A Sustainability Model for the Assessment of Civil Engineer Works

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Abstract: - The present paper presents an evaluation tool proposed by authors, which can appreciate the overall sustainability of a specific construction work. This specific model is a flexible and target oriented tool, based on a simple quantitative equation. The analysis can be performed with a relative small number of measurable parameters, but which offer conclusive results. The final result is a sustainability index, which can be used as parameter of comparison between different solutions. The applicability of the model is exemplified on three case studies: Rehabilitation of two buildings, using different strengthening solutions and transportation of prefabricated RC elements by different means.

Key-Words: - sustainability; assessment; specific model; construction works; transportation;

1 Introduction

As defined in the Report of the World Commission on Environment and Development: Our Common Future (WCED 1987) [1], sustainability links together issues of the natural system with social challenges and economic growth, in a time frame of present and future. This is the reason why it is represented as a confluence of the three pillars: economy, environment and society.

The construction industry plays an important role in the social - economic development, but also has a great impact on the local and global environment. It is a major consumer of non-renewable resources and generates a great amount of waste and greenhouse gases [2].

A sustainable construction develops the idea of low embodied energy, reduced greenhouse gas emissions, low operation and maintenance costs, durability, adaptability, comfort and responsibly sourced materials with recycled contents [3].

In many countries directives and certificates has still been developed and adopted, which evaluate the sustainability performances of buildings. The rating and certification tools are intended to encourage the implementation of sustainable criteria in the design, construction, operation, maintenance, and deconstruction of buildings [4]. That means that the traditional decision criteria should be completed with environmental, economic and social ones. The tools can be used as a decision making support, since they transform the sustainability goals into quantifiable issues, which evaluate the overall performances of a building [5]. Although there may be different perspectives in the approach of sustainability, most of the rating tools do not respect the definition of sustainability. The three domains are not treated proportional, environmental aspects gaining higher importance than social and economic performances. Furthermore, most of the rating tools are focused on entire buildings, without permitting the sustainability evaluation of individual elements, processes or rehabilitation solutions.

The present paper presents an evaluation method developed by the authors, which intend to be used as an assessment tool for individual construction works, respecting the definition of sustainability. It combines parameters of each dimension and is based only on quantitative values. The model results in a Sustainability Index SI which can be used as a parameter for the comparison of different solutions. After a theoretical presentation, the applicability of the specific model is exemplified on three case studies: Rehabilitation of two buildings, using different strengthening solutions and transportation of prefabricated RC elements on road, railway or water.

2 Specific Model

Sustainability of construction works can be assessed using different rating tools. In many countries directives and certificates has still been developed and adopted, which evaluate the sustainability performances of entire buildings [6]. These rating tools offer a global assessment, are very
comprehensive with high applicability but present also some disadvantages [7], [8], [9], [10], [11], [12]:

• Some of the models do not cover all three dimensions of sustainability;

• The tools include a great number of criteria and parameters and many of them are very difficult or impossible to quantify;

• The tools are available mainly for entire buildings, and can be applied with difficulties on other types of construction activities;

The authors elaborated an assessment tool, the specific model, which has the aim to help engineers to assess the sustainability of different construction works. The specific model is a flexible and target oriented evaluation tool, which was developed mainly for the comparison of different solutions, but can be used also for self-assessment. It has a larger applicability then the global models and can be used for partial building works, production of building materials, rehabilitation works, transport of prefabricated elements, construction technologies etc. All the parameters are quantified. The model is based on a quantitative equation, which covers parameters from each dimension of sustainability. Similar approach has been suggested also by [13], but it was only a general proposal, without any practical application. Another similar formula has been proposed by [14], which intended to solve the problem that for some parameters “higher is better”, while for other “lower is better”. A disadvantage of this model is that it takes in account three values for a single parameter: calculated value, standard value and best practice, which are difficult or impossible to be found for some applications. Furthermore, for cases where “higher is better” the model gives not proper results.

An initial version of the specific model has been proposed by the authors in [15], [16], [17]. The model was applied on entire buildings, but also on rehabilitation works. It has been continuously developed and is presented in the paper. The model can be applied using two proceeding: the direct appreciation, which results in a sustainability index SI and the inverse appreciation, which results in an unsustainability index $\overline{SI}$. In both cases, the final score is a dimensionless value between 0 and 1, where 1 is the best and 0 the worst value for SI and vice - versa for $\overline{SI}$. The correlation between the two indexes is:

$$SI + \overline{SI} = 1$$  \hspace{1cm} (1)

The sustainability index can be calculated using the following equations:

$$SI = S_{env} + S_{eco} + S_{soc}$$  \hspace{1cm} (2)

$$S_{env} = \sum_{i=1}^{n} \alpha_i \times \frac{P_{i}^{env}}{P_{i}^{env}}$$  \hspace{1cm} (3)

$$S_{eco} = \sum_{i=1}^{n} \beta_i \times \frac{P_{i}^{eco}}{P_{i}^{eco}}$$

$$S_{soc} = \sum_{i=1}^{n} \gamma_i \times \frac{P_{i}^{soc}}{P_{i}^{soc}}$$

Where:

$SI$ – Sustainability Index;

$S_{env}$, $S_{eco}$, $S_{soc}$ – sustainability indexes for the environmental, economic and social dimensions;

$\alpha_i$ – weighting factor of each parameter for the environmental dimension

$\beta_i$ – weighting factor of each parameter for the economic dimension

$\gamma_i$ – weighting factor of each parameter for the social dimension;

$P_{i}^{env}$, $P_{i}^{eco}$, $P_{i}^{soc}$ - the calculated value for each parameter;

$P_{i}^{Reenv}$, $P_{i}^{Reco}$, $P_{i}^{Resoc}$ - the reference value for each parameter.

The weights for each parameter are established through the estimation of their sustainability impacts on micro and macro level. Independent on the importance of each parameter, environmental issues contribute with 40%, while economic and social issues each with 30% to the final score, according to the definition of sustainability. Depending on researcher the distribution of the weightings may be changed.

In case of a comparison between different solutions, the reference value represents the best value from each solution; while in case of a self-assessment the best practices available are taken as reference values.

For situations of “higher is better” the ratios in eq. (3), which involve such parameters, become $\frac{P_{i}}{P_{i}^{R}}$ (see Eq. (6)).
The unsustainability index results from eq. (1) and is obtained from:

$$\overline{SI} = \overline{S_{env}} + \overline{S_{eco}} + \overline{S_{soc}}$$  \hspace{1cm} (4)

$$\overline{S_{env}} = \sum_{i=1}^{n} \alpha_i \times \frac{p_{env} - p_{\text{Ref}_{env}}}{p_{\text{Ref}_{env}}}$$

$$\overline{S_{eco}} = \sum_{i=1}^{n} \beta_i \times \frac{p_{eco} - p_{\text{Ref}_{eco}}}{p_{\text{Ref}_{eco}}}; \overline{S_{soc}} = \sum_{i=1}^{n} \gamma_i \times \frac{p_{soc} - p_{\text{Ref}_{soc}}}{p_{\text{Ref}_{soc}}}$$  \hspace{1cm} (5)

The weighting factors for each parameter remain unchanged.

For situations of “higher is better” the ratios in eq. (5), which involve such parameters, become $$\frac{p_i - p_{\text{Ref}_i}}{p_{\text{Ref}_i}}$$ (see Eq. (7)).

The correlation between the two indexes is presented in Figure 1, for a theoretical construction work with four solutions. Practical applications of the specific model are presented in the next chapter.

Fig 1. The correlation between the sustainability and unsustainability index

3 Applications of the specific model

3.1 Case study 1 – Rehabilitation of the Western University of Timisoara, Romania

Subsection

3.1.1 Description and assessment of the building

The Western University of Timisoara, built in 1962-1963, has many buildings, among them the Main Building that is used as administrative part as well as classrooms for students. The RC structure consists of:

- Transversal and longitudinal frames with eight stores and two spans of 5.6 m and eleven bays of 3.8m;
- Floors with girder mesh in two directions and a slab of 100mm;
- Foundation with a thick slab and deep beams in two directions.

From visual examination and non-destructive measurements no important damages of the RC structure were observed. Performing a structural analysis, including seismic action at present-day level, the following were noticed:

- The drift limitation conditions are not within the admissible limits at the ground store;
- Weakness of reinforcement and insufficient anchorage of beam-positive reinforcement at the beam-column joint, especially in longitudinal direction.

Rehabilitation solutions consist in strengthening of the columns located at the ground storey. Some columns were strengthened in 1999 to prevent local damages due to reinforcement corrosion, while the others were rehabilitated in 2004 for decreasing the lateral displacement and for homogeneous column stiffness at the ground storey [18].

3.1.2 Calculation of the sustainability and unsustainability indexes

Different solutions have been proposed for the strengthening of the columns: Coating with steel profiles, reinforced concrete jacketing, and composites based on CFRP (lamellas and sheets). Details of the solutions are presented in Figure 2.

Analysing the characteristics of the solutions, several parameters from each dimension have been selected for evaluation, which were considered the most representative for a correct comparison. These parameters are the following: CO2 emissions arising from the manufacturing, transport and execution of the building materials, total cost, consolidating time (workload), increasing of the capable bending moment and stiffness of the consolidated element.

To quantify the parameters, different databases, codes and bulletins have been used, [19], [20], [21], [22], [23]. Adjusting eq. (3) and (5), the indexes resulted from:

$$\overline{SI} = 0.4 \times \frac{C}{C} + 0.2 \times \frac{C - C_{Ref}}{C_{Ref}} + 0.1 \times \frac{W}{W} + 0.1 \times \frac{\Delta B}{\Delta B_{Ref}} + 0.2 \times \frac{K}{K_{Ref}}$$  \hspace{1cm} (6)

$$\overline{SI} = 0.4 \times \frac{C - C_{Ref}}{C} + 0.2 \times \frac{C - C_{Ref}}{C_{Ref}} + 0.1 \times \frac{W - W_{Ref}}{W} + 0.1 \times \frac{\Delta B - \Delta B_{Ref}}{\Delta B_{Ref}} + 0.2 \times \frac{K_{Ref} - K}{K_{Ref}}$$  \hspace{1cm} (7)
Where C, C^R, Co, Co^R, W, W^R, ΔB, ΔB^R, K, K^R are given in Table 1. The specific value of each parameter, for 1m² of rehabilitated element, with their corresponding indexes, is summarized in Table 1. The best value of each parameter has been considered as reference.

### Table 1 Rehabilitation of the Western University using different solutions

<table>
<thead>
<tr>
<th>Western University of Timisoara</th>
<th>Steel Profiles</th>
<th>RC Jacketing</th>
<th>CFRP</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂, C, Emissions [kg/m²]</td>
<td>41.70</td>
<td>93.1</td>
<td>25.47</td>
<td>25.47</td>
</tr>
<tr>
<td>Cost, Co, [euro/m²]</td>
<td>91.66</td>
<td>68.4</td>
<td>155.70</td>
<td>68.4</td>
</tr>
<tr>
<td>Workload, W, [man-hour/m²]</td>
<td>4.29</td>
<td>5.9</td>
<td>1.86</td>
<td>1.9</td>
</tr>
<tr>
<td>Increase of bending moment, ΔB, [kNm/m²]</td>
<td>62.37</td>
<td>57.2</td>
<td>58.26</td>
<td>62.37</td>
</tr>
<tr>
<td>Stiffness, K, [kNm/m²]</td>
<td>241.61</td>
<td>292.6</td>
<td>169.13</td>
<td>292.62</td>
</tr>
<tr>
<td>Sustainability Index SI</td>
<td>0.702</td>
<td>0.633</td>
<td>0.797</td>
<td>1</td>
</tr>
<tr>
<td>Unsustainability Index SI</td>
<td>0.298</td>
<td>0.367</td>
<td>0.203</td>
<td>0</td>
</tr>
</tbody>
</table>

A graphical representation of the results in Figure 3, underlines the correlation between the two indexes. Each solution showed advantages and disadvantages: coating with CFRP had by far the lowest CO₂ emissions and shortest consolidating time, but without assuring the drift limitation conditions, which was the main objective of the rehabilitation. Furthermore it was very expensive; RC jacketing resulted in a good stiffness, relative good price, but high workload in comparison to coating with steel profiles. By applying the specific model, the most sustainable solution proved to be the CFRP procedure; RC jacketing and steel profiles have comparably SI, but as final solution the coating with steel profiles has been applied due to its stiffness.

### 3.2 Case study 2 – Rehabilitation of the Timisoreana Brewery, Romania

#### 3.2.1 Description and assessment of the building

The Timisoreana Brewery is a reinforced concrete framed structure, with one section of five storeys.
and a tower of nine storeys. The brewery and the tower were built in 1961 and the extension in 1971. The industrial building’s vertical structure is a spatial frame, while the foundation system consists of isolated RC foundations under columns. The RC monolithic floors are made of main girders, secondary beams and a one way reinforced slab. From visual examination and non-destructive in situ assessment several problems have been identified at slabs, main girders, secondary beams and columns:

- Concrete cover spalled over large surface;
- Complete corrosion of many stirrups and deep corrosion of main reinforcement;
- Some broken reinforcement;
- Dangerous inclined cracks;

The damages were mainly produced by concrete carbonation and chloride ion penetrations, favoured by high RH (≈80%) and temperature (over 40°C). Performing a structural analysis, including seismic action at present-day level, the following were noticed:

- High vulnerability to seismic actions due to structural irregularities;
- Some elements were characterized by inadequate longitudinal reinforcement (column) and shear reinforcement (beams).

The necessary rehabilitation of the RC structure was adopted for all types of damages and has been performed in two steps. First, in 1999 the main girders, secondary beams and the columns were strengthened for both local damage and inadequate reinforcement, by jacketing with reinforced concrete.

In 2003 due to continues operation and subsequent damage of the structure, new assessment was required. It was found that some beams and one column were characterized by inadequate longitudinal reinforcement and shear reinforcement as well as corrosion of many stirrups at beams. The strengthening solution adopted was based on CFRP composites [24].

### 3.2.2 Calculation of the sustainability and unsustainability indexes

As in the case of the first example (Western University of Timisoara) different rehabilitation solutions were proposed. Details of the solutions are presented in Figure 4 and Figure 5. The parameters and indexes have been determined similar but with slight modifications (structural stiffness was not a problem of vulnerability). The results are summarized in Table 2, separately for column and girder.

![Fig. 4 Strengthening of the column by RC jacketing and CFRP composites](image1.png)

**Fig. 4** Strengthening of the column by RC jacketing and CFRP composites

![Figure 5: Strengthening of the girder by RC jacketing and CFRP composites](image2.png)

**Figure 5:** Strengthening of the girder by RC jacketing and CFRP composites

**Table 2** Rehabilitation of the Timisoreana Brewery using different solutions
For both elements, the most sustainable solution proved to be the coating with CFRP. In 1999 the solution with RC has been chosen due to the lack of experience of the authors in the field of CFRP at that time. In 2003 the sustainable solution has been applied fulfilling all technical and technological requirements.

### 3.3 Case study 3 – Transportation of prefabricated RC elements

#### 3.3.1 Description of the cargo

The aim of this example is to demonstrate the applicability of the specific model also on other types of construction activities. An industrial hall made of prefabricated reinforced concrete elements have to be transported from Timisoara to Galati (690km on road). The structure consists of 97 elements (beams and columns), weighting 450t. Due to the great mass, four transport opportunities have been evaluated: on road by trucks, on railway by train, on inland water (Danube River) by barge and a combined solution by truck and barge, because in many situations there is no direct access on inland water (like in case of Timisoara).

#### 3.3.2 Calculation of the sustainability and unsustainability indexes

For the evaluation of the sustainability of each transport method different parameters have been assessed. The most important were the CO₂ emissions, costs, transport duration, emissions of dust and noise. To calculate the sustainability index the following scenarios have been considered:

Scenario 1 – The transport on road is done by trucks with cargo capacity of 20t. The distance is 690km. The elements are handled ones at loading and ones at downloading. Noise is considered as the maxim level of sound produced by the convoy of trucks [25].

Scenario 2 – The transport on railway is done by freight trains with cars up to 50t loading capacity on a distance of 720km. Having rail access to the manufacturer, the elements are loaded directly in the cars, skipping supplementary handling. At the final destination the elements will be handled twice. The noise level of the train has been considered at a speed of 70km/h [26].

Scenario 3 – The combined transport is necessary because Timisoara has no direct access on the Danube River. The elements are transported on road by trucks to Moldova Noua (150km), from there to Galati on barges (950km), repeating the load and download process two times. The noise level of trucks has been considered in this scenario.

Scenario 4 – This scenario considers that the entire transport is done on water, with two processes of loading and downloading. Because barges have no disturbing effect on settlements, the minimum noise level imposed by standards has been considered.

For all scenarios, the values for specific CO₂ and dust emissions, costs and duration were taken from different databases and catalogues [27], [28], [29], [30], [31], [32]. All specific values were obtained for a cargo of 450t and the minimum distance of 690km.

Adjusting eq. (3) and (5) the indexes resulted from:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Column</th>
<th>Girder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RC</td>
<td>CFRP</td>
</tr>
<tr>
<td>CO₂ Emissions, C, [kg/m²]</td>
<td>141.19</td>
<td>14.88</td>
</tr>
<tr>
<td>Cost, Co, [euro/m²]</td>
<td>92.20</td>
<td>85.23</td>
</tr>
<tr>
<td>Workload, W, [man-hour/m²]</td>
<td>8.58</td>
<td>1.84</td>
</tr>
<tr>
<td>Increase of bending moment, ΔB, [kNm/m²]</td>
<td>55.07</td>
<td>11.65</td>
</tr>
<tr>
<td>Sustainability Index SI</td>
<td>0.548</td>
<td>0.763</td>
</tr>
<tr>
<td>Unsustainability Index SI</td>
<td>0.452</td>
<td>0.237</td>
</tr>
</tbody>
</table>
The results are summarized in Table 3.

<table>
<thead>
<tr>
<th>Transport solution</th>
<th>Truck 690km</th>
<th>Train 720km</th>
<th>Combined Truck 150km</th>
<th>Barge 950km</th>
<th>Only Barge 1100km</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ Emissions, C, kg/1000km</td>
<td>123.13</td>
<td>24</td>
<td>46.14</td>
<td>22.43</td>
<td>22.43</td>
<td></td>
</tr>
<tr>
<td>Cost, Co, [Euro/1000tkm]</td>
<td>39.4</td>
<td>56.04</td>
<td>35.26</td>
<td>0.04</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Duration, D, [hour/1000tkm]</td>
<td>0.11</td>
<td>0.12</td>
<td>0.30</td>
<td>0.31</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Dust (PM10+VOC), PM, [g/1000tkm]</td>
<td>0.13</td>
<td>0.04</td>
<td>0.06</td>
<td>0.04</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Noise, N, [dB]</td>
<td>90</td>
<td>110</td>
<td>90</td>
<td>50</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Sustainability Index SI</td>
<td>0.305</td>
<td>0.689</td>
<td>0.412</td>
<td>0.931</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Unsustainability Index SÌ</td>
<td>0.695</td>
<td>0.311</td>
<td>0.588</td>
<td>0.069</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Each mean of transport shows advantages and disadvantages. Transportation on water is by far the most sustainable solution, even if the duration is much higher than for other cases. But its main disadvantage represents its applicability. Barges need ports and access to water, which is not possible in all situations. Like in the case of Timisoara – Galati, a combined alternative was proposed. Transport by trucks to the nearest port and then further on water. Due to great CO₂ and dust emissions of the trucks this alternative is becoming less sustainable. Transport by freight trains resulted to be the most viable solution in this situation. Transport by trucks is suitable for smaller cargos, and for places where none of the above mentioned means can be applied, due to the lack of infrastructure.

3 Conclusions

Sustainability is defined as the confluence of the environmental, economic and social dimensions. For a correct assessment of sustainability performances, all the three dimensions should be treated in equal way. The construction industry has great environmental impacts, contributes to the economic growth, but has also social responsibility. It should implement sustainability issues in all types of activities, including entire life cycle. Using evaluation models, sustainability issues can be assessed and quantified, which may help engineers in the decision making regarding different solutions. The presented specific model, resulting in a sustainability index of different construction works, offers many advantages and opportunities. It is a method to appreciate the overall sustainability of a specific application, which finally leads to optimum design solutions. It is a flexible tool, based on a simple quantitative equation, which can be applied on a series of practical problems. The analysis can be performed with a relative small number of measurable parameters, but which offer conclusive results. Due to its flexibility, the proposed model can be applied on entire building, building elements, rehabilitation methods, production of construction materials, transport solutions, construction technologies etc.

From the presented case studies some useful conclusions can be underlined. A sustainable solution not always represents the best solution, it must be also technically useful; for instance, the CFRP solution resulted as the most sustainable, but due to its insufficient stiffness, could not fulfil the technical requirements. Similar problem appeared in the case of the transport of prefabricated elements. Although the most sustainable solution proved to be the transport on water by barge, due to the lack of direct access to water, a less sustainable solution had to be obtained.
References:
[27] South Coast Air Quality Management District, 1993. CEQA Air Quality Handbook. Tables A9-8-B, A9-8-C and A9-8-D