EnvironalPlanning: Analytic Network Process Model for Environmentally Conscious Construction Planning

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Abstract: Although the construction pollution index has been put forward and proved to be an efficient approach to reducing or mitigating pollution level during the construction planning stage, the problem of how to select the best construction plan based on distinguishing the degree of its potential adverse environmental impacts is still a research task. This paper first reviews environmental issues and their characteristics in construction, which are critical factors in evaluating potential adverse impacts of a construction plan. These environmental characteristics are then used to structure two decision models for environmental-conscious construction planning by using an analytic network process (ANP), including a complicated model and a simplified model. The two ANP models are combined and called the *EnvironalPlanning* system, which is applied to evaluate potential adverse environmental impacts of alternative construction plans.

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Introduction

Environmental issues in construction typically include soil and ground contamination, water pollution, construction and demolition waste, noise and vibration, dust, hazards emissions and odors, wildlife and natural features demolition, and archaeological destruction (Coventry and Woolveridge 1999). Over the last 30 years, there have been numerous studies related to environmental issues in construction. Some examples include the study on air pollution (Henderson 1970), noise pollution (U.S. EPA 1971), water pollution (McCullough and Nicklen 1971), and solid waste pollution (Spivey 1974a) generated from construction sites. On the other hand, although the expression of environmental management (EM) in construction was first coined in the *U.S. National Environmental Policy Act* of 1969 (Warren 1973), the embryonic concept of EM in construction was not formulated until the late 1970s when the role of environmental inspector was introduced in the design and construction phases of projects. The environmental inspector, who plays the role of environmental monitor (Dodds and Sternberger 1992), is a specialist whose academic background or experience results in considerable understanding of environmental impacts and applicable control measures, and acts as an advisor to construction engineers on all matters of EM (Spivey 1974b; Henningson 1978). Moreover, enthusiasm for establishing an environmental management system in a commercial construction company has grown quickly following two main important EM standards *BS 7750* (enacted in 1992) and *ISO 14000* series of standards (enacted in 1996). The EM standards are regarded as guidance to construction industry from passive and one-sided construction management on contamination reduction to active and all-round EM.

However, current approaches to environmental control and management appear to be very qualitative. Our searching results from the American Society for Civil Engineering (ASCE's) *CEBD* and the Ei's *Compendex* databases (see Table 1) indicate that only 2% of papers provide quantitative methods for EM in construction in the total number of papers related to EM in construction. In particular, to our knowledge there have been very few studies on integrating concerns of EM in the construction planning stage. Construction planning involves the choice of construction technology, equipment, and materials, the definition of work tasks, the layout of construction site, the estimation of required resources and durations for individual tasks, the estimation of costs, the preparation of a project schedule, and the identification of any interactions among the different work tasks etc. (Hendrickson and Au 2000; Hendrickson and Horvath 2000). As a fundamental and challenging task, construction planning should not only strive to meet common concerns such as time, cost and quality requirement, but also explore possible measures to minimize environmental impacts of the projects at the outset.

Although our previous work on proposing the concept of construction pollution index (CPI) as a quantitative approach has proven to be useful for indicating, reducing, or mitigating pollution level during construction planning stage (Chen et al. 2000; Li et al. 2002), the problem of how to select the best construction plan based on leveling the magnitude of adverse environmental impacts of construction operations/activities is still a research task. Moreover, the major premise of CPI's application in construction plan evaluation is that each construction activity's CPI can be linearly aggregated, and this hypothesis cannot directly

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Table 1. Statistical Classification of Refereed Articles on Environmental Issues in Construction

Research highlight	Reference starting point	Reference number (as of December 31, 2002)	
		ASCE's *CEDB*[a] (Since 1972)	Ei's *Compendex*[b] (Since 1970)
Technology		94	358
Environmental-friendly innovated technology	Taylor et al. (1976)	36	65
Pollution prevention and minimization		58	293
Air pollution	Henderson (1970)	—	—
Noise pollution	USEPA (1971)	—	—
Water pollution	McCullough and Nicklen (1971)	—	—
Waste pollution	Spivey (1974a,b)	—	—
Management		213	367
Environmental survey	Spivey (1974a,b)	12	41
Environmental/quality management system	Dohrenwend (1973)	11	28
Environmental/quality management approach	Dohrenwend (1973)	7	18
Information technology	Kawal (1971)	183	280
Material		60	183
Eco-friendly regenerated construction material	Emery (1974)	35	93
Waste reuse and recycling	Spivey (1974a,b)	25	90

[a]ASCE's *CEDB* is available online via http://www.pubs.asce.org/cedbsrch.html

[b]Ei's *Compendex* is available online via http://www.engineeringvillage2.org/

reflex the complicated nonlinear causal relationship on environmental impact among construction activities. In this paper, we introduce the use of analytic network process (ANP) model to develop a decision model which is called *EnvironalPlanning*. The *EnvironalPlanning* system can integrate important considerations of construction planning, which include time, cost, quality, and safety with the evaluation of the impact of various environmental factors, so that the most suitable plan can be obtained.

Methodology

A construction plan is normally evaluated through fixed criteria for cost, time, quality, safety, and so on during the planning period. Since effective planning has considerable influence on the successful completion of a construction project, both construction managers and researchers are aware of tools used to prepare and evaluate a construction plan. The analytic hierarchy process (AHP), which is known as a powerful and flexible decision making process to help people set priorities and make the best decision when both qualitative and quantitative aspects of a decision need to be considered, has been utilized in various areas of construction research and practice since the late 1970s (Zeeger and Rizenbergs 1979), including construction planning. In this regard, the AHP method is recommended by construction researchers as a useful multicriteria assessment tool for its stronger mathematical foundation, its ability to gauge consistency of judgments, and its flexibility in the choice of ranges at the subcriteria level (Khasnabis et al. 2002).

However, a notable weakness of AHP is that it cannot deal with interconnections between decision factors in the same level, because an AHP model is structured in a hierarchy in which no horizontal links are allowed. In fact, this weakness can be overcome by using a senior multicriteria analytical technique known as ANP. The ANP is more powerful in modelling complex decision environments than the AHP because it can be used to model very sophisticated decisions involving a variety of interactions and dependencies (Meade and Sarkis 1999; Saaty 1999). These advantages are embodied in a lot of examples of applications of the ANP (Peniwati Srisoepardani 1996). For example, Saaty (1996) recommended the ANP to be used in cases where the most thorough and systematic analysis of influences needs to be made. Apart from this, the ANP method has been successfully applied to the strategic evaluations of environmental practices and programs in both of manufacturing and business to help in analyzing various project, technological, or business decision alternatives, and it also has been proven to be useful for modeling dynamic strategies and systemic influences on managerial decision related to the EM (Meade and Sarkis 1999). As a result, the ANP is selected as a tool in this study.

Environmental Indicators

In order to find suitable environmental indicators to evaluate a construction plan, an extensive literature review was conducted according to this classification of environmental indicators. The literature review on environmental issues in construction was conducted in several target dominant databases including the civil engineering database (CEDB) of the American Society of Civil Engineers (ASCE), the *Compendex* database of the Engineering Index (Ei), the Engineering News Record executive search engine (enr.com), and magazines of the McGraw–Hill Companies, the Construction Plus (CN+) search engine (www.cnplus.co.uk) of the Emap Construction Network, and the advanced search engine of the U.S. Environmental Protection Agency (U.S. EPA) (epa.gov). In addition to these five dominant databases, a commonly used search engine, Google, was also employed to search for online literature. For our search results, we retrieved thousands of articles and reports related to environmental impacts and the EM in construction practice.

The summary of the literature retrieved is listed in Table 1 which indicated that about 367 references in the ASCE's *CEDB* and 908 references in the Ei's *Compendex*, related to the subject of environmental-friendly construction technology, construction management, and construction material are identified.

Environmental indicators here refer to factors that can bring adversely or favorably impact on the natural environment by a

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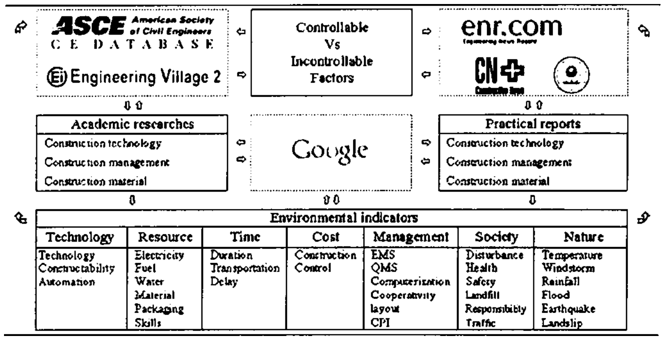

Fig. 1. Framework for collecting environmental indicators

construction project and can directly influence construction planning. Based on this, environmental factors can be grouped into adverse environmental factors (denoted as EA factors) and favorable environmental factors (denoted as EF factors). The third category of indicators is those that may lead to adverse or favorable environmental impact, depending on the specific environmental conditions in which a construction project is executed. This category of environmental indicators called uncertain environmental indicators, or EU factors.

Following the classification described above, a procedure for collecting environmental indicators is further illustrated in Fig. 1. It indicates that the environmental indicators were collected based on an extensive literature review of databases and online materials. The environmental indicators are interrelated with technology, resource, time, cost, management, society, and surrounding nature in which a construction project is executed.

The environmental indicators for construction planning are collected and sorted by their environmental impacts (EI_i) in Table 2. The value of environmental impacts for an environmental indicator i (EI_i) is calculated using the following equation, which is a sum of 8 generally recognized, and most concerned, environmental hazards and/or pollutions caused by the indicator. These eight hazards include soil and ground contamination, ground and underground water pollution, construction and demolition waste, noise and vibration, dust, hazardous emissions and odors, wildlife and natural features impacts and archaeology impacts (Chen et al. 2000):

$$\mathrm{EI}_i = \sum_{j=1}^{8} \mathrm{EI}_{i,j} \quad (j = 1,2, \ldots ,8) \tag{1}$$

where EI_i=total environmental impact caused by environmental indicator i; and EI_{ij}=individual environmental impact caused by eight possible hazards including soil and ground contamination (j=1), ground and underground water pollution (j=2), construction and demolition waste (j=3), noise and vibration (j=4), dust (j=5), hazardous emissions and odors (j=6), wildlife and natural features impacts (j=7), and archaeology impacts (j=8) caused by the environmental indicator i. Its value is defined to be one of the three choices $\{-1,0,+1\}$, where -1 represents that the environmental indicator will intensify the level of hazard; 0 represents uncertain effect that the environmental indicator will bring; and +1 represents that the environmental indicator will reduce the level of hazard. It is necessary to note that the value range of $\{-1,0,+1\}$ is empirically defined by us, based on our experience in identifying and measuring environmental impacts in the construction industry.

The assumed value of environmental impact of each environmental indicator (EI_i) is then used to reclassify the environmental indicators which have been achieved from the literature review in order that the new classification can be more flexible to all kinds of construction projects. The environmental indicators, together with their original classification and corresponding values of $\mathrm{EI}_{i,j}$, are listed in Table 2. According to the results of environmental impacts listed in Table 2, all environmental indicators are finally classified into EA factors ($\mathrm{EI}_i<0$), EF factors ($\mathrm{EI}_i>0$), and EU factors ($\mathrm{EI}_i=0$) (see Table 3). These reclassified environmental indicators are to be used for constructing an ANP model for evaluating environmental impact of a construction plan.

In addition to the classification of these environmental indicators and their EI_i values, Table 3 also provides corresponding values of experimental plan alternatives including plans A, B, and C, based on a construction background in Shanghai, China.

Analytic Network Process Model and Approach

As defined by Saaty (1996; 1999), the ANP is a general theory of relative measurement used to derive composite priority ratio scales from individual ratio scales that represent relative measurements of the influence of elements that interact with respect to control criteria. The ANP is a coupling of two parts: one is a control hierarchy or network of criteria and subcriteria that control the interactions (interdependencies and feedback); another is a network of influences among the nodes and clusters. Moreover, the control hierarchy is a hierarchy of criteria and subcriteria for which priorities are derived in the usual way with respect to the goal of the system being considered. The criteria are used to compare the components of a system, and the subcriteria are used to compare the elements of a component. Steps of the ANP analysis for the environmental-conscious construction planning is laid out below from Steps A to D.

Step A: Analytic Network Process Model Construction

This step aims to construct an ANP model for evaluation based on determining the control hierarchies such as benefits, costs, opportunities and risk, as well as the corresponding criteria for comparing the components (clusters) of the system and subcriteria for comparing the elements of the system, together with a determination of the clusters with their elements for each control criteria or subcriteria.

The *EnvironalPlanning* system is outlined in Fig. 2. The decision environment includes exterior environment and internal environment. In the exterior *EnvironalPlanning* environment, the downward arrow indicates the process of transferring data required by the ANP, the upward arrow indicates the process of feedback with evaluation results from the ANP, and the feedback process (loop) between the exterior environment and the internal environment indicates a circulating pipe for environmental priority evaluation of alternative construction plans. In the internal *EnvironalPlanning* environment, connections among four clusters and 35 nodes are modeled by two-way and looped arrows to describe the interdependences between the clusters and nodes. The four clusters are Plan Alternatives (C_1), EA factors (C_2), EU factors (C_3), and EF factors (C_4). Corresponding to the four clusters, there are 35 nodes including 3 nodes in C_1 ($N_{1\,1\sim3}$), 14 nodes in C_2 ($N_{2\,1\sim14}$), 3 nodes in C_3 ($N_{3\,1\sim3}$), and 15 nodes in C_4 ($N_{4\,1\sim15}$). Fig. 2 illustrates the *EnvironalPlanning* system implemented using an ANP with all interior clusters and nodes,

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Table 2. Environmental Indicators and Their Potential Environmental Impacts to Construction Plan

Class	Environmental indicators	Unit	Potential environmental impacts (EI_i)									Representative references
			$EI_{i,1}$[a]	$EI_{i,2}$[b]	$EI_{i,3}$[c]	$EI_{i,4}$[d]	$EI_{i,5}$[e]	$EI_{i,6}$[f]	$EI_{i,7}$[g]	$EI_{i,8}$[h]	$\sum_{j=1}^{s} EI_{i,j}$	
Technology	Cleaner technologies and automation ratio	percent	+1	+1	+1	+1	+1	+1	+1	+1	+8	Rosenfeld and Shapira (1998);Jones and Klassen (2001);Tiwari (2001);Reddy and Jagadish (2003)
	Constructability	percent	0	0	0	0	0	0	0	0	0	Mifkovic and Petersen (1975);Hinckley (1986);Bonforte and Keeber (1993)
Resource	Electricity consumpt in amount	kilowatthour[i]	0	0	−1	−1	−1	−1	0	0	−4	Hendrickson and Horvath (2000)
	Fuel consumption amount	joule	−1	−1	−1	−1	−1	−1	−1	−1	−8	Mohr (1975); Peyton (1977); Reardon (1995); Peurifoy (2002)
	Water consumption amount	ton	−1	−1	−1	0	+1	0	−1	0	−4	Gambatese and James (2001)
	Wastewater treatment/reuse ratio	percent	+1	+1	+1	0	0	0	0	0	+3	Leung (1999)
	Material serviceability	percent	0	0	+1	0	0	0	0	0	+1	Orofino (1989); Suprenant (1990); Horvath and Hendrickson (1998); Lippiatt (1999)
	Material durability	percent	+1	+1	+1	0	0	0	0	0	+3	Orofino (1989); Suprenant (1990); Horvath and Hendrickson (1998); Lippiatt (1999)
	Cargo packaging recycling ratio	percent	0	0	+1	0	+1	+1	0	0	+3	Ross and Evans (2003)
	Generative material use ratio	percent	0	0	0	0	0	0	0	0	0	Austin (1991); Masters (2001);Sawhney (2002); Reddy and Jagadish (2003)
	Waste generating rate	percent	−1	−1	−1	0	−1	0	0	0	−4	Gavilan and Bernold (1994)
	Waste reuse & recycling ratio	percent	+1	0	+1	0	0	0	0	0	+2	Walter (1976); Gidley and Sack (1984); Rhatigan and Irwin (2001)
	Health & safety risk to staff	percent	0	0	0	+1	+1	+1	+1	0	+4	Morris (1976); Wong et al. (1985); Austin (1991); Sauni et al. (2001); Abdelhamid et al. (1999); Bello and Everett(2002)
	Required skills on staff	percent	0	0	+1	0	+1	0	0	0	+2	Chen et al. (2002)
Time	Construction duration	day	−1	−1	−1	−1	−1	−1	−1	−1	−8	Morris and Novak (1976)
	Transportation time	hour	0	0	0	−1	−1	−1	−1	11	−5	
	Construction delay risk	hour	0	0	−1	0	−1	−1	0	0	−3	Suprenant and Malisch (2000)
Cost	Construction cost	dollars	−1	−1	−1	−1	−1	−1	−1	−1	−8	Koehn (1976)
	Environmental control cost	dollars	+1	+1	+1	+1	+1	+1	+1	+1	+8	Parker (1998)
Management	ISO 14001 EMS adoption	percent	+1	+1	+1	+1	+1	+1	+1	+1	+8	Kloepfer (1997)
	ISO 9001 QMS adoption	percent	0	0	0	0	0	0	0	0	0	Osuagwu (2002)
	Computerizations	percent	+1	+1	+1	+1	+1	+1	+1	+1	+8	Sailor (1974); Arnfalk (1999)
	Cooperativity/Unionization risk	percent	+1	+1	+1	+1	+1	+1	+1	+1	+8	Schodek (1976)
	Site layout suitability	percent	+1	+1	+1	+1	+1	+1	+1	+1	+8	Tatum (1978)
Society	Public health & safety risk	percent	−1	−1	−1	−1	−1	−1	0	0	−6	Griffith (1994); USEPA (2002a,b,c)
	Waste disposal price	dollars	+1	+1	+1	+1	+1	+1	+1	+1	+8	Austin (1991)
	Legal involvements	percent	+1	+1	+1	+1	+1	+1	+1	+1	+8	Lavers and Shiers (2000); Grigg et al. (2001)
	Public traffic disruptions	day	0	0	0	−1	−1	−1	−1	0	−4	USEPA (2002a,b,c)
	Cargo transportation burden	ton mile	0	0	0	−1	−1	−1	−1	0	−4	USEPA (2002a,b,c)
Nature	Temperature affection risk	percent	0	−1	−1	0	−1	0	0	0	−3	Morris (1976); Tian (2002)
	Storm affection risk	percent	0	0	−1	0	−1	−1	0	0	−3	Rutherford (1981); Sparks et al. (1989); Carper (1990)
	Earthquake affection risk	percent	−1	−1	−1	0	−1	−1	0	0	−5	Islam (1999); Maitra (1999); Rosowsky (2002)

Note: Empricial value of $EI_{i,j}.EI_{i,j} \in =(-1,0,+1)$ (−1 represents adverse environmental impact, 0 represents indefinite environmental impact, and 1 represents favorable environmental impact).

[a]$EI_{i,1}$ represents environmental impact for soil and ground contamination.

[b]$EI_{i,2}$ represents environmental impact for ground and underground water.

[c]$EI_{i,3}$ represents environmental impact for construction and demolition waste.

[d]$EI_{i,4}$ represents environmental impact for noise and vibration.

[e]$EI_{i,5}$ represents environmental impact for dust.

[f]$EI_{i,6}$ represent environmental impact for hazardous emissions and odors.

[g]$EI_{i,7}$ represent environmental impact for wildlife and natural features impacts.

[h]$EI_{i,8}$ represents environmental impact for archaeology impacts.

[i]The kilowatthour (kWh) is a unit of energy equivalent to 1 kW of power expended for 1 h of time. An energy expenditure of 1 kWh represents 3,600,000 J (3.600×10^6 J) (source: http://whatis.techtarget.com/).

Table 3. Environmental Indicators and Corresponding Value of Plan Alternatives for Analytic Network Process Model

				Plan alternatives		
Classification	Environmental indicators	Unit	EI_i[a]	A	B	C
Environmental adverse factors	1.1 Fuel consumption amount (FCA)	Megajoule	−8	36k	45k	49k
	1.2 Construction duration (COD)	day	−8	500	560	450
	1.3 Construction cost (COC)	dollars (million)	−8	30	31	29
	1.4 Public health & safety risk (PHS)	percent	−6	10	20	25
	1.5 Transportation time (TRT)	hour	−5	4.0k	4.5k	4.8k
	1.6 Earthquake affection risk (EAR)	percent	−5	0.01	0.01	0.01
	1.7 Electricity consumption amount (ECA)	kilowatthours	−4	30k	45k	50k
	1.8 Water consumption amount (WCA)	ton	−4	3.1k	3.8k	4.1k
	1.9 Waste generating rate (WGR)	percent	−4	1.2	3.0	3.5
	1.10 Public traffic disruptions (PTD)	day	−4	39	60	70
	1.11 Cargo transportation burden (CTB)	ton mile	−4	450k	500k	550k
	1.12 Construction delay risk (CDR)	hour	−3	150	200	220
	1.13 Temperature affection risk (TAR)	percent	−3	10.0	8.9	8.7
	1.14 Storm affection risk (SAR)	percent	−3	2.0	1.8	1.8
Environmental uncertainty factors	2.1 Constructability (COB)	percent	0	100	100	100
	2.2 Generative material use ratio (GMU)	percent	0	20	10	8
	2.3 ISO 9001 QMS adoption (QMS)	percent	0	100	100	100
Environmental-friendly factors	3.1 Cleaner technologies & Automation ratio (CTA)	percent	+8	80	50	40
	3.2 Computerizations (PCA)	percent	+8	80	80	80
	3.3 Environmental control cost (ECC)	dollars (million)	+8	0.8	0.5	0.5
	3.4 ISO 14001 EMS adoption (EMS)	percent	+8	0	0	0
	3.5 Cooperativity/Unionization risk (COP)	percent	+8	100	80	60
	3.6 Site layout suitability (SLS)	percent	+8	80	60	50
	3.7 Waste disposal price (WDP)	dollars (million)	+8	0.10	0.25	0.29
	3.8 Legal & Responsibility risk (LRR)	percent	+8	0.10	0.23	0.32
	3.9 Health & safety risk to staff (HSR)	percent	+4	0.10	0.21	0.28
	3.10 Wastewater treatment/reuse ratio (WTR)	percent	+3	90	50	40
	3.11 Material durability (MAD)	percent	+3	100	80	80
	3.12 Cargo packaging recycling ratio (CPR)	percent	+3	100	50	0
	3.13 Waste reuse & recycling ratio (WRR)	percent	+2	90	30	35
	3.14 Required skills on staff (RSS)	percent	+2	80	60	60
	3.15 Material serviceability (MAS)	percent	+1	100	80	80

Note: The corresponding value of plan alternatives is calculated based on relative information and data in each construction plan alternative and no formulas and details are to be provided for these calculations in this paper.

[a]$EI_{i,j}$ value equals to $\Sigma EI_{i,j}$ (see Table 3).

and exterior related participators. Concerning the interdependences between any two clusters and any two nodes, the *EnvironalPlanning* system structured here is a simple ANP model containing feedback and self-loops among the clusters, but with no control model, because there is an implicit control criterion with respect to which all judgments (paired comparisons) are made in this model: *Environmental Impact*. For example, when comparing the cluster EA factors (C_2) to cluster EF factors (C_4), the latter is obviously more important for reducing negative environmental impacts, and similarly when the node comparisons are made (see Step B), relative importance of the nodes can be decided in the same way. Table 2 lists the 35 environmental indicators used in constructing the ANP model and the corresponding references from which the indicator is retrieved.

Step B: Paired Comparisons

This step aims to perform pairwise comparisons among the clusters, as well as pairwise comparisons between nodes, as they are interdependent on each other. On completing the pairwise com-

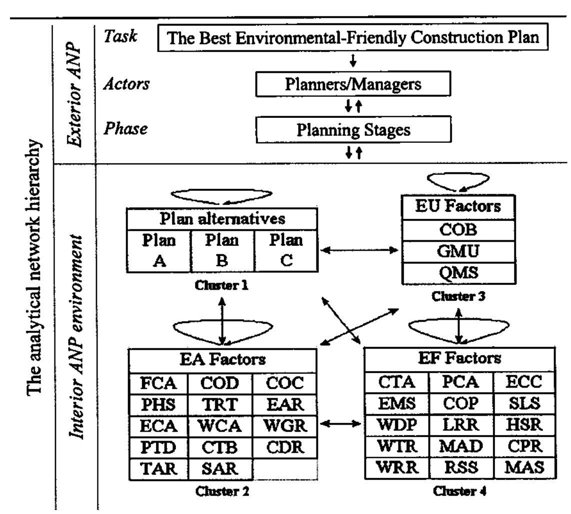

Fig. 2. *EnvironalPlanning* analytic network process environment

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Table 4. Pairwise Judgment of Indicator *i*

Indicator	Pairwise judgement scale[a]								
	1	2	3	4	5	6	7	8	9
Indicator *i*									
Plan A	×	×	✔	×	×	×	×	×	×
Plan B	×	×	×	×	✔	×	×	×	×
Plan C	×	×	×	×	×	×	✔	×	×
Indicator I_i	×	×	×	×	✔	×	×	×	×
Indicator I_j	×	×	×	×	✔	×	×	×	×

Note: The fundamental scale of pairwise judgment is given in Fig. 3. The symbol × denotes item under selection for pairwise judgment, and the symbol ✔ denotes selected pairwise judgment.

[a]1=equal; 2=equal to moderately dominant; 3=moderately dominant; 4=moderately to strongly dominant; 5=strongly dominant; 6=strongly to very strongly dominant; 7=very strongly dominant; 8=very strongly to extremely dominant; and 9=extremely dominant.

parisons, the relative importance weight (denoted as a_{ij}) of interdependence is determined by using a scale of pairwise judgment, where the relative importance weight is valued from 1 to 9 (Saaty 1996). The fundamental scale of pairwise judgment is given in Table 4.

The weight of interdependence is determined by a human decision maker who is abreast with professional experience and knowledge in the application area. In this study, it is determined by the authors as the objective of this study is mainly to demonstrate the usefulness of the ANP model in evaluating the potential environmental impact due to executing a construction plan.

Weights for all interdependences for a particular construction plan are then aggregated into a series of submatrices. For example, if the cluster of plan alternatives includes Plans A, B, and C, and each of the plans is connected to nodes in the cluster of EF factors, pairwise judgments of the cluster thus result in relative weights of importance between each plan alternative and each EF factor. The aggregation of the weights thus forms a 3×14 submatrix located at "W_{21}" in Fig. 3. It is necessary to note that pairwise comparisons are necessary to all connections (clusters and nodes) in the ANP model to identify the level of interdependences which are fundamental in the ANP procedure. The series of submatrices are then aggregated into a supermatrix which is denoted as supermatrix *A* in this study, and it will be used to derive the initial supermatrix in the later calculation in Step C.

Table 4 gives a general form for pairwise judgment among environmental indicators and construction plan alternatives, which is adopted in this study. For example, for the environmental indicator 1.1 Fuel consumption amount (FCA) (EA factor 1), the pairwised judgments are given in Table 4, because the fuel consumption in Plan A is the least among the three plan alternatives, while the fuel consumption in Plan C is the highest; in

Supermatrix

$$W=\begin{bmatrix} W_{11} & W_{12} & W_{13} & W_{14} \\ W_{21} & W_{22} & W_{23} & W_{24} \\ W_{31} & W_{32} & W_{33} & W_{34} \\ W_{41} & W_{42} & W_{43} & W_{44} \end{bmatrix}$$

Cluster: C_1 C_2 C_3 C_4

Node: $N_{1_{1-3}}$ $N_{2_{1-14}}$ $N_{3_{1-3}}$ $N_{4_{1-15}}$

Submatrix

$$W_{IJ}=\begin{bmatrix} w_1|_{I,J} & \cdots & w_1|_{I,J} \\ w_2|_{I,J} & \cdots & w_2|_{I,J} \\ \cdots & \cdots & \cdots \\ w_i|_{I,J} & \cdots & w_i|_{I,J} \\ \cdots & \cdots & \cdots \\ w_{N_{I_1}}|_{I,J} & \cdots & w_{N_{I_n}}|_{I,J} \end{bmatrix}$$

Note: *I* is the index number of rows; and *J* is the index number of columns; both I and J correspond to the number of cluster and their nodes ($I, J \in (1, 2, \ldots, 35)$), N_I is the total number of nodes in cluster *I*, *n* is the total number of columns in cluster *I*. Thus a 35×35 supermatrix is formed.

Fig. 3. Formulation of supermatrix and its submatrix for *EnvironalPlanning* system

addition to this judgment in property, quantitative pairwise judgments are also conducted in order to define plan alternatives' priorities. After finishing a series of pairwise judgments, from environmental indicator 1 to *n*, the calculation of the ANP can thus be conducted following Steps C to D. Besides the pairwise judgment between an environmental indicator and a construction plan, the developed *EnvironalPlanning* system contains all other pairwise judgments between each two environmental indicators (I_i and I_j in Table 4) and this essential initialization is set up based on the quantitative attribute of each plan alternative which has been given in Table 3.

Step C: Supermatrix Calculation

This step aims to form a synthesized supermatrix to allow for the resolution of the effects of the interdependences that exists between the elements (nodes and clusters) of the ANP model. The supermatrix of the *EnvironalPlanning* system is a two-dimensional partitioned matrix consisting of 16 submatrices (see Fig. 3).

In order to obtain useful information for construction plan selection, the calculation of supermatrix is to be conducted following three substeps which transform an initial supermatrix to a weighted supermatrix, and then to a synthesized supermatrix.

At first, an initial supermatrix of the ANP model is created. The initial supermatrix consists of local priority vectors obtained from the pairwise comparisons between clusters and nodes. A local priority vector is an array of weight priorities containing a single column [denoted as $w^T=(w_1,w_2,\ldots,w_i,\ldots,w_n)$], whose components (denoted as w_i) are derived from a judgment comparison matrix *A* and deduced by the following equation (Saaty 2001):

$$w_i|_{I,J}=\sum_{i=1}^{I}\left(a_{ij}\Big/\sum_{j=1}^{J}a_{ij}\right)\Big/J \qquad (2)$$

where $w_i|_{I,J}$=weighted/derived priority of node *i* at row *I* and column *J*; and a_{ij}=matrix value assigned to the interdependence relationship of node *i* to node *j*. The initial supermatrix is constructed by substituting the submatrices into the supermatrix as indicated in Fig. 3. A detail of the initial supermatrix is listed in Fig. 4.

After the formation of the initial supermatrix, a weighted supermatrix is transformed. This process multiplies every node in a cluster of the initial supermatrix by the weight of the cluster, which has been established by pairwise comparison among the

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Super Matrix	Cluster	Plan alternatives			EA Factors														EU Factors			EF Factors														
	Node	Plan A	Plan B	Plan C	FCA	COD	COC	PHS	TRT	EAR	ECA	WCA	WGR	PTD	CTB	CDR	TAR	SAR	COB	GMU	QMS	CTA	PCA	ECC	EMS	COP	SLS	WDP	LRR	HSR	WTR	MAD	CPR	WRR	RSS	MAS
Initial supermatrix	PlanA	0.59173	0.67381	0.66942	0.58155	0.76116	0.71738	0.61185	0.57143	0.70097	0.70735	0.65865	0.66120	0.65707	0.69096	0.74291	0.77202	0.73338	0.24883	0.40648	0.59891	0.65308	0.41261	0.33194	0.72574	0.25000	0.49339	0.65003	0.67491	0.71881	0.70905	0.75825	0.74074	0.74446	0.77858	0.70735
	PlanB	0.33322	0.22554	0.24264	0.30900	0.16623	0.19420	0.17890	0.28571	0.19288	0.17003	0.15618	0.27178	0.19631	0.21764	0.18671	0.17344	0.19907	0.15606	0.26024	0.12619	0.25069	0.32749	0.13879	0.21221	0.25000	0.19580	0.17443	0.22385	0.22335	0.21184	0.09051	0.18518	0.14990	0.14282	0.17003
	PlanC	0.07506	0.10065	0.08795	0.10945	0.07261	0.08842	0.20925	0.14286	0.10615	0.12262	0.18517	0.06703	0.14663	0.09140	0.07038	0.05455	0.06754	0.59511	0.33328	0.27491	0.09623	0.25990	0.52926	0.06205	0.50000	0.31081	0.17553	0.10124	0.05783	0.07911	0.15125	0.07407	0.10564	0.07860	0.12262
	FCA	0.10534	0.11897	0.08027	0.00000	0.10956	0.06693	0.05852	0.08534	0.08051	0.12142	0.04187	0.10848	0.16334	0.06290	0.08018	0.08553	0.12853	0.10717	0.06976	0.09477	0.09090	0.09182	0.12693	0.11094	0.10905	0.07435	0.09544	0.08839	0.07943	0.10799	0.09429	0.08013	0.08565	0.11627	0.12823
	COD	0.08575	0.09606	0.06923	0.06614	0.00000	0.07155	0.06768	0.07937	0.09047	0.09891	0.08121	0.13433	0.11498	0.11408	0.07879	0.06744	0.10216	0.12303	0.07093	0.06816	0.10367	0.08708	0.08669	0.05887	0.10506	0.07630	0.10706	0.10523	0.08640	0.05556	0.07038	0.10552	0.08386	0.07824	0.09811
	COC	0.10967	0.06625	0.08715	0.09591	0.10821	0.00000	0.05006	0.05355	0.07583	0.12965	0.06155	0.07063	0.11884	0.06309	0.07953	0.06175	0.09594	0.11593	0.07627	0.06524	0.07906	0.11574	0.06963	0.08676	0.07471	0.12042	0.08510	0.09669	0.06815	0.11560	0.08776	0.06663	0.06872	0.17051	0.07477
	PHS	0.05896	0.08657	0.07203	0.27822	0.09669	0.08462	0.00000	0.11144	0.08037	0.14763	0.06968	0.03993	0.11363	0.03904	0.07055	0.04312	0.05655	0.07327	0.08398	0.08717	0.08476	0.06818	0.08647	0.10097	0.07580	0.07833	0.06913	0.09519	0.09487	0.06883	0.07414	0.08194	0.09510	0.15673	0.09756
	TRT	0.07590	0.08339	0.06735	0.06214	0.07140	0.07135	0.07358	0.00000	0.13044	0.08627	0.10738	0.06886	0.09180	0.09052	0.07067	0.08738	0.07708	0.07582	0.08128	0.05877	0.06138	0.08113	0.08310	0.07317	0.10513	0.06010	0.09430	0.09627	0.07280	0.09479	0.10098	0.08221	0.10656	0.09161	0.07868
	EAR	0.06053	0.08280	0.05976	0.00003	0.05976	0.07150	0.05791	0.08777	0.00000	0.05205	0.13726	0.05821	0.05674	0.07260	0.05418	0.06642	0.05731	0.05076	0.07447	0.07723	0.07211	0.06421	0.05552	0.05638	0.07040	0.08161	0.04763	0.07413	0.08221	0.06940	0.08915	0.07734	0.04626	0.07756	0.05108
	ECA	0.05575	0.05925	0.07108	0.04919	0.07821	0.07640	0.07685	0.08411	0.07698	0.00000	0.03969	0.05573	0.05169	0.07886	0.14818	0.09097	0.06826	0.04905	0.08010	0.06232	0.08928	0.05490	0.05464	0.04990	0.04380	0.08970	0.07423	0.05697	0.04882	0.07608	0.07864	0.08077	0.06474	0.07102	0.05837
	WCA	0.09342	0.05505	0.06545	0.09751	0.08669	0.06784	0.09035	0.09319	0.07881	0.07212	0.00000	0.11684	0.05195	0.07231	0.06587	0.07832	0.10490	0.06009	0.07301	0.07579	0.06351	0.09442	0.05482	0.07291	0.06960	0.06287	0.07295	0.05726	0.07828	0.07011	0.08152	0.08179	0.05727	0.06105	0.06977
	WGR	0.03059	0.04846	0.06521	0.12876	0.06777	0.10128	0.07991	0.05533	0.07414	0.04960	0.05087	0.00000	0.05465	0.09608	0.07497	0.09068	0.04307	0.07087	0.05652	0.06354	0.05516	0.08894	0.06262	0.07361	0.08156	0.08571	0.09631	0.06634	0.05054	0.05436	0.05144	0.03810	0.05216	0.05365	0.05570
	PTD	0.06184	0.06204	0.07164	0.11627	0.06849	0.06940	0.05780	0.04722	0.09445	0.05766	0.04220	0.06152	0.00000	0.05354	0.07184	0.13666	0.09464	0.06493	0.07041	0.07286	0.04193	0.05352	0.09505	0.05713	0.05422	0.06941	0.04372	0.06928	0.09103	0.07118	0.05815	0.05364	0.05767	0.04401	0.06551
	CTB	0.06683	0.06364	0.09214	0.00003	0.06091	0.07960	0.10298	0.08735	0.06928	0.06846	0.07381	0.05853	0.03781	0.00000	0.07495	0.07988	0.07465	0.07285	0.08415	0.08009	0.08492	0.05577	0.05653	0.04703	0.03780	0.04502	0.07692	0.05753	0.07724	0.05953	0.06575	0.07065	0.09614	0.02502	0.05047
	CDR	0.06287	0.04898	0.06476	0.10576	0.08005	0.08740	0.10315	0.04911	0.07998	0.05219	0.08987	0.06021	0.04510	0.06485	0.00000	0.06476	0.05492	0.04346	0.06590	0.06627	0.05238	0.03381	0.06026	0.09537	0.06865	0.04420	0.03896	0.05117	0.07766	0.06578	0.04369	0.06112	0.07515	0.00775	0.04076
	TAR	0.07424	0.07131	0.07187	0.00003	0.06490	0.08447	0.07536	0.09023	0.03723	0.03565	0.09898	0.11297	0.05414	0.07815	0.06487	0.00000	0.04198	0.04644	0.06052	0.06369	0.05317	0.09109	0.04790	0.06707	0.05448	0.04909	0.03941	0.04393	0.03756	0.03835	0.05424	0.08642	0.05712	0.03526	0.04732
	SAR	0.05830	0.05724	0.06205	0.00003	0.04736	0.06765	0.10587	0.07599	0.03151	0.02838	0.10564	0.05377	0.04533	0.11399	0.06542	0.04709	0.00000	0.04633	0.05271	0.06409	0.06778	0.01940	0.05984	0.04989	0.04974	0.06290	0.05883	0.04163	0.05501	0.05243	0.04987	0.03374	0.05361	0.01133	0.08368
	COB	0.14663	0.65481	0.32749	0.33333	0.25992	0.28488	0.57691	0.59567	0.64422	0.63484	0.51020	0.30769	0.21038	0.63699	0.23771	0.45995	0.54981	0.00000	0.66667	0.83333	0.21184	0.67816	0.42857	0.69096	0.43306	0.07558	0.35843	0.09362	0.28150	0.26837	0.54981	0.21764	0.39146	0.65065	0.27056
	GMU	0.19631	0.09534	0.25990	0.33333	0.41260	0.21739	0.08110	0.30848	0.08522	0.07796	0.33381	0.07692	0.42385	0.10473	0.60719	0.22113	0.36806	0.33333	0.00000	0.16667	0.07911	0.14242	0.14286	0.09140	0.10050	0.69521	0.30885	0.62411	0.17494	0.11722	0.08213	0.69096	0.27841	0.12683	0.64422
	QMS	0.65707	0.24986	0.41261	0.33333	0.32748	0.49773	0.34200	0.09585	0.27056	0.28720	0.15600	0.61539	0.36577	0.25828	0.15510	0.31892	0.08213	0.66667	0.33333	0.00000	0.70905	0.17942	0.42857	0.21764	0.46644	0.22922	0.33272	0.28227	0.54355	0.61441	0.36806	0.09140	0.33013	0.22252	0.08522
	CTA	0.06978	0.13581	0.09747	0.08541	0.12058	0.07396	0.07200	0.05038	0.06935	0.09011	0.08748	0.07074	0.05165	0.08325	0.17483	0.07979	0.05076	0.08972	0.09466	0.08421	0.00000	0.06791	0.09726	0.07905	0.07995	0.08398	0.09585	0.07552	0.11789	0.08479	0.11562	0.07246	0.07493	0.08947	0.05433
	PCA	0.06765	0.10166	0.06898	0.07213	0.10517	0.07433	0.06863	0.07873	0.11342	0.05564	0.08112	0.06453	0.06474	0.06052	0.07122	0.06746	0.06890	0.09150	0.08175	0.04338	0.08162	0.00000	0.07706	0.05764	0.10059	0.08513	0.13292	0.08269	0.08543	0.10780	0.09512	0.07526	0.10719	0.10402	0.07714
	ECC	0.04528	0.07058	0.07280	0.06653	0.08054	0.06898	0.06085	0.05897	0.11526	0.06928	0.08142	0.06853	0.07147	0.07039	0.13798	0.05209	0.06317	0.09652	0.07732	0.08372	0.08985	0.12482	0.00000	0.10093	0.09452	0.06109	0.07433	0.06940	0.06606	0.08457	0.10003	0.07261	0.10268	0.10218	0.08153
	EMS	0.07303	0.09716	0.04755	0.07644	0.07295	0.06155	0.07930	0.06325	0.06595	0.07934	0.06952	0.05622	0.06539	0.06242	0.11292	0.05924	0.09940	0.08495	0.07807	0.05746	0.06197	0.05388	0.08136	0.00000	0.06772	0.07217	0.05960	0.03993	0.07416	0.11041	0.08678	0.07107	0.06924	0.07954	0.07248
	COP	0.07325	0.05540	0.08961	0.07072	0.07120	0.08342	0.05428	0.07395	0.05102	0.07549	0.09550	0.09723	0.05547	0.06535	0.09721	0.08351	0.05295	0.06380	0.07241	0.10434	0.05613	0.07541	0.06079	0.07437	0.00000	0.09136	0.11458	0.07763	0.08908	0.10088	0.06598	0.06965	0.09144	0.07724	0.04398
	SLS	0.07273	0.09930	0.07944	0.05045	0.04997	0.04530	0.09840	0.05725	0.05402	0.07848	0.06171	0.07328	0.09160	0.07219	0.08442	0.09874	0.08300	0.06477	0.05290	0.08149	0.06885	0.09060	0.07502	0.08543	0.05501	0.00000	0.08388	0.10075	0.09265	0.07554	0.09617	0.08762	0.05689	0.07970	0.06888
	WDP	0.06701	0.04032	0.03982	0.08386	0.05507	0.02491	0.06818	0.07712	0.08193	0.04684	0.10862	0.07793	0.07888	0.08796	0.06049	0.08256	0.06858	0.06005	0.03884	0.07142	0.07238	0.05282	0.05302	0.04019	0.07674	0.06576	0.00000	0.04635	0.05999	0.08680	0.05677	0.09358	0.06093	0.08033	0.08480
	LRR	0.05020	0.04022	0.07242	0.03047	0.06676	0.07938	0.04408	0.05815	0.06766	0.03772	0.02836	0.06558	0.05455	0.08147	0.03434	0.05674	0.06652	0.06669	0.06538	0.06280	0.05217	0.07690	0.04572	0.08360	0.08920	0.08440	0.05026	0.00000	0.10495	0.06605	0.06553	0.05851	0.05535	0.08228	0.07084
	HSR	0.09017	0.07464	0.08631	0.04293	0.05494	0.07725	0.07469	0.05417	0.06595	0.06957	0.06516	0.04750	0.05151	0.08844	0.02392	0.07661	0.06037	0.04745	0.06102	0.05742	0.07679	0.09456	0.07196	0.05625	0.06553	0.06844	0.05254	0.12612	0.00000	0.07628	0.07745	0.04634	0.05996	0.04719	0.06779
	WTR	0.04907	0.03931	0.05085	0.05552	0.06893	0.04367	0.05882	0.08600	0.04791	0.05678	0.02535	0.04918	0.08239	0.05309	0.02290	0.06716	0.09108	0.05567	0.04848	0.04056	0.08948	0.07601	0.08436	0.06750	0.08223	0.05880	0.05484	0.09333	0.03897	0.00000	0.06445	0.10172	0.07737	0.06165	0.08999
	MAD	0.08851	0.03819	0.07871	0.06837	0.06154	0.07590	0.06150	0.08811	0.06500	0.06816	0.08073	0.06791	0.07243	0.03851	0.03429	0.05593	0.07447	0.05849	0.06484	0.07627	0.06475	0.03850	0.09050	0.05727	0.05464	0.06395	0.04192	0.07855	0.07380	0.07604	0.00000	0.08634	0.10036	0.05105	0.05797
	CPR	0.07507	0.03948	0.02564	0.07972	0.05084	0.05727	0.03913	0.05334	0.05722	0.05940	0.02041	0.05137	0.08164	0.06558	0.02648	0.06248	0.04896	0.06564	0.05972	0.06524	0.08317	0.07762	0.07752	0.10130	0.05818	0.07710	0.08736	0.05861	0.04136	0.02714	0.05039	0.00000	0.05395	0.04600	0.05540
	WRR	0.06955	0.06796	0.07446	0.08191	0.04750	0.07615	0.07372	0.07670	0.05971	0.10870	0.08119	0.06394	0.07829	0.04381	0.05278	0.04768	0.06532	0.07241	0.06496	0.06964	0.07278	0.05289	0.09420	0.05269	0.05467	0.07967	0.03596	0.05047	0.07056	0.03930	0.04360	0.06986	0.00000	0.04699	0.06954
	RSS	0.05114	0.03281	0.04609	0.07877	0.04541	0.09009	0.04965	0.05091	0.05022	0.03130	0.09731	0.09745	0.05323	0.05240	0.03455	0.06509	0.06175	0.04363	0.06013	0.05468	0.06523	0.06127	0.03005	0.06801	0.05792	0.06225	0.07039	0.03455	0.04372	0.06441	0.04255	0.03405	0.05294	0.00000	0.07032
	MAS	0.05756	0.06716	0.06984	0.05677	0.04858	0.06782	0.09677	0.07297	0.03539	0.07320	0.01613	0.04860	0.04675	0.07463	0.03166	0.04493	0.04477	0.03871	0.07954	0.04738	0.06482	0.05682	0.06118	0.07577	0.06311	0.04589	0.04560	0.06611	0.04140	0.00000	0.03956	0.06092	0.03678	0.05235	0.03500
Weighted supermatrix	PlanA	0.14793	0.16845	0.16735	0.14539	0.19029	0.17934	0.15296	0.14286	0.17524	0.17684	0.16466	0.16530	0.16427	0.17274	0.18573	0.19300	0.18335	0.06221	0.10162	0.14973	0.01196	0.00755	0.00608	0.01329	0.00458	0.00903	0.01190	0.01236	0.01316	0.01298	0.01388	0.01356	0.01363	0.01425	0.01295
	PlanB	0.08330	0.05638	0.06066	0.07725	0.04156	0.04855	0.04473	0.07143	0.04822	0.04251	0.03905	0.06794	0.04908	0.05441	0.04668	0.04336	0.04977	0.03902	0.06506	0.03155	0.00459	0.00600	0.00254	0.00389	0.00458	0.00358	0.00319	0.00410	0.00409	0.00388	0.00166	0.00339	0.00274	0.00261	0.00311
	PlanC	0.01876	0.02516	0.02199	0.02736	0.01815	0.02211	0.05231	0.03571	0.02654	0.03065	0.04629	0.01676	0.03666	0.02285	0.01760	0.01364	0.01689	0.14878	0.08332	0.06873	0.00176	0.00476	0.00969	0.00114	0.00915	0.00569	0.00321	0.00185	0.00106	0.00145	0.00277	0.00136	0.00193	0.00144	0.00225
	FCA	0.02634	0.02974	0.02007	0.00000	0.02739	0.01673	0.01463	0.02134	0.02013	0.03035	0.01047	0.02712	0.04084	0.01572	0.02005	0.02138	0.03213	0.02679	0.01744	0.02369	0.05735	0.05793	0.00808	0.06999	0.06880	0.04691	0.06021	0.05576	0.05011	0.06813	0.05949	0.05055	0.05404	0.07335	0.08090
	COD	0.02144	0.02401	0.01731	0.01653	0.00000	0.01789	0.01692	0.01984	0.02262	0.02473	0.02030	0.03358	0.02875	0.02852	0.01970	0.01686	0.02554	0.03076	0.01773	0.01704	0.06540	0.05494	0.05469	0.03714	0.06628	0.04813	0.06754	0.06639	0.05450	0.03505	0.04440	0.06657	0.05291	0.04936	0.06190
	COC	0.02742	0.01656	0.02179	0.02398	0.02705	0.00000	0.01251	0.01339	0.01896	0.03241	0.01539	0.01766	0.02971	0.01577	0.01988	0.01544	0.02398	0.02898	0.01907	0.01631	0.04988	0.07301	0.04393	0.05473	0.04713	0.07597	0.05369	0.06100	0.04300	0.07293	0.05537	0.04204	0.04335	0.10757	0.04717
	PHS	0.01474	0.02164	0.01801	0.06956	0.02417	0.02116	0.00000	0.02786	0.02009	0.03691	0.01742	0.00998	0.02841	0.00976	0.01764	0.01078	0.01414	0.01832	0.02099	0.02179	0.05347	0.04301	0.05455	0.06370	0.04782	0.04942	0.04361	0.06005	0.05985	0.04342	0.04678	0.05170	0.06000	0.09888	0.06155
	TRT	0.01897	0.02085	0.01684	0.01554	0.01785	0.01784	0.01840	0.00000	0.03261	0.02157	0.02685	0.01722	0.02295	0.02263	0.01767	0.02185	0.01927	0.01895	0.02032	0.01469	0.03873	0.05119	0.05243	0.04616	0.06633	0.03791	0.05949	0.06073	0.04593	0.05980	0.06370	0.05186	0.06722	0.05779	0.04963
	EAR	0.01513	0.02070	0.01494	0.00001	0.01494	0.01788	0.01448	0.02194	0.00000	0.01301	0.03431	0.01455	0.01418	0.01815	0.01355	0.01661	0.01433	0.01269	0.01862	0.01931	0.04549	0.04051	0.03503	0.03557	0.04442	0.05148	0.03005	0.04677	0.05186	0.04378	0.05624	0.04879	0.02919	0.04893	0.03222
	ECA	0.01394	0.01481	0.01777	0.01230	0.01955	0.01910	0.01921	0.02103	0.01925	0.00000	0.00992	0.01393	0.01292	0.01972	0.03705	0.02274	0.01707	0.01226	0.02003	0.01558	0.05633	0.03463	0.03447	0.03148	0.02763	0.05659	0.04683	0.03594	0.03080	0.04800	0.04961	0.05095	0.04084	0.04480	0.03682
	WCA	0.02335	0.01376	0.01636	0.02438	0.02167	0.01696	0.02259	0.02330	0.01970	0.01803	0.00000	0.02921	0.01299	0.01808	0.01647	0.01958	0.02622	0.01502	0.01825	0.01895	0.04007	0.05957	0.03458	0.04600	0.04391	0.03966	0.04602	0.03612	0.04939	0.04423	0.05143	0.05160	0.03613	0.03852	0.04401
	WGR	0.00765	0.01212	0.01630	0.03219	0.01694	0.02532	0.01998	0.01383	0.01853	0.01240	0.01272	0.00000	0.01366	0.02402	0.01874	0.02267	0.01077	0.01772	0.01413	0.01589	0.03480	0.05611	0.03950	0.04644	0.05145	0.05407	0.06076	0.04185	0.03188	0.03430	0.03245	0.02404	0.03290	0.03385	0.03514
	PTD	0.01546	0.01551	0.01791	0.02907	0.01712	0.01735	0.01445	0.01181	0.02361	0.01442	0.01055	0.01538	0.00000	0.01339	0.01796	0.03417	0.02366	0.01623	0.01760	0.01822	0.02645	0.03377	0.05996	0.03604	0.03421	0.04379	0.02758	0.04370	0.05743	0.04491	0.03668	0.03384	0.03638	0.02777	0.04133
	CTB	0.01671	0.01591	0.02304	0.00001	0.01523	0.01990	0.02575	0.02184	0.01732	0.01711	0.01845	0.01463	0.00945	0.00000	0.01874	0.01997	0.01866	0.01821	0.02104	0.02002	0.05357	0.03518	0.03566	0.02967	0.02385	0.02841	0.04853	0.03629	0.04873	0.03756	0.04148	0.04457	0.06065	0.01578	0.03184
	CDR	0.01572	0.01224	0.01619	0.02644	0.02001	0.02185	0.02579	0.01228	0.02000	0.01305	0.02247	0.01505	0.01128	0.01621	0.00000	0.01619	0.01373	0.01087	0.01647	0.01657	0.03304	0.02133	0.03802	0.06017	0.04331	0.02789	0.02458	0.03228	0.04899	0.04150	0.02757	0.03856	0.04741	0.00489	0.02571
	TAR	0.01856	0.01783	0.01797	0.00001	0.01622	0.02112	0.01884	0.02256	0.00931	0.00891	0.02475	0.02824	0.01353	0.01954	0.01622	0.00000	0.01050	0.01161	0.01513	0.01592	0.03354	0.05746	0.03022	0.04231	0.03437	0.03097	0.02486	0.02771	0.02369	0.02420	0.03422	0.05452	0.03603	0.02224	0.02986
	SAR	0.01458	0.01431	0.01551	0.00001	0.01184	0.01691	0.02647	0.01900	0.00788	0.00710	0.02641	0.01344	0.01133	0.02850	0.01635	0.01177	0.00000	0.01158	0.01318	0.01602	0.04276	0.01224	0.03775	0.03147	0.03138	0.03968	0.03711	0.02626	0.03471	0.03308	0.03146	0.02129	0.03382	0.00715	0.05279
	COB	0.03666	0.16370	0.08187	0.08333	0.06498	0.07122	0.14423	0.14892	0.16106	0.15871	0.12755	0.07692	0.05260	0.15925	0.05943	0.11499	0.13745	0.00000	0.16667	0.20833	0.01146	0.03668	0.02318	0.03737	0.02342	0.00409	0.01938	0.00506	0.01523	0.01451	0.02974	0.01177	0.02117	0.03519	0.01463
	GMU	0.04908	0.02383	0.06498	0.08333	0.10315	0.05435	0.02027	0.07712	0.02131	0.01949	0.08345	0.01923	0.10596	0.02618	0.15180	0.05528	0.09202	0.08333	0.00000	0.04167	0.00428	0.00770	0.00773	0.00494	0.00543	0.03760	0.01670	0.03375	0.00946	0.00634	0.00444	0.03737	0.01506	0.00686	0.03484
	QMS	0.16427	0.06246	0.10315	0.08333	0.08187	0.12443	0.08550	0.02396	0.06764	0.07180	0.03900	0.15385	0.09144	0.06457	0.03877	0.07973	0.02053	0.16667	0.08333	0.00000	0.03835	0.00970	0.02318	0.01177	0.02523	0.01240	0.01800	0.01527	0.02940	0.03323	0.01991	0.00494	0.01785	0.01204	0.00461
	CTA	0.01744	0.03395	0.02437	0.02135	0.03015	0.01849	0.01800	0.01259	0.01734	0.02253	0.02187	0.01769	0.01291	0.02081	0.04371	0.01995	0.01269	0.02243	0.02366	0.02105	0.00000	0.02015	0.02886	0.02346	0.02372	0.02492	0.02844	0.02241	0.03498	0.02516	0.03431	0.02150	0.02223	0.02655	0.01612
	PCA	0.01691	0.02542	0.01724	0.01803	0.02629	0.01858	0.01716	0.01968	0.02836	0.01391	0.02028	0.01613	0.01619	0.01513	0.01781	0.01686	0.01722	0.02288	0.02044	0.01084	0.02422	0.00000	0.02287	0.01710	0.02985	0.02526	0.03944	0.02454	0.02535	0.03199	0.02823	0.02233	0.03181	0.03087	0.02289
	ECC	0.01132	0.01764	0.01820	0.01663	0.02013	0.01724	0.01521	0.01474	0.02881	0.01732	0.02035	0.01713	0.01787	0.01760	0.03450	0.01302	0.01579	0.02413	0.01933	0.02093	0.02666	0.03704	0.00000	0.02995	0.02805	0.01813	0.02206	0.02059	0.01960	0.02509	0.02968	0.02155	0.03047	0.03032	0.02419
	EMS	0.01826	0.02429	0.01189	0.01911	0.01824	0.01539	0.01982	0.01581	0.01649	0.01984	0.01738	0.01406	0.01635	0.01560	0.02823	0.01481	0.02485	0.02124	0.01952	0.01436	0.01839	0.01599	0.02414	0.00000	0.02010	0.02142	0.01768	0.01185	0.02201	0.03276	0.02575	0.02109	0.02055	0.02360	0.02151
	COP	0.01831	0.01385	0.02240	0.01768	0.01780	0.02085	0.01357	0.01849	0.01276	0.01887	0.02388	0.02431	0.01387	0.01634	0.02430	0.02088	0.01324	0.01595	0.01810	0.02609	0.01666	0.02238	0.01804	0.02207	0.00000	0.02711	0.03400	0.02303	0.02643	0.02993	0.01958	0.02067	0.02713	0.02292	0.01305
	SLS	0.01818	0.02482	0.01986	0.01261	0.01249	0.01133	0.02460	0.01431	0.01351	0.01962	0.01543	0.01832	0.02290	0.01805	0.02110	0.02469	0.02075	0.01619	0.01322	0.02037	0.02043	0.02688	0.02226	0.02535	0.01632	0.00000	0.02489	0.02990	0.02749	0.02242	0.02854	0.02600	0.01688	0.02365	0.02044
	WDP	0.01675	0.01008	0.00995	0.02097	0.01377	0.00623	0.01705	0.01928	0.02048	0.01171	0.02715	0.01948	0.01972	0.02199	0.01512	0.02064	0.01714	0.01501	0.00971	0.01786	0.02148	0.01567	0.01573	0.01193	0.02277	0.01951	0.00000	0.01375	0.01780	0.02576	0.01685	0.02777	0.01808	0.02384	0.02516
	LRR	0.01255	0.01006	0.01811	0.00762	0.01669	0.01985	0.01102	0.01454	0.01691	0.00943	0.00709	0.01640	0.01364	0.02037	0.00859	0.01419	0.01663	0.01667	0.01634	0.01570	0.01548	0.02282	0.01357	0.02481	0.02647	0.02505	0.01491	0.00000	0.03114	0.01960	0.01945	0.01736	0.01642	0.02441	0.02102
	HSR	0.02254	0.01866	0.02158	0.01073	0.01373	0.01931	0.01867	0.01354	0.01649	0.01739	0.01629	0.01188	0.01288	0.02211	0.00598	0.01915	0.01509	0.01186	0.01525	0.01436	0.02279	0.02806	0.02135	0.01669	0.01945	0.02031	0.01559	0.03743	0.00000	0.02263	0.02298	0.01375	0.01779	0.01400	0.02012
	WTR	0.01227	0.00983	0.01271	0.01388	0.01723	0.01092	0.01471	0.02150	0.01198	0.01419	0.00634	0.01230	0.02060	0.01327	0.00572	0.01679	0.02277	0.01392	0.01212	0.01014	0.02655	0.02255	0.02503	0.02003	0.02440	0.01745	0.01627	0.02769	0.01156	0.00000	0.01913	0.03019	0.02296	0.01829	0.02670
	MAD	0.02213	0.00955	0.01968	0.01709	0.01538	0.01898	0.01538	0.02203	0.01625	0.01704	0.02018	0.01698	0.01811	0.00963	0.00857	0.01398	0.01862	0.01462	0.01621	0.01907	0.01921	0.01142	0.02685	0.01699	0.01621	0.01898	0.01244	0.02331	0.02190	0.02256	0.00000	0.02562	0.02978	0.01515	0.01720
	CPR	0.01877	0.00987	0.00641	0.01993	0.01271	0.01432	0.00978	0.01334	0.01430	0.01485	0.00510	0.01284	0.02041	0.01640	0.00662	0.01562	0.01224	0.01641	0.01493	0.01631	0.02468	0.02303	0.02300	0.03006	0.01726	0.02288	0.02592	0.01739	0.01227	0.00805	0.01495	0.00000	0.01601	0.01365	0.01644
	WRR	0.01739	0.01699	0.01862	0.02048	0.01188	0.01904	0.01843	0.01917	0.01493	0.02717	0.02030	0.01598	0.01957	0.01095	0.01320	0.01192	0.01633	0.01810	0.01624	0.01741	0.02160	0.01570	0.02795	0.01564	0.01622	0.02364	0.01067	0.01498	0.02094	0.01166	0.01294	0.02073	0.00000	0.01395	0.02064
	RSS	0.01278	0.00820	0.01152	0.01969	0.01135	0.02252	0.01241	0.01273	0.01255	0.00782	0.02433	0.02436	0.01331	0.01310	0.00864	0.01627	0.01544	0.01091	0.01503	0.01367	0.01936	0.01818	0.00892	0.02018	0.01719	0.01847	0.02089	0.01025	0.01297	0.01911	0.01263	0.01010	0.01571	0.00000	0.02087
	MAS	0.01439	0.01679	0.01746	0.01419	0.01215	0.01696	0.02419	0.01824	0.00885	0.01830	0.00403	0.01215	0.01169	0.01866	0.00792	0.01123	0.01119	0.00968	0.01989	0.01184	0.01923	0.01686	0.01816	0.02248	0.01873	0.01362	0.01353	0.01962	0.01229	0.00000	0.01174	0.01808	0.01091	0.01554	0.01039
Limiting supermatrix	N_i^T	0.11231	0.04149	0.03543	0.03296	0.03001	0.03051	0.02979	0.02779	0.02271	0.02280	0.02551	0.02222	0.02271	0.02268	0.02091	0.02048	0.01879	0.08042	0.04520	0.07300	0.02196	0.02019	0.01991	0.01859	0.01942	0.01899	0.01658	0.01562	0.01725	0.01513	0.01749	0.01546	0.01721	0.01416	0.01428

Note: N_i stands for any of the 35 nodes involved in the four clusters including Plan alternatives, EA Factors, EU Factors, and EF Factors.

Fig. 4. Supermatrix for *EnvironalPlanning* system

four clusters. In the weighted supermatrix, each column is stochastic, i.e., sum of the column amounts to 1 (Saaty 2001) (see Fig. 4).

The last substep is to compose a limiting supermatrix, which is to raise the weighted supermatrix to powers until it converges/stabilizes when all the columns in the supermatrix have the same values. Saaty (1996) indicated that as long as the weighted supermatrix is stochastic, a meaningful limiting result can be obtained for prediction. The approach to arrive at a limiting supermatrix is by taking repeatedly the power of the matrix, i.e., the original weighted supermatrix, its square, its cube, etc., until the limit is attained (converges), in which case the numbers in each row will all become identical. Calculus type algorithm is employed in the software environment of *Super Decisions*, designed by Bill Adams and the Creative Decision Foundation, to facilitate the formation of the limiting supermatrix and the calculation result is listed in Fig. 4.

So far, the formulations of supermatrices and submatrices used in the *EnvironalPlanning* system are illustrated in Fig. 3, and calculation results of the initial supermatrix, the weighted supermatrix, and the limiting supermatrix are given in Fig. 4. As the limiting supermatrix is set up, the following step is to select a proper plan alternative using results from the limiting supermatrix.

Step D: Selection

This step aims to select the best construction plan based on the computation results of the limiting supermatrix of the ANP model. The main results of the ANP model computations are the overall priorities of construction plans obtained by synthesizing the priorities of individual construction plans against different environmental indicators. The selection of the best construction plan which has the highest environmental priority can be conducted by a limiting priority weight, which is defined in the following equation:

$$W_i = w_{C_{\mathrm{Plan}},i}/w_{C_{\mathrm{Plan}}} = w_{C_{\mathrm{Plan}},i}/(w_{C_{\mathrm{Plan}},1} + \cdots + w_{C_{\mathrm{Plan}},n}) \qquad (3)$$

where W_i=synthesized priority weight of plan alternative i ($i=1,\ldots,n$) (n=total number of plan alternatives, $n=3$ in this study); and $w_{C_{\mathrm{Plan}},i}$=limited weight of plan alternative i in the limiting supermatrix. Because the $w_{C_{\mathrm{Plan}},i}$ is transformed from pairwise judgments conducted in Step B, it is reasonable to be regarded as priority of the plan alternative i and thus to be used in Eq. (3). According to the computation results in the limiting supermatrix in Fig. 4, $w_{C_{\mathrm{Plan}},i}=(0.11231, 0.04149, 0.03543)$, so the $W_i=(0.59351, 0.21926, 0.18723)$, and as a result, the best environmental-conscious construction plan is Plan A.

In addition to the complicated *EnvironalPlanning* system developed in Fig. 2, another ANP model, called the simplified *EnvironalPlanning* system for alternative construction plan selection, was developed with 15 nodes selected from the total 35 nodes of the complicated *EnvironalPlanning* system in Fig. 2. In order to decrease the number of elements in a supermatrix of the simplified *EnvironalPlanning* system, similar subcomponents of EF factors are combined including a combination of subcomponent 3.1 and 3.2 for environmental-friendly construction and management technology (Technology) and a combination of subcomponent 3.3 and 3.4 for environmental control cost (ECC). Finally, the nodes for the simplified *EnvironalPlanning* system include FCA, COD, and COC in EA factors cluster, COB, GMU, and QMS in the EU factors cluster, CTA+PCA, ECC+EMS, COP, SLS, WDP, and LRR in the EF factors cluster, and Plans A, B, and C in the Plan Alternatives cluster. The rule for selecting nodes in the EA EF factors clusters is the absolute value of EI is 8. According to the computation results in the synthesized supermatrix for the simplified *EnvironalPlanning* system, $w_{C_{\mathrm{Plan}},i}=(0.110243, 0.036108, 0.042977)$, so the $W_i=(0.58229, 0.19072, 0.22700)$, so Plan A is also selected.

Table 5. Comparison between Two *EnvironalPlanning* Systems Using Priority Weight

Analytic network process model	Number of nodes	Synthesized priority weight W_i Plan A	Plan B	Plan C	Selected plan
Simplified	15	0.58229	0.19072	0.22700	A
Complicated	35	0.59351	0.21926	0.18723	A

Interestingly, both complicated *EnvironalPlanning* and simplified *EnvironalPlanning* systems led to the same conclusion that Plan A is the best environmental-conscious construction plan. Besides the selected plan, it is also noticed that priority queues of these plan alternatives are also equivalent (see Table 5). Considering the load of performing pairwise comparisons on the clusters and nodes would be multiplied many times in a complicated *EnvironalPlanning* system, the simplified *EnvironalPlanning* system appears to be more practical and efficient.

According to the attributes of plan alternatives listed in Table 3, the comparison results using W_i also imply that the most preferable plan alternative to environmental-conscious construction is the plan that regulates the construction practice with least consumption on fuel and water, a lowest ratio of wastage, and a maximum ratio of recycle and reuse on materials and packaging etc. This indicates the *EnvironalPlanning* ANP can provide a quite reasonable comparison result for the aim of environmental-conscious construction and thus can be applied in construction practice.

Recommendations

In summary, in order to apply the *EnvironalPlanning* model in practice, the following steps are recommended:

1. Selection of an ANP model between the simplified EnvironalPlanning model and the complicated *EnvironalPlanning model*;
2. Original assessment of plan alternatives on all environmental indicators using Table 3;
3. Pairwise comparisons among all environmental indicators using Table 4;
4. Supermatrix calculation following the three substeps to transform an initial supermatrix to a limiting supermatrix with reference to Fig. 4;
5. Calculation of each limiting priority weight of plan alternative using limiting supermatrix and decision making on plan alternatives using Table 5; and
6. If none of the plan alternatives meets environmental requirements, adjustments to the plans are needed and re-evaluation of the plans by repeating the procedure from Step 2.

Conclusions

This paper presents an ANP model, which is called the *EnvironalPlanning* system, for environmental-conscious construction planning when plan alternatives need to be selected for reducing

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adverse environmental impacts in construction. The *EnvironalPlanning* system was constructed and illustrated using ANP, and both the simplified *EnvironalPlanning* and complicated *EnvironalPlanning* systems are developed. The simplified model consists of 4 clusters and 15 corresponding nodes, while the complicated model consists of 4 clusters and 35 corresponding nodes. In addition, performances of the two models are compared and results indicated that while the complicated model yielded accurate results, the simplified model is easy to use.

The *EnvironalPlanning* system structured in this paper is based on the ANP model containing feedback and self-loops among the clusters (see Fig. 2), but with no control model. However, there is an implicit control criterion with respect to which all judgments are made in this model: environmental impact. For example, when comparing the cluster EA factors (C_2) to cluster EF factors (C_4), the latter one is more important for reducing negative environmental impacts, and similar judgments are made during node comparisons. The supermatrix computations are conducted for the overall priorities of plan alternatives which are obtained by synthesizing the priorities of the alternatives from all the subnetworks of the ANP model. Finally, the synthesized priority weight W_i is used to distinguish the degree of potential environmental impacts due to the implementation of a construction plan.

However, problems also exist in current *EnvironalPlanning* systems, for example, the reliability of the three clusters including EA factors (C_2), EU factors (C_3), and EF factors (C_4), and their nodes cannot be measured. Because the sorting criteria rely on the calculation results of the EI_i, subjective judgments can influence the accuracy of the system. Further studies are therefore needed to investigate these issues.

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