International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:10, No:12, 2016

Environmental Decision Making Model for Assessing On-Site Performances of Building Subcontractors

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***Abstract*—**Buildings cause a variety of loads on the environment due to activities performed at each stage of the building life cycle. Construction is the first stage that affects both the natural and built environments at different steps of the process, which can be defined as transportation of materials within the construction site, formation and preparation of materials on-site and the application of materials to realize the building subsystems. All of these steps require the use of technology, which varies based on the facilities that contractors and subcontractors have. Hence, environmental consequences of the construction process should be tackled by focusing on construction technology options used in every step of the process. This paper presents an environmental decision-making model for assessing on-site performances of subcontractors based on the construction technology options which they can supply. First, construction technologies, which constitute information, tools and methods, are classified. Then, environmental performance criteria are set forth related to resource consumption, ecosystem quality, and human health issues. Finally, the model is developed based on the relationships between the construction technology components and the environmental performance criteria. The Fuzzy Analytical Hierarchy Process (FAHP) method is used for weighting the environmental performance criteria according to environmental priorities of decision-maker(s), while the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is used for ranking on-site environmental performances of subcontractors using quantitative data related to the construction technology components. Thus, the model aims to provide an insight to decision-maker(s) about the environmental consequences of the construction process and to provide an opportunity to improve the overall environmental performance of construction sites.

***Keywords*—**Construction process, construction technology, decision making, environmental performance, subcontractors.

I. Introduction

BUILDING construction is the start of the building life cycle, which causes adverse impacts on both the natural and built environments. Pollo and Rivotti indicate that the construction process is responsible for 15% of the overall impacts of building life cycle stages [1]. Environmental loads of the construction process are related to discharges to land and water, waste, water abstraction, ground and water contamination, noise, vibration, national and local sensitive flora, fauna and habitat types [2]. There are some studies, which focus on the environmental impacts of the construction process, with different perspectives to reduce the overall damages resulted from the process [3]-[8]. The last version of BREAAM, which is a green building rating system developed by the Building Research Establishment in the UK, added construction practices as one of the key criteria to create awareness and encourage environmental and social management of construction sites [9]. However, the environmental consequences of the construction process are not taken into account in developing countries due to unfamiliarity, lack of information and tools regarding with this subject. In Turkey, taking environmental measures during the construction processes has become more crucial than ever due to the rapidly increasing construction activities, which are mostly conducted in dense city centers, as a result of an ongoing urban renewal process. Therefore, it is important to develop an approach to be employed for environmental assessment of the construction process by stakeholders.

"Analyzing the inputs of the construction process can provide insight to assess the environmental impacts of the construction process" is the primary argument of this research [10]. Construction technologies are inputs of the construction process, which consist of information, tools (material, equipment and labor) and the methods (techniques, activities, processes) used for realizing buildings. While information, labor, and techniques have second-level relationships with environmental impacts, material and equipment have a dynamic and direct relationship. The distinctive characteristics and numerous options of material and equipment cause environmental impacts at different levels, which provide an opportunity for decision maker(s) to analyze their decisions by aiming for an improvement in environmental performance of the construction process. The same design can be realized by using different construction technology options, which also means that different subcontractors can apply it. Subcontractors have different facilities to be assigned during the construction process that they should consider for an improved environmental performance. Therefore, this paper presents an environmental decision-making model for assessing on-site environmental performances of subcontractors based on the construction technology options they provide. The model is a part of a previously developed model, which can be adapted to be used in different contexts with various types of data [11]. Within the context of this paper, it is used to assess and analyze subcontractors at the construction planning phase by the decision maker(s), who can be a contractor, design team, construction site team and an owner, to make inferences and to reveal facts about on-site environmental performances of subcontractors. This kind of assessment requires environmental performance criteria with their defined significance levels, and quantitative data on construction technology components. For this purpose, first

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the construction technology components are analyzed and classified, and then the environmental performance criteria are defined. Finally, the model is developed as a multi-criteria decision-making model by using the FAHP and the TOPSIS methods.

II. Construction Technologies

Construction technology includes information, tools (materials, equipment and labors) and methods (techniques, activities, processes) [12] (Fig. 1).

Information is required during every phase of the construction process by different stakeholders. It can be gathered from building codes and regulations, standards, material catalogs, specifications, reports related to previous works, periodicals, books, etc. [12]. Environmental management of construction sites requires a well-developed background to be a part of the decision-making process. Therefore, it is important for stakeholders to have sufficient *knowledge* and *data* about construction project and construction technologies to make the best decisions on environmental priorities and subcontractors.

Tools involve *materials, equipment* and *labors*. *Materials* are classified as *basic, supplementary* and *joining materials* according to their function within a building element [11]. *Basic materials* consist of the core, cladding, and protective materials (e.g. thermal insulation, waterproofing, etc.), which are responsible for forming the building elements by meeting the necessary performance requirement. *Supplementary materials*, e.g. joint filters, sections and profiles, are used to complete a building element system to provide it functioning properly or to provide a base for the assemblage. *Joining materials*, e.g. bonding agents and fixing materials, are required to bring together the basic and the supplementary materials to form the building element. *Equipment* is necessary to perform different tasks, which are *transportation, formation, preparation,* and *application*, in the various stages of construction. Equipment is also classified based on their operation principles as *human powered, fossil fuel based* and *electrically driven. Labor* can be defined according to the hierarchical order as *unskilled labor* and *skilled labor*, and specialty type such as roofer, plumber, electrician, etc. *Methods* consist of *techniques* and *processes* in which these techniques are used while performing a variety of *activities*. These processes can be classified as *transportation*, *formation* and *preparation* of materials, and *application* of building subsystems. There are basically three *construction techniques* as *formation, preparation* and *application*. *Formation and preparation techniques* are related to on-site activities performed on materials, while *application techniques* are used to bring together materials to form the building subsystem.

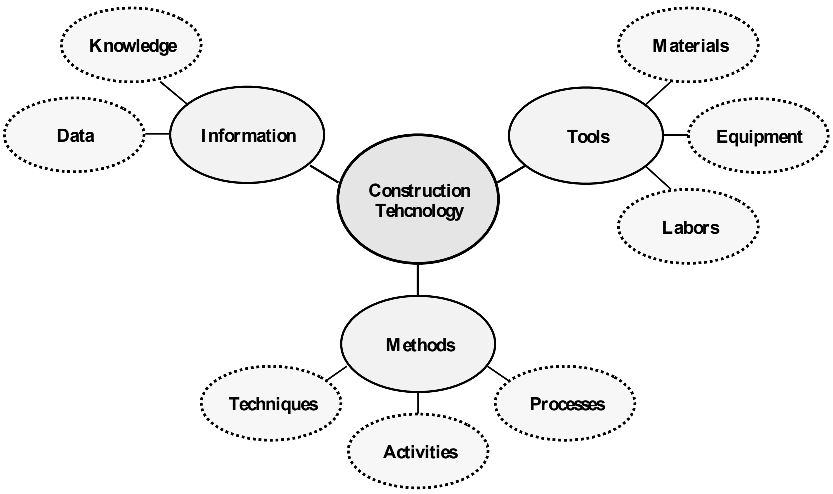

Fig. 1 Construction technology components

III. Environmental Performance Criteria

Environmental performance can be indicated concerning environmental impacts caused by the building and building processes. It is directly related to environmental aspects, which can be regarded as impacts or loads such as the use of resources, production of waste, odors, noise and harmful emissions to land, water, and air, etc. [13]. This study takes into account the construction process as the environmental aspect of a specific construction project, which includes a variety of activities resulting in adverse environmental impacts. Environmental impact assessment tools and relevant databases [14]-[16], environmental performance assessment standards [13], [17]-[19] and previously mentioned studies are analyzed to define environmental performance criteria for the construction process. In addition to this, Turkish regulations on Waste Management [20], Controlling the Packaging Waste [21], Controlling the Dust [22], Protection of Workers from Risks Related to Noise [23] and Protection of Workers from Risks Related to Vibration [24] are analyzed, which have to be adapted to the construction process. Finally, environmental performance assessment criteria for the construction process are set forth as shown in Table I.

TABLE I
ENVIRONMENTAL PERFORMANCE CRITERIA FOR THE CONSTRUCTION PROCESS

Damage Categories	Environmental Aspects	Environmental Indicators
DC1 Resources	EA1 Nonrenewable energy	EI1 Fossil fuel consumption
	EA2 Renewable energy	EI2 Electricity consumption
DC2 Ecosystem Quality	EA3 Damage to natural resources	EI3 Water consumption
	EA4 Terrestrial eco-toxicity	EI4 Solid waste generation
	EA5 Aquatic eco-toxicity	
DC3 Human Health	EA6 Respiratory effects	EI5 Dust/volatile generation
	EA7 Hearing impairment	EI6 Noise generation
	EA8 Skeletal/muscular disorders	EI7 Vibration generation

IV. ENVIRONMENTAL DECISION MAKING MODEL

The environmental decision-making model for the construction process is developed based on the relationship within the construction technologies, and between the construction technologies and the environmental performance criteria.

Information is the key to the model, which has a significant role in every decision related to materials, equipment, labors and construction techniques. Material preferences offer construction technique options, which define required equipment for construction.

The relationship between the environmental performance criteria and the construction technology components can be clearly stated if environmental indicators are taken into account as indicated below:

- Fossil fuel and electricity consumption are related to equipment due to the operational energy type.
- Water consumption mainly correlates with joining material type because of the on-site preparation of some bonding agents involves water usage.
- Material forming contributes to solid waste generation by producing material pieces of no use, while material packages can also result in waste generation.
- Preparation of bonding agents and the formation of materials result in dust/volatile generation.
- Noise and vibration generation are related to equipment type.

The selection of subcontractors based on their on-site environmental performances lies behind these relationships, which makes assessment process complicated for decision maker(s). Hence, the model is developed as a multi-criteria decision-making model to define best subcontractors based on specified environmental performance criteria. Integrated FAHP and TOPSIS methods are selected to be adapted to the model to calculate the weight of the environmental performance criteria according to environmental priorities of the decision maker(s) and to rank subcontractors based on these weighted criteria.

FAHP is developed based on Saaty's AHP [25], which uses fuzzy ratios instead of exact ratios [26]. The basic aim of FAHP is the same as AHP, which is to define the weight of the assessment criteria, sub criteria and alternatives by taking into account decision maker(s)' standard of judgment through pairwise comparisons [27]. The most important difference between AHP and FAHP is the scales and statements used for pairwise comparisons. FAHP uses linguistic statements instead of numerical ones, which enables assessment in a subjective environment and makes judgment easier for the decision maker(s), and integrates fuzzy numbers into the assessment [11]. TOPSIS was first developed to provide choosing the best solution among alternatives. The selected alternative is expected to be close to the ideal solution, while it is distant from the non-ideal solution. The decision-maker(s) define the weight of the assessment criteria and then assess different alternatives with respect to each assessment criteria. Therefore, the assessment process requires a limited number of steps that makes the assessment easier for the decision maker(s) [28].

The Environmental Decision Making Model (EDM) (Fig. 2) is developed by following the steps below:

1. The on-site environmental performance of the subcontractor is defined as *the decision problem.*
2. *The main goal* is set forth as sorting subcontractors according to their on-site environmental performances based on the decision maker(s) environmental priorities and goals.

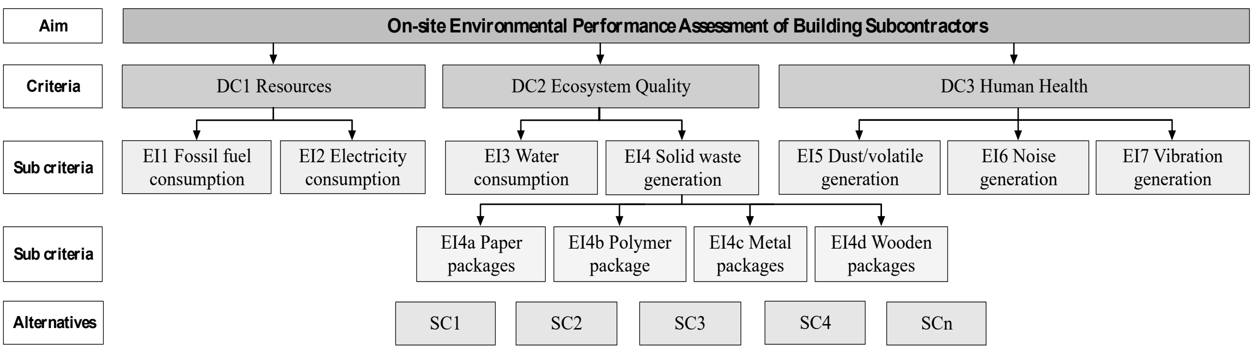

Fig. 2 Environmental decision making model for construction process

3. Damage Categories and Environmental Indicators are included in the model as *the decision criteria and sub criteria*. Environmental Aspects are excluded from the model as they only explain the impacts caused by the indicators.
4. Alternatives of subcontractors are defined as *the decision alternatives.*
5. *The decision maker(s)* are designated as owner(s), architect(s), and contractor, who are/can be directly involved in the construction planning process. The owner cannot participate in the decision process if he/she does not have a background in environmental knowledge.
6. *FAHP* is used to define the weight of the parameters based on the pairwise comparisons of the *environmental performance criteria by the decision maker(s).*
7. *The quantitative data regarding with construction technologies* is provided by subcontractors based on their previous experiences and available facilities.
8. *TOPSIS* is used for *ranking alternatives of subcontractors* by using quantitative data gathered from the subcontractors and weight of the environmental performance criteria.

The EDM consists of the steps below:

1. Definition of alternative subcontractors for a specific design or design alternatives.
2. Designation of the decision maker(s).
3. Realization of pairwise comparisons with the decision maker(s).
4. Definition of the weight of the Damage Categories and the Environmental Indicators through mathematical calculations of FAHP.
5. Obtaining quantitative data about construction technology components from each subcontractor, which are used for the construction of design alternative(s) in question.
6. Performing mathematical calculations of TOPSIS to rank the subcontractors.
7. Analysis of the results within relationships between construction technology components and environmental performance criteria to choose the best subcontractor or improve the performance of a particular contractor.

V. Application of the Model

The EDM was used to assess on-site environmental performances of subcontractors, who were assigned to construct three different floor systems that are in question to be used in an office project (Table II).

The aim of the application was to select best floor system design alternative based on the on-site environmental performances of their subcontractors. The head of the design team, who is also responsible for on-site supervision and has a background in environmentally conscious design, was assigned as the decision maker for the assessment process. First, the respondent performed pairwise comparisons to be able to get the weights of the environmental performance criteria. The respondent considered their experiences from previous construction sites to analyze each criterion. Linguistic statements and fuzzy triangular numbers, which are proposed by Buckley (26), were used for the pairwise comparisons and the calculations (Table III). According to pairwise comparisons, FAHP calculations were performed, and weights were gathered for each criterion. Then, quantitative data about construction technology components were collected for each of the design alternatives from specifications of subcontractors, material and equipment catalogs, and the Turkish Unit Price library by following the proposed data gathering process (Fig. 3). Then these quantitative data were used for TOPSIS calculations to rank the three floor systems designs based on the on-site performance of the selected subcontractors.

TABLE II
FLOOR SYSTEMS ALTERNATIVES

	Basic and supplementary materials
Floor system-1	• Artificial precast floor tile (20 mm) • Adhesive (8 mm) • Screed (42 mm) • Reinforced concrete slab (270 mm)
Floor system-2	• Linoleum covered panel (40 mm) • Metal pedestal for raised floor system • Dust free epoxy paint • Reinforced concrete slab (270 mm)
Floor system-3	• Ceramic floor tile (8 mm) • Ceramic adhesive (5 mm) • Cement-acrylic based liquid waterproofing • Screed with mesh reinforcement (50 mm) • Aerated concrete filling (137 mm) • Reinforced concrete slab (270 mm)

TABLE III
LINGUISTIC STATEMENTS AND RELATED FUZZY TRIANGULAR NUMBERS

Linguistic Statements	Fuzzy Triangular Numbers
Equally important	(1, 1, 1)
Weakly important	(2, 3, 4)
Fairly important	(4, 5, 6)
Strongly important	(6, 7, 8)
Absolutely important	(9, 9, 9)

VI. Results & Discussion

The weights of the Damage Categories and Environmental Performance Indicators that were gathered through FAHP calculations, and the ranks of the subcontractors of each floor system alternatives that were gathered through TOPSIS calculations are shown in Table IV.

DC1 Resources, DC3 Human Health, and DC2 Ecosystem Quality damage categories obtained 49%, 43%, and 8% weights, respectively. Based on these weights and quantitative data, FS-3 got the 1^{st} rank; FS-1 got the 2^{nd} rank and FS-2 obtained the 3^{rd} rank according to the damage categories. In accordance with these results, FS-3 has the highest impact on the environment and is followed by FS-1 and FS-2. The motives of these results can be explained as follows:

- FS-3 and FS-1 have on-site prepared bonding agent usage as part of the construction technique and for the additional screed layer, which causes water and electricity consumption during the preparation process.
- These preparation processes and filling layer of FS-3 cause dust and noise generation.

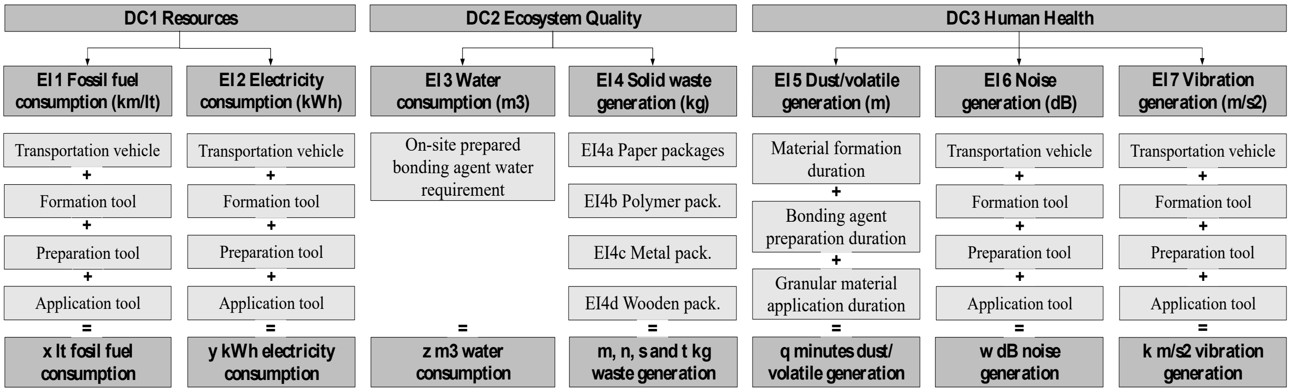

Fig. 3 Required quantitative datasets obtained for related construction technology components

- On the other hand, FS-2 does not require any additional preparation process, which may be harmful to the ecosystem and human health.

EI1 Fossil Fuel Consumption and EI2 Electricity Consumption indicators obtained equal weights as 50% and, subcontractors for the alternatives in question are ranked for DC1 Resources damage category as FS-3, FS-1, and FS-2, respectively. In comparison to the FS-2; FS-3 and FS-1 have additional transportation and preparation processes in consequence of the amount of materials and the type of the joining materials, which contributes to these results due to increase in fossil fuel and electricity consumption of equipment usage.

TABLE IV
ON-SITE ENVIRONMENTAL PERFORMANCE ASSESSMENT RESULTS FOR THE CONTRACTORS OF FLOOR SYSTEM ALTERNATIVES

		Environmental Performance Criteria													
		DC1 Resources	DC2 Ecosystem Quality	DC3 Human Health	EI1 Fossil Fuel Consumption	EI2 Electricity Consumption	EI3 Water Consumption	EI4 Solid Waste Generation	EI4a Paper Packages	EI4b Polymer Packages	EI4c Metal Packages	EI4d Wooden Packages	EI5 Dust/ Volatile Generation	EI6 Noise Generation	EI7 Vibration Generation
FAHP Weights		49%	8%	43%	50%	50%	50%	50%	7%	23%	59%	10%	62%	30%	9%
Ranks	FS-1	2			2		1		2				1		
	FS-2	3			3		3		1				3		
	FS-3	1			1		2		2				2		

DC: Damage Categories; EP: Environmental Performance Indicators; FS: Floor System Alternatives

EI3 Water Consumption and EI4 Solid Waste Generation indicators also obtained equal weights as 50% and, according to DC2 Ecosystem Quality damage category FS-1 got the 1st rank and followed by FS-3 and FS-2, respectively. Both FS-1 and FS-3 have the same construction technology characteristics based on water consumption as mentioned before, while FS-1 generates more solid waste due to packaging properties of artificial precast floor tiles, which has the significant role in the results.

EI4c Metal, EI4b Polymer, EI4d Wooden and EI4a Paper packages sub-indicators of the EI4 Solid Waste Generation indicator got 59%, 23%, 10% and 7% weights, respectively. While FS-2 got the 1st rank for EI4 Solid Waste Generation indicator, FS-1 and FS-3 obtained the 2nd rank. The results can be interpreted as follows:

- FS-1 and FS-3 generate wooden and paper wastes, while FS-2 generates paper and polymer wastes.
- The judgments of the respondent for the waste generation and waste treatment were based on the waste management of the previous construction sites they were involved in.
- According to the respondent's assessment, polymer wastes got the second highest rank, which makes FS-2 the worst option related to waste criteria.

EI5 Dust/Volatile Generation, EI6 Noise Generation and EI7 Vibration Generation indicators of DC3 Human Health damage category obtained weights as 62%, 30% and 9%, respectively. For this damage category, FS-1 got the 1st rank, while FS-3 got the 2nd and FS-2 got the 3rd rank. The motives of these results can be explained as follows:

- FS-1 and FS-3 have on-site bonding agent preparation process, and FS-3 has aerated concrete filling, which causes dust.
- FS-1 requires more time for preparation process, which makes it the most hazardous alternative for human health.
- The equipment used for the transportation of the materials, the preparation, and the application causes more noise and vibration for FS-1 and FS-3 due to additional materials and processes than FS-2 has.

VII. CONCLUSION

The presented environmental decision-making model for assessing on-site performances of subcontractors reveals the role of the construction process on the environmental impacts. Although the quantitative data that are gathered for the construction technology components can give an overview of these impacts; priorities, concerns or expectations of the decision maker(s) have a substantial effect on the overall results. The fundamental requirement of the model is to inform decision maker(s) about environmental performance criteria, classification of construction technologies, the relationships among them and the virtue of the pairwise comparisons to avoid or to lessen bias and conflicts on the results. The background, experiences, and knowledge on environmental issues possessed by the decision maker(s) should also be considered in the assignment of the decision maker(s). It is also important to get the required quantitative data, properly. Therefore, the model provides an opportunity to analyze the environmental consequences of the construction process through pairwise comparisons, data gathering process and analysis of the final results. The results of the application process show that the model can be used for selecting best subcontractor based on on-site environmental performance, and it can provide a chance to subcontractors to analyze and improve their activities and construction technology facilities in consideration of environmental aspects.

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