IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

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To cite this article: Anna Sobotka *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **471** 112051

Sustainability of Construction Processes – Requirements, Criteria, Evaluation Concept

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Abstract The application of the principles of sustainable construction in practice is covered by research and legislative works, the effect of which are standards and other documents helping designers and investors in the assessment of construction products and buildings in their life cycle. The research, presented in the literature, focus primarily on the study of environmental impacts, particularly in the phase of manufacturing building products. However, there are no in-depth studies on the assessment of construction processes. This paper focuses on the analysis and evaluation of construction processes, from the perspective of the sustainable development requirements. The proposed methodology allows a systematic analysis of the three pillars of sustainable construction, i.e. the environmental, economic and social aspects, based on quantitative assessment indicators. Due to a limited scientific recognition in the area of social aspect assessment, it was subjected to a particularly thorough analysis and a procedure allowing the evaluation of the impact of construction works on the neighbourhood (surroundings) was developed. Noise, emissions of substances as well as vibrations and shocks were considered as the representative indicators characterizing the social aspect of the effects of construction on the environment. This approach is justified by the high harmfulness of these factors to health in the work environment. Depending on the nature of the impacts, their values were determined based on the noise level (noise), the concentration of respirable dusts (emissions of substances) as well as peak particle velocity and vibration levels (vibrations and shocks). It is recommended to represent them in the assessment by multiplicity of standards or reference levels. The proposed method of analysis of building processes may be applied to the planning of construction works with the least adverse impact on the environment.

1. Introduction

Since the Earth Summit in Rio de Janeiro (1992) [1], there has been a growing interest in the issue of sustainable development and intensive implementation of its postulates in various areas of human activity. The model of a sustainable economy assumes a properly and consciously created relationship between economic growth, care for the environment and quality of life (including human health). Due to the significant impact of civil engineering on dynamic social and economic development and its responsibility for the environment, the building construction sector is regarded as one of the key areas creating sustainable development. In response to changing requirements and aspirations, the concept of sustainable construction was born as it could be an innovative sector, enabling satisfying social needs, economically and environmentally friendly. The paper presents a general concept of evaluation of construction processes from the point of view of sustainable building requirements, hence the proposed approach allows simultaneous assessment of environmental, economic, and social properties.

2. Sustainability assessment of construction processes

Popularization of sustainable production models should not be limited only to architectural or structural and material solutions, but ought to also include technical and organizational solutions of construction processes. Their comprehensive analysis and multi-criteria evaluation that includes social, environmental and economic criteria allow choosing the variant which meets the sustainable development requirements to the greatest extent (Figure 1).

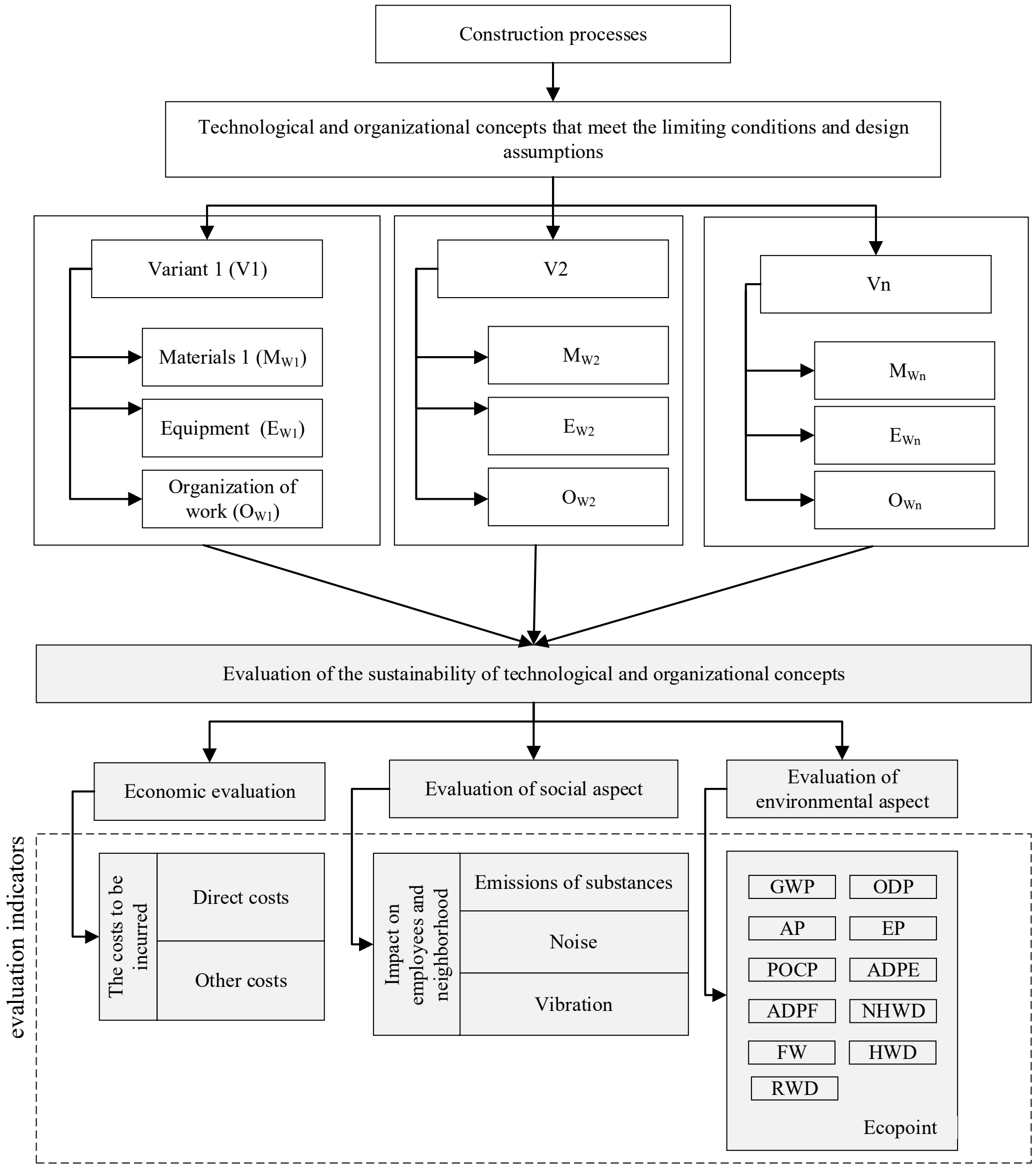

Figure 1. Graphical model of construction processes evaluation

In the analysis, the criteria are represented by a set of indicators which reflect e.g. the degree of conformity with applicable standards. Taking into account the importance of individual indicators/ features (according to the decision maker's preferences), the evaluation of the i^{th} variant of the construction process P_i can be obtained using the weighted sum method (WSM):

$$P_i = \sum_{j=1}^{n} a_{ij} w_j \tag{1}$$

a_{ij} − value of the measure of the i[th] variant according to the j[th] criterion, j = 1,2, ..., n, i = 1, ..., m,
w_j − weight of j[th] criterion.

2.1. Environmental analysis

Environmental analysis is a structured procedure aimed at identifying and quantifying materials and energy used in construction processes, released emissions and generated waste, as well as assessing their impact on the environment. A framework for environmental assessment in the life cycle has been proposed in the standard [2].The key stages of the analysis are: determining the objective and scope of research, depending on how the analysis results are used (1), analysis of the input and output set for selected construction processes (2), assessment of the construction processes impact on the environment, expressed in the impact category set (3) and interpretation of results (4). The EN 15643-2: 2011 standard [3] recommends an assessment based on a comprehensive set of environmental indicators. However, taking into account the strong correlation between standard indicators, it is recommended to conduct the analysis based on a set of 11 environmental criteria, considering their weights according to [4] (Table 1).

Table 1. Environmental criteria and their weights based on [4]

Criterion	Criterion weight [%][a]	R_i
Global warming potential **(GWP)**	24.1	12,300
Net use of fresh water **(FW)**	15.2	377
Depletion potential of the stratospheric ozone layer **(ODP)**	13.5	0.22
Acidification potential of soil and water **(AP)**	8.4	71.20
Eutrophication potential **(EP)**	8.2	32.50
Radioactive waste disposed **(RWD)**	7.0	3.91
Abiotic depletion potential for non-fossil resources **(ADPE)**	6.6	39.10
Formation potential of tropospheric ozone **(POCP)**	5.8	21.50
Hazardous waste disposed **(HWD)**	5.0	187.43
Abiotic depletion potential for fossil resources **(ADPF)**	4.0	273,000
Non-hazardous waste disposed **(NHWD)**	2.1	3,750

A one-point evaluation of the analyzed solutions is made on the basis of the Ecopoint unit determined according to the relationship [5]:

$$E_p = \sum_{i=1}^{n} N_i \times w_i \qquad (2)$$

where:
N_i − normalized environmental impact value for the i[th] category,
w_i − weight of i[th] environmental impact category.

In order to take into account the simultaneous impact of many factors and their influence on the variant's environmental profile, the values of environmental indicators are normalized according to the following formula:

$$N_i = S_i / R_i \qquad (3)$$

where:
i – environmental impact category, i=1,2,...,n; n=11,
N_i − normalized environmental impact value for the i[th] category,
S_i − characteristic environmental impact value for the i[th] category
R_i − reference unit for i[th] environmental impact category (annually per EU-28 resident).

2.2. Economic analysis

The economic analysis of construction processes involves the cost calculation and reference the costs to the estimate investment value (EIV).

$$C_p = \frac{C_j}{EIV}$$
$$C_j = L_j + M_{nj} + E_j + O_{cj} \quad (4)$$

L_j – cost of labour per unit,
M_{nj} – cost of material per unit,
E_j – cost of equipment per unit,
O_{cj} – other costs.

These costs should also take into account the potential costs incurred by the neighbourhood.

2.3. Social analysis

Due to limited scientific recognition in the area of social aspect assessment, it was subjected to a particularly detailed analysis and a procedure to examine the impact of construction works on the neighborhood was developed.

The methodical framework, principles and requirements related to the social assessment of the building are included in the third part of the standard EN 15643 [6]. The standard specifies the categories of evaluation indicators, among which particularly important for construction processes is the "impact on neighbourhood" category characterized by the following indicators: noise, substance emissions, vibration and shocks. These indicators have also been classified as hazardous to health in the workplace environment [7]. Therefore, it is suggested to evaluate the impact of noise, dust and vibration from the point of view of both, a worker and a bystander. The specificity of construction processes and the variability of works conditions hinder the unequivocal assessment their harmfulness at workplaces. This results in a lack of awareness of the risks and need to protect employees with Personal Protective Equipment.

It needs to be highlighted that the choice of structural and material solutions is limited in case of construction works, hence the proposed variant solutions should include various determinants (limitations, design assumptions, etc.).

3. Evaluation criteria for social aspect of construction works

3.1. Noise

Noise is understood as each undesirable sound which can be noxious or hazardous to health or increase the work-related accident risk [7]. The noise harmful levels are presented in Table 2.

Table 2. Noise levels and their characteristics [8]

Noise level [dB]	Characteristics of noise
<35	Basically harmless
35-70	A negative impact on the nervous system, leading to fatigue, drop in labor productivity.
70-90	The ongoing continuously, can degrade performance work, headaches, permanent loss of hearing.
>90	It causes vibration of some internal organs of the body, it can cause permanent diseases, and even their total destruction.

Sound wave propagations models [9] are used to determine the level of noise impact on bystanders and workers. The model choice is determined by the characteristics of space in which the sound propagates. In case of a sound source oriented in an open space, the noise (sound pressure level) at distance r from the source (L_{Ir}) is calculated according to the following formula [9]:

$$L_{Ir} = L_N + 10lg\Phi - 10lg\Omega - 20lg\frac{r}{r_0} \quad (5)$$

L_N − sound power level, eg. equipment characteristics, dB,
Φ − the source direction factor,
Ω − a solid angle in which sound propagation occurs,
r_0 − reference radius, 1 m.

Sound intensity in decibels defines the ratio of the sound pressure to the audible threshold, expressed in a logarithmic scale. Such noise level does not, however, reflect its harmfulness, hence it is suggested to express the noise impact using the multiplicity of the standard noise exposure level for an 8-hour workday [10][11]. The equivalent noise level L_{EX} is calculated according to the following formula [12]:

$$L_{EX} = L_{Ir} + 10log\frac{t_e}{t_0} \quad (6)$$

t_e − time of exposure to noise at a given level, h,
t_0 − reference time, h.

Then the multiplicity of the norm (component a_{ij}) is as follow:

$$k_{L_{EX,8h}} = 10^{(L_{EX}-L_{EXdop})\cdot 0,1} \quad (7)$$

L_{EXdop} − permissible noise exposure level for an 8-hour working day, dB.

Table 3 includes examples of the noise standard multiplicity values corresponding to the model sound intensity levels.

Table 3. Noise standard multiplicity [10]

Sound level for an 8-hour workday [dB]	Multiplicity of standards	Sound level for an 8-hour workday [dB]	Multiplicity of standards
80	0.32	**95**	10.00
85	1.0	**100**	31.62
90	3.16	**105**	100

The noise impact on bystanders should be calculated in an analogous manner, assuming the maximum allowed noise level in the environment according (in this case) to the Polish Regulation of the Minster of Environment [13].

3.2. Substance emissions

Basic substance emissions to the environment, which accompany the construction works, are dust emissions [14]. It should be emphasized that pneumoconiosis are the most frequent occupational diseases among the construction workers. The dust harmfulness depends on many factors, e.g. size, type and shape of dust particles, exposure time, content of free crystalline silica [15]. Widespread respiratory diseases are observed mainly in workers exposed to free crystalline silica (FCS), asbestos and wood dust. Inhalation of highly concentrated dust, particularly the FCS, leads to changes in the respiratory system, reduces the respiratory efficiency, causes obstructive changes, pulmonary fibrosis, allergic changes, and also lung and pleura cancer.

The dominating hazardous dust emission sources include grinding, polishing, demolition and drilling (dust emissions from material processing), enhanced by the use of equipment [14]. In addition, the internal combustion engines are emission sources of the PM2.5 and PM10 suspended particles which contain toxic substances [15].

Similarly to noise, the suggested indicator of particulates emissions is the multiplicity of the standard – in this case of respirable dusts containing free crystalline silica (due to its high harmfulness). The standards should be based on national legislation, for example (in this case) the Regulation of the Minister of Labour and Social Policy on maximum allowed concentrations and intensity of hazardous substances in the workplace [11].

The average weighed concentration C_w for an 8-hour workday is calculated according to the following formula [16]:

$$C_w = \frac{c_1 \cdot t_1 + c_2 \cdot t_2 + \cdots + c_n \cdot t_n}{8} \tag{8}$$

c_n − model concentration of respirable dust for individual works, mg/m^3,
t_n − duration of individual works, h.

Then, the multiplicity of the standard $k_{C_{EX,8h}}$ (component a_{ij}) is defined by the following formula:

$$k_{C_{EX,8h}} = \frac{C_w}{NDS} \tag{9}$$

NDS- occupational exposure limit, mg/m^3.

Information on average concentration of respirable dust containing silica in construction processes can be found in literature (examples in Table 4).

Table 4. Concentration of respirable dusts in selected construction works [17]

Construction process	Geometric mean concentration of respirable dusts [mg/m^3]
Demolition of concrete elements using pneumatic hammers	0.96
Cutting concrete on the construction site	0.76
Making a concrete mix on site	0.91
Sanding concrete surface	0.63

Evaluation of direct impact of the dust-polluted air on bystanders would require using multiparametric models. Therefore, for evaluation of the social aspect in this case it is suggested to use the particulates emissions index, expressed as a PM2.5 equivalent in kg, standardized with a reference value (e.g. annually per EU-28 inhabitant).

3.3. Vibration

The harmful impact of vibration on the existing buildings should be considered and evaluated quantitatively in case of areas particularly exposed to vibration caused by construction works. Construction equipment used on site transmits the energy to the ground and generates vibration that propagates in the subsoil area and damages the building elements [18]:

- non-structural elements – hairline cracks, cracks of paint coats and plasters, loosened fastening of doors and windows in walls, cracking and detachment of ceramic tiles and cladding, hairline cracks and cracks of partition walls;
- structural elements – damage causing the reduction of strength, including hairline cracks and cracks of foundations, load-bearing walls, joints between walls, lintels, posts, etc.

Vibration also causes poor physical coordination, extends the visual and motor response time, causes tiredness and changes in nervous and osteoparticular systems (vibration disease) in workers, and discomfort and dysfunctions in bystanders not directly related to construction works in progress.

It is proposed to replace the complex evaluation process of vibration impact on the neighbourhood with a simplified model. The measure most widely used in evaluation of the vibration impact on buildings is the maximum vibration velocity (peak particle velocity, PPV [m/s]) defined as the maximum momentary velocity of the vibratory motion. The PPV depending on the equipment used on construction site (Table 5) is calculated according to the formula [19]:

$$PPV_{equip} = PPV_{ref} \cdot \left(\frac{7.62}{D}\right)^n \tag{10}$$

$D -$ distance from vibration source (equipment) to the receiver, m
$PPV_{equip} -$ vibration from the equipment, m/s,
$PPV_{ref} -$ reference PPV, m/s,
$n -$ the value related to the attenuation rate through ground.

Table 5. PPV_{ref} and Lv_{ref} reference level for selected construction equipment [19]

Type of equipment	PPV_{ref} [m/s]	$L_{v,ref}$[VdB]
Pile driver:		
driven piles	$3.86 \cdot 10^{-2}$	112
screw piles	$1.86 \cdot 10^{-2}$	105
Vibratory roller	$5.33 \cdot 10^{-3}$	94
Hydraulic hammer	$2.26 \cdot 10^{-3}$	87
A large bulldozer	$2.26 \cdot 10^{-3}$	87
Transport car	$1.93 \cdot 10^{-3}$	86
Pneumatic hammer	$8.89 \cdot 10^{-4}$	79
A small bulldozer	$7.62 \cdot 10^{-5}$	58

Evaluation of vibration impact on adjacent buildings involves a comparison of PPV_{equip} with the limit value typical for specific building categories shown in Table 6. The vibration evaluation m_{wb} (component a_{ij}) as a measure of vibration impact on adjacent buildings is defined by the following formula:

$$m_{wb} = \frac{PPV_{equip}}{PPV}. \tag{11}$$

Table 6. Evaluation criteria of vibration harmfulness for buildings by building category [20]

Buildings category	PPV [m/s]
I. The buildings of reinforced concrete or steel structures e.g. factories, retaining walls, bridges, steel towers, canals, underground chambers, tunnels	$1.27 \cdot 10^{-2}$
II. Buildings with a concrete or masonry structures, e.g. buildings with concrete foundations and floors as well as concrete or brick walls, retaining walls made of bricks	$7.62 \cdot 10^{-3}$
III. Buildings with wooden ceilings and masonry walls	$5.08 \cdot 10^{-3}$
IV. Buildings particularly susceptible to vibration damages	$3.05 \cdot 10^{-3}$

Evaluation of vibration harmfulness for workers and bystanders is based on average vibration velocity $L_v(D)$, typical for used construction equipment (Table 5) and calculated according to the formula [19]:

$$L_v(D) = L_{v,ref} - a\ log\left(\frac{D}{7{,}62}\right) \quad (12)$$

$D -$ distance from vibration source (equipment) to the receiver (worker or bystander), m,
$L_{v,ref} -$ reference vibration velocity level, m/s,
$a -$ damping factor depends on the type of subgrade, a = 30 for average conditions.

Evaluation of vibration impact on people involves a comparison of $L_v(D)$ with perception threshold, assuming that a significant irritation and discomfort is caused by vibration characterized by L_v=70 VdB. The vibration impact m_{wp} on people (component a_{ij}) is calculated according to the formula:

$$m_{wp} = \frac{L_v(D)}{L_v} \quad (13)$$

4. Conclusion

The presented methodology allows an analysis and evaluation of construction processes in the light of the sustainable development requirements. The paper includes the detailed evaluation guidelines for the environmental, economic and social aspects.

The advantage of the proposed method lies in its objectivity resulting from the application of quantitative evaluation indicators; the disadvantage is the need to adapt the calculation models which level of generality will affect the quality of results. Therefore, the key factor for development of the presented approach will be improvement of calculation models, development of databases and the tools to support the analysis of construction processes. The issue for discussion remains whether to take average or extreme values into the assessment.

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