then, according to these deflections, the reactions / non-reactions with the soil are set for the respective frame elements (part of structure).

### 3. Optimization of the tunnel lining

#### 3.1. Description of the solved structure.

Our optimization problem concerns a utility tunnel, the original design geometry of which is shown in figure 1. To obtain an optimized design (defined by the objective function), a 1 m long part of the tunnel structure is considered. This part of the structure (frame) is discretized on finite elements (figure 1). The bottom of the tunnel (i.e. elements $e_1$ to $e_{24}$) is not subject to optimization and its thickness is a constant 600 mm, as shown in figure 1.

As regards concrete, shotcrete corresponding to concrete with a strength class of C25/30 will be used, as well as B500B steel.

#### 3.1.1. Optimized variables. The optimized design variables are the height $h^{(e)}$ of the individual rectangular cross sections (i.e. thickness of the tunnel lining), which are predefined for each of the
finite elements $e$, and their reinforcement, which are given by the area of the reinforcement placed at
the top and bottom surface ($A_{s1}^{(e)}$ and $A_{s2}^{(e)}$), and that of the corresponding transverse reinforcement
($A_{sr1}^{(e)}$ and $A_{sr2}^{(e)}$): see figure 2. It is assumed that the optimized variables are constant along the length
of the finite element.

\begin{align}
A_{s1}^{(e)} &= A_{s1}^{(e_k)} \quad \forall e_j, e_k \in E_{1i}, \quad i = 1, \ldots, n, \\
\bigcup_{i=1}^{n} E_{1i} &= E.
\end{align}

This occurs analogically for $A_{s2}$ and subsets $E_{2n}$, $i = 1, \ldots, n$.

Using the optimization algorithm, different types of reinforcement can be designed for each finite
element. In practice, however, such a solution is not feasible. Therefore, the next step will be to
introduce reinforcement types, which is equivalent to dividing the set $E$ of elements $e$ that form the
frame into a prescribed number $n$ of subsets $E_{1i}$, $i = 1, \ldots, n$, where in each subset the value of $A_{s1}$ must
be the same (these subsets must contain consequent elements):

\begin{align}
A_{s1}(e_j) &= A_{s1}(e_k) \quad \forall e_j, e_k \in E_{1i}, \quad i = 1, \ldots, n, \\
\bigcup_{i=1}^{n} E_{1i} &= E.
\end{align}

The division into subsets will be realized via the simple ‘take-the-best’ method. The starting point
of this method can be defined with the assumption that each subset will contain exactly one finite
element. Then, every possible way of joining two consecutive subsets in both the top and the bottom
reinforcement (since they are dependent) will be calculated and the one with the best objective
function value will be chosen as the next step. This will be repeated until the number of subsets for
both top and bottom reinforcement is reduced to the predefined value.

The anchorage length will be added to each reinforcement type. For the solution to be viable, some
assumptions must be made:

- individual bars are placed at a distance of 150 mm from each other, enabling the
  reinforcement profile to be derived from areas $A_{s1}$ and $A_{s2}$;
- the anchorage length is equal to the reinforcement profile multiplied by 30 for steel
  reinforcement (bonding condition);
- the anchorage length is added twice to each reinforcement bar (to the beginning and end of the
  bar), except for the first reinforcement type, which includes element $e_1$, to which the
  anchorage length is added only once (as it is next to the axis of symmetry of the tunnel).

The amount of material used for anchoring is then added to the overall weight of reinforcement in
the objective function.
3.1.2. The load. The load on the tunnel is caused by pressure from the surrounding soil and underground water. Due to complicated geo-mechanical properties, it is necessary to consider two limit values for the at-rest lateral earth pressure coefficient $K_0$. The first, $K_0 = 0.593$, is derived from Jaky’s equation, while the second, $K_0 = 1.25$, is set manually according to the level of soil solidification (typical for neogenous clay in the Brno area, where the tunnel is situated).

The vectors of load in the equilibrium conditions are compiled for combinations of load cases (not for individual load cases) due to nonlinearity (cracking, Winkler soil model). It is predicted that the self-weight of the frame, the soil pressure and the water pressure act together, therefore the number of possible combinations for the ULS was reduced to 8. The equilibrium conditions for the SLS are solved for two load combinations (because of the two values of the coefficient $K_0$).

3.1.3. Life cycle assessment. The lifetime assessment of the structure was formulated as follows:

(a) The construction process phase includes the exploitation of raw materials, transport, and manufacturing techniques used to produce the materials and structure. The resulting environmental impacts and unit costs are shown in table 1; the method of their calculation and the input values are described in [15][16] and GEMIS.

(b) Utilisation and operation phase - we assume the lifetime, maintenance and repair work described in table 2 will occur. The unit costs and environmental impacts of this phase are shown in table 1.

(c) The end of life phase (i.e. demolition) – this phase was not considered.

| Phase | Material, activity | Unit | $E_{\text{Energy}}$ [MJ/unit] | $GWP_{\text{eqiv}}$ [kg/unit] | $AP_{\text{eqiv}}$ [g/unit] | $POCP_{\text{eqiv}}$ [g/unit] | Unit cost [€/unit] |
|-------|-------------------|------|-----------------|------------------|----------------|-----------------|----------------|
| (a)   | Concrete C25/30   | m$^3$| 2966.38         | 362.29           | 1104.61        | 40.24           | 370.37         |
|       | Steel rebar       | kg   | 27.70           | 2.537            | 15.57          | 0.6242          | 1.11           |
| (b)   | Concrete surface repair type 1$^a$ | cm$^2$ m | 35.59         | 4.34 | 13.25 | 0.4829 | 8.70 |
|       | Concrete surface repair type 2$^b$ | cm$^2$ m | 41.52         | 5.07 | 15.46 | 0.5634 | 6.11 |
|       | Replacement of reinforcement | kg | 30.47 | 2.79 | 17.13 | 0.6867 | 1.85 |

$^a$ Thickness of repaired layer 30 mm.

$^b$ Thickness of repaired layer 70 mm.

Table 2. Maintenance and repair work conducted on inner tunnel surface.

| Maintenance and repair work after: | 20 years | 40 years | 60 years |
|-----------------------------------|----------|----------|----------|
| Concrete surface repair type 1 (thickness 30 mm) | 20.0 % | 25.0 % | 30.0 % |
| Concrete surface repair type 2 (thickness 70 mm) | 5.0 % | 7.5 % | 10.0 % |
| Replacement of inner reinforcement | 3.0 % | 5.0 % | 5.0 % |

3.2. Optimization

3.2.1. Solved variants and requirements. A case study was carried out for two tunnel lining optimization variants. Because the structure is fabricated from shotcrete, it is possible to perform calculations for a tunnel lining of variable thickness, i.e. the optimized variable $h$ for each element was left independent. Optimization is also performed for the lining with a constant thickness, i.e. optimized values $h$ were bound by the following constraining condition:

$$h(e_i) = h(e_{i+1}), \ i = 1, \ldots, 19. \quad (5)$$

A maximum of two types of reinforcement ($n = 2$) were used around the perimeter of the tunnel lining independently for the inner and outer surfaces of the lining.
3.2.2. **Monocriterial optimization.** Prior to performing the multicriterial optimization, equation (1), values were required for $X_{\text{best}}$ (where $X = GWP_{i,\text{tot}}, AP_{i,\text{tot}}, POCP_{i,\text{tot}}, PE_{\text{tot}}$ or $C_{\text{tot}}$). Therefore, the optimization of the structure was performed according to each sub-criterion separately, e.g. for the GWP criterion, the optimization was performed to minimize the objective function (2), the resulting optimal solution being labelled $O_{\text{GWP}}$ and the value of the objective function $GWP_{i,\text{best}}$, etc. This produced five optimal solutions according to the individual criteria ($O_{\text{GWP}}, O_{\text{AP}}, O_{\text{POCP}}, O_{\text{PE}}, O_{\text{C}}$) and values of objective functions $GWP_{i,\text{best}}, AP_{i,\text{best}}, POCP_{i,\text{best}}, PE_{\text{best}}$ and $C_{\text{best}}$; these are listed and displayed in red in the graph in figure 3. For the purpose of comparison, all observed criteria for all solutions (shown in blue) were then calculated.

The volume of concrete and the weight of the reinforcement of the resulting solutions are shown in table 3.

![Graphs showing the amount of environmental impact, energy consumption, and cost of the optimal solution](image)

**Figure 3.** Amount of environmental impact, energy consumption and cost of optimal solution carried out for sub-criteria.

| Variant | Variable $h$ | Constant $h$ |
|---------|-------------|--------------|
| Concrete [m$^3$] | Steel [kg] | Concrete [m$^3$] | Steel [kg] |
| O_GWP | 3.050 | 207.0 | 3.418 | 360.8 |
| O_AP | 3.178 | 194.1 | 3.942 | 310.6 |
| O_POCP | 3.192 | 193.2 | 3.986 | 307.6 |
| O_PE | 3.107 | 200.0 | 3.620 | 337.7 |
| O_C | 2.727 | 278.4 | 2.808 | 492.7 |

**Table 3.** The resulting volume of concrete [m$^3$] and amount of reinforcement [kg] in the construction process phase (monocriterial optimization).
From the analysis, during which optimization was carried out for the sub-criteria of the objective function, the following can be concluded:

- If the optimization criterion was cost, a thinner lining was designed using a smaller volume of concrete ($h_{O-C} = 232$ mm for constant lining thickness, $h_{O-C} = \text{from 150 to 357 mm for variable lining thickness}$) and a larger amount of reinforcement in comparison to the optimizations in which any of the investigated environmental impacts were the criteria.
- The greatest lining thickness and the smallest amount of reinforcement was designed for POCP minimization ($h_{O-POCP} = 329$ mm for constant lining thickness, $h_{O-POCP} = \text{from 150 to 433 mm for variable lining thickness}$). In other words, a thicker tunnel lining and a corresponding lower quantity of reinforcement is better from the environmental point of view, but is more expensive.

### Table 4. Weighting coefficients.

| Labelling of optimization results | $w_{\text{GWP}}$ | $w_{\text{AP}}$ | $w_{\text{POCP}}$ | $w_{\text{PE}}$ | $w_{\text{C}}$ |
|----------------------------------|------------------|------------------|-------------------|-----------------|----------------|
| O_W1                             | 0.20             | 0.20             | 0.20              | 0.20            | 0.20           |
| O_W2                             | 0.125            | 0.125            | 0.125             | 0.125           | 0.50           |
| O_W3                             | 0.05             | 0.05             | 0.05              | 0.05            | 0.80           |

The values of the objective functions of the resulting solutions are summarized in table 5. The resulting thickness of lining and reinforcement is displayed in figure 5 (only O_W1 and O_W3); the volume of concrete and weight of reinforcement are shown in table 6. The results for environmental impacts, energy consumption and the cost of optimized solutions for both lining thickness variants (constant and variable) are displayed in the graphs in figure 4.

### Table 5. Values of objective function

| Variant | Variable $h$ | Constant $h$ |
|---------|-------------|-------------|
| O_W1    | 1.0069      | 1.0165      |
| O_W2    | 1.0123      | 1.0240      |
| O_W3    | 1.0111      | 1.0185      |

### Table 6. The resulting volume of concrete [m$^3$] and amount of reinforcement [kg] in the construction process phase (multicriterial optimization)

| Variant | Variable $h$ | Constant $h$ |
|---------|--------------|--------------|
| Material | Concrete [m$^3$] | Steel [kg] | Concrete [m$^3$] | Steel [kg] |
| O_W1    | 3.083        | 202.5        | 3.555           | 344.5      |
| O_W2    | 3.009        | 213.4        | 3.370           | 368.1      |
| O_W3    | 2.884        | 237.4        | 3.060           | 426.0      |
Figure 4. Amount of environmental impact, energy consumption and cost of optimal solution carried out for multiple-criteria.

Figure 5. Thickness of lining and reinforcement of solved variants.
In the case of a lining with a constant thickness, there are greater differences in the results depending on the choice of weighted coefficients. A greater weighted coefficient lowers the value of the relevant criterion, and vice versa. In the case of tunnel lining variants with variable lining thickness, the designs for all three cases of weighted coefficients are less different.

It is clear from table 6 that the thickness of a lining, and its strengthening using steel reinforcement, are dependent on the choice of weighting coefficients in the objective function (weighting coefficients for the environmental aspects are selected in contrast with the price, see table 4, just as the results of monocriterial optimization show).

4. Conclusion
A study was conducted concerning the optimization of a structure according to life cycle environmental criteria and life cycle costs. In the investigated case, lowering the volume of concrete and raising the amount of reinforcement led to decreasing costs and increasing environmental burdens, i.e. environmental impact criteria are diametrically opposed to the criterion of cost.

This method has also been applied to the optimized design of load-bearing structures, e.g. frames or flat structures. The described mathematical algorithm is sufficiently general to allow the use of the application when designing other engineering systems.

Acknowledgements
This paper has been produced under project No. LO1408 "AdMaS UP - Advanced Materials, Structures and Technologies", supported by the Ministry of Education, Youth and Sports under "National Sustainability Program I". Some knowledge were gained within the solution under project No. TA03030851 "Rehabilitation of tunnels - technology, materials and methodology" supported by the Technology Agency of the Czech Republic has been used.

References
[1] Choi C K and Kwak H G 1990 Optimum RC member design with predetermined discrete sections J. Struct. Eng.-ASCE 116 2634–55
[2] Spires D and Arora J S 1990 Optimal design of tall RC-framed tube buildings J. Struct. Eng.- ASCE 116 877–97
[3] Lee C and Ahn J 2003 Flexural design of reinforced concrete frames by genetic algorithm J. Struct. Eng.-ASCE 129 762–74
[4] Camp C V and Huq F 2013 CO2 and cost optimization of reinforced concrete frames using a big bang-big crunch algorithm Eng. Struct. 48 363–72
[5] Govindaraj V and Ramasamy J V 2007 Optimum detailed design of reinforced concrete frames using genetic algorithms Eng. Optimiz. 39 471–94
[6] Kwak H G and Kim J 2009 An integrated genetic algorithm complemented with direct search for optimum design of RC frames Comput.-Aided Des. 41 490–500
[7] Camp C, Pezeshk S and Hansson H 2003 Flexural design of reinforced concrete frames using a genetic algorithm J. Struct. Eng.-ASCE 129 105–15
[8] Paya I, Yepes V, González-Vidosa F and Hospitaler A 2008 Multiobjective optimization of concrete frames by simulated annealing Comput.-Aided Civil Infrastruct. Eng. 23 596–610
[9] Paya-Zaforralez I, Yepes V, Hospitaler A and González-Vidosa F 2009 CO2-optimization of reinforced concrete frames by simulated annealing Eng. Struct. 31 1501–08
[10] Kaveh A and Ardalani S 2016 Cost and CO2 emission optimization of reinforced concrete frames using enhanced colliding bodies algorithm Asian Journal of Civil Engineering 17 831–858
[11] Akin A and Saka M P 2014 Harmony search algorithm based optimum detailed design of reinforced concrete plane frames subject to ACI 318-05 provisions Comput. Struct. 147 79–95
[12] Hájek P, Fiala C, Jensen B B and Lanikova I 2013 Integrated life cycle assessment of concrete structures, fib bulletin 71
[13] Laniková I, Štěpánek P, Venclovský J. 2016 Optimization of a tunnel lining reinforced with FRP Key Eng. Mat. 691 148–59
[14] Drud S A 1996 Conopt: a system for large scale nonlinear optimization ARKI Consulting and Development A/S Bagsvaerd Denmark
[15] Laníková I, Štěpánek P and Simůnek P 2014 Optimized design of concrete structures considering environmental aspects *Adv. Struct. Eng.* 17 495–511

[16] Hájek P, Fiala C and, Kynčlová M 2011 Life cycle assessments of concrete structures - A step towards environmental savings *Struct. Concr.* 12 13–22