Knowledge-Driven ANP Approach to Vendors Evaluation for Sustainable Construction

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Abstract: This paper presents a multicriteria decision-making approach to evaluate contractor candidates in the open competition of construction project procurement by means of a knowledge-framed analytic network process (KANP), which embeds a construction knowledge framework into a formal analytic network process procedure. An applied KANP model named KANP.BID is set up and used in an experimental case study. The paper concludes that the KANP.BID model is a viable and capable tool for selecting the most appropriate tender alternative under criteria of sustainable construction. It is expected that the proposed KANP.BID model can attract interest from both practitioners and researchers in terms of further research and development.

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Introduction

Sustainable construction requires innovative solutions based on comprehensive concerns of sustainable development (Defra 2006) to address key issues in both engineering and managerial domains; it is a progressive process embedded in the construction supply chain that could meet the needs for current projects undertaken by individual professional groups without compromising the ability of other professional groups and the social individuals to meet their own needs at present and in the future. As defined by UK DTI (2004), sustainability is of increasing importance to the efficient, effective, and responsible operation of business. Regarding the sustainability at all stages inside the loop of an individual project, key themes for action by the construction sector have been benchmarked by the UK DTI (2004), and these include the following:

- Design for minimum waste;
- Lean construction and minimize waste;
- Minimize energy in construction and use;
- Eliminate pollution;
- Preserve and enhance biodiversity;
- Conserve water resources;
- Respect people and local environment; and
- Monitor and report (i.e., use benchmarks), etc.

In order to achieve these objectives of sustainable construction, environmental consciousness is essential for practitioners to deal with potential and existing adverse environmental impacts due to construction and demolition activities. In this regard, research and development initiatives have been taken across the world by both academics and professionals to address a number of issues in terms of environmental-friendly design, construction, and use. For example, life-cycle assessment has been adopted as a tool to assess the environmental impacts of building materials and building systems in Australia (RMIT 2004); a series of quantitative approaches to reducing or the mitigating pollution level at the construction planning stage have been put forward to support the selection of the most appropriate construction plan (Chen et al. 2000; Chen et al. 2005; Chen and Li 2006); performance-based built environment rating systems such as the National Australian Built Environment Rating System (DEH 2004) have been developed to support sustainability evaluation of the built environment. It is believed that these efforts may finally lead the construction industry to becoming more and more sustainable.

Adverse environmental impacts such as soil contamination, water pollution, solid and liquid waste, noise, dust, hazards emissions and odors, wildlife and natural features demolition, archeological destruction, and uncontrolled ground vibration have become major concerns and received increased attention from professionals from different sectors across the world since the early 1970s, especially after the BS 7750 and the ISO 14001 environmental management system (EMS) were promulgated one after another in the 1990s. Although many professionals and academics have put much effort (either practice or research) into environmental management in their territories (NAE 1999), much of it has only been conducted in qualitative forms focusing on the use of regulations and guidelines. For example, a literature review conducted by the writers in 2003 revealed that only 2% of research work provided quantitative methods related to environ-

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mental management for the construction industry (Chen and Li 2006). However, it has become increasingly important to adopt quantitative methods for substantial support to understand the influence of environmental considerations in business decisions, which involves numerous decision-making requirements throughout any project life cycle (NAS 2005), and these requirements may generally focus on the following:

- Environmental performance and competitive advantages;
- Customers and investors demands for environmental performance by businesses;
- Supply chains and production networks;
- Sectoral standard setting;
- Decision factors in industrial ecology;
- Environmental accounting and disclosure practices; and
- Government policy influence on business decision making.

In this regard, a set of quantitative methods have been put forward for effective prevention, control and reduction of adverse environmental impacts that may generate at an earlier stage, midterm, and later stage of projects (Chen and Li 2006); in addition, these quantitative methods have been further integrated under a knowledge-driven managerial framework based on a standard EMS process and other processes normally adopted in projects management (Chen et al. 2004). Although it is expected that this knowledge-driven system can facilitate quantitative environmental management throughout the life cycle of projects for sustainable construction, there is still a research task needed to develop effective tools for the system that can be used to support decision making in project procurement at the preconstruction stage. To enable practitioners to make decisions with confidence in selecting the most appropriate vendors in dynamic situations, there is an increasing demand for tools that can incorporate multicriteria decision-making techniques, with which practical solutions related to knowledge and innovation are systematically addressed.

In the area of construction procurement, many issues have been explored previously by researchers and practitioners. For example, O'Connor et al. (1987) discussed constructibility concepts for engineering and procurement; Crowley and Hancher (1995) put forward a method to evaluate the risk of cost growth in competitively procured construction projects; and Avila (1997) discussed the local agency procurement and selection process for professional engineering consultant services. Ogunlana (1999) discussed profitable partnering in construction procurement. Rowlinson and McDermott (1999) wrote a guide to the best practice in construction procurement systems. Addis and Talbot (2001) provide a guide to delivering environmentally responsible projects with regard to sustainable construction procurement. Brown et al. (2001) described a new project procurement process called the project delivery process by applying systematic processes to selecting partners on a short-term construction project; Gransberg and Molenaar (2003) described a synthesis of eight design-builder selection methods for public infrastructure projects based on results from a survey conducted by the Design-Build Institute of America (DBIA); El Wardani et al. (2006) made a comparison study on four procurement methods for design-build projects. Pryke (2006) discussed legal issues associated with emergent actor roles in procurement based on prime contracting adopted in the public sector procurement in the United Kingdom. Ashworth (2006) and Hackett et al. (2006) provided a comprehensive review and guide on relevant issues in construction procurement.

In terms of multicriteria decision-making support in construction procurement, Muya et al. (1999) used the analytic hierarchy process (AHP) to evaluate logistics factors and their contribution to the improvements in construction materials supply; Alhazmi and McCaffer (2000) introduced a project procurement system selection model using AHP; Cheung et al. (2001) put forward an objective-subjective method to improve objectivity in procurement selection using AHP; Al-Tabtabai (2002) applied AHP to aid project managers in selecting the best procurement strategy; Kashiwagi (2004) summarized a rating method for vendor evaluation inside a performance information procurement system (PIPS), which was put forward by Dr. Kashiwagi in the 1980s with wide use in the United States afterwards (Kashiwagi and Byfield 2002a,b) and was further introduced globally by Morledge et al. (2006). Based on the literature review, it has been determined that research into construction procurement has been deployed in different domains such as the procurement process, information system, and decision-making support.

The selection of the most appropriate vendor for a specific construction project is a group decision-making process. During the same period when this paper was submitted to the Journal for review, Elfvengren et al. (2004) put forward an analytic network process (ANP) model to support group decision making in alliance partner selection in the Proceedings of the 13th International Working Seminar on Production Economics held in Innsbruck, Austria. This research initiative further reminded the writers that it is a useful attempt to apply the ANP in vendors evaluation in construction projects procurement. Compared with other two multicriteria decision-making tools currently adopted in vendors evaluation, including AHP and the rating method, the ANP has significant advantages. For example, the ANP model can measure all possible interrelations among indicators, while either AHP or rating methods cannot. This advantage is extremely important under the scenario that clients need to consider and quantitatively measure interrelations among some indicators.

This paper aims to present a multicriteria decision-making approach to evaluating tender alternatives (vendors) in open competition of construction projects procurement by means of a knowledge-framed analytic network process (KANP). The KANP approach integrates a knowledge framework based on the Australian and New Zealand Standard Industrial Classification (ANZSIC) (ABS 2004) (see Table 3) with a formal ANP (Saaty 1996, 2005) procedure. To support decision making in selecting the most appropriate vendor for each specific construction project, a knowledge-framed multicreteria decision-making model, named KANP.BID, is then set up using the KANP approach. In other words, the KANP.BID model adopts ANP under a construction knowledge framework to evaluate tender alternatives under the criteria of sustainable construction.

To undertake the task, this paper first reviews relevant sustainable issues and their characteristics focusing on clients' requirements at the construction procurement stage, as it is believed that critical factors are necessary in evaluating vendors under the criteria of sustainable construction. All possibly useful assessment criteria such as qualification, profit, risk, constructability, etc., which are generally adopted in construction procurement, are then used to set up the KANP.BID model. During model construction, a novel pairwise comparison approach called the PairWiser tool is introduced with regard to maximizing knowledge reuse for increasing benefits and to minimize knowledge retrieval for reducing time use. An experimental case study is conducted to demonstrate the effectiveness of the KANP.BID model to support decision making in vendor selection. The paper concludes that the KANP method and the derivative KANP.BID model are viable and capable tools for practitioners to use in construction procurement; meanwhile, recommendations are also made with regard to further research and development of the model.

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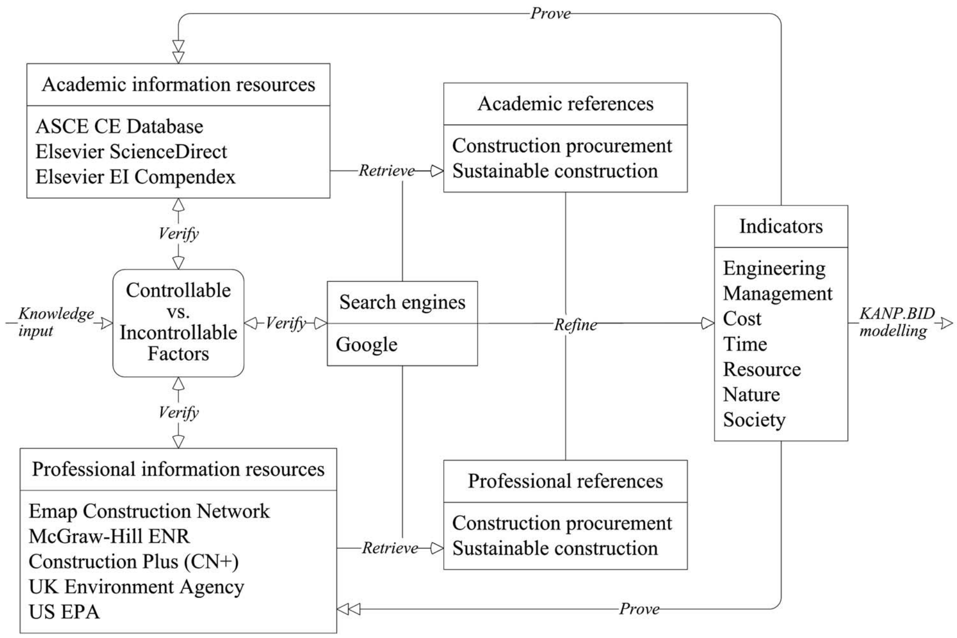

Fig. 1. Framework for collecting KANP.BID indicators

The significant contributions of this paper include a set of criteria applied to sustainability evaluation in construction projects procurement, the PairWiser tool to facilitate the application of ANP, and the KANP.BID model for vendor selection in construction procurement under criteria of sustainable construction. It is expected that practitioners can either use the KANP.BID model or its methodology for vendors evaluation purposes in construction procurement, which is associated with the relevance to sustainable construction. In addition to the knowledge framework adopted in the KANP.BID model, practitioners and researchers can further specifically adopt an appropriate knowledge structure based on other main standard industrial classifications such as the North American Industry Classification System (NAICS) (U.S. Census Bureau 2002), and the United Kingdom Standard Industrial Classification of Economic Activities (UKSIC2003) (U.K. Office for National Statistics 2003) to facilitate the evaluation in different locations. Moreover, the philosophy of the KANP method and PairWiser method can also benefit researchers from multicriteria decision-making areas.

Criteria for Evaluation

KANP.BID criteria are a group of evaluation indicators that are to be used to set up the model and to select the most appropriate vendor in construction project procurements. Along with general evaluation criteria applied to construction project procurements such as cost, experience, qualification, and risk, the KANP.BID criteria are comprised of some new indicators that can be used to evaluate the need of sustainable construction, which has been defined in the Introduction section. Based on this definition, a procedure based on extensive literature review for collecting suitable KANP.BID criteria is illustrated in Fig. 1.

The extensive literature review for collecting KANP.BID criteria was then conducted through the access to several top academic and professional information resources in the construction engineering and management fields, which includes the following:

1. The Civil Engineering Database (CEDB) from ASCE;
2. The ScienceDirect database from the Elsevier B.V.;
3. The Compendex database from the Elsevier Engineering Information Inc.;
4. The Engineering News-Record (ENR) executive search engine ⟨www.enr.com⟩ and magazines from the McGraw-Hill Companies (2008);
5. The Construction Plus (CN+) search engine ⟨www.cnplus.co.uk⟩ from the Emap Construction Network (2008);
6. The advanced search engines from the United States Environmental Protection Agency (US EPA) of the United States ⟨www.epa.gov⟩ and the Environment Agency of the United Kingdom ⟨www.environment-agency.gov.uk⟩; and
7. Conference publications of the CIBW92 Procurement systems group.

In addition to these dominant information resources, a commonly used search engine, Google, was also employed to search for additional online literature. Regarding the search results, the writers retrieved and went through thousands of articles and reports relevant to the research topic. After sorting and refining, the KANP.BID criteria are interrelated with engineering, management, cost, time, resource, surrounding nature, and society with which the processes of a construction project are accordingly deployed and executed after procurement, and therefore are critical criteria to adopt.

Table 1 gives a list of KANP.BID indicators collected from the extensive literature review. There are a total of 55 indicators classified into seven classes of interrelated evaluation criteria as mentioned above. In order to demonstrate the evaluation process and result, the writers specify each indicator with a specified unit in Table 1.

According to these specifications for indicators, all percentages are to be measured by decision makers based on their knowledge and judgment in the experimental case study, while other indicators that have specific units can be measured by objective

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Table 1. KANP.BID Indicators and Related Values of Vendor Options

Cluster	Node (indicators for sustainability evaluation)	Unit	Vendors *A*	*B*	*C*
Engineering	E1: Suitability of the design & construction	%	95	90	85
	E2: Reliability of the design	%	100	95	105
	E3: Durability of the building/civil infrastructure	Year	65	50	70
	E4: Constructability of the design	%	100	100	100
	E5: Flexibility of variation and renovation	%	100	90	80
	E6: Automation of the building/civil infrastructure	%	90	85	100
	E7: Cleaner technologies & automation ratio	%	80	50	40
Management	M1: ISO EMS accreditation	%	100	0	0
	M2: ISO QMS accreditation	%	100	100	100
	M3: Qualification in design & construction	%	100	90	95
	M4: Experience in similar project	%	100	80	70
	M5: Computerization in design & construction	%	90	80	80
	M6: Cooperativity risk in design & construction	%	10	20	30
	M7: Unionization risk in design & construction	%	100	80	60
	M8: Suitability of site layout design & control	%	85	60	50
	M9: Pollution controllability in design & construction	%	90	80	50
	M10: Accountability in design & construction	%	100	100	100
Time	T1: Duration from design to completion	Day	560	600	650
	T2: Transportation arrangements in construction	h	4.5k	4.8k	5.2k
	T3: Interference possibility in design & construction	%	20	30	50
	T4: Delay risk in design & construction	h	150	250	220
	T5: Overrun risk in design & construction	%	10	25	30
	T6: Responsivity in design & construction	%	100	90	90
Cost	C1: Lifecycle cost of the project or the bidding price	Millions $	190	210	230
	C2: Variation possibility in design & construction	%	10	20	30
	C3: Overrun risk in design & construction	%	10	20	30
	C4: Financial risk in the project's life cycle	%	10	12.5	15
	C5: Emergency risk	%	0.1	0.3	0.5
Resources	R1: Electricity consumption in construction	kWh	35k	45k	55k
	R2: Fuel consumption in construction	MJ	38k	49k	52k
	R3: Water consumption in construction	t	3.8k	4.6k	4.9k
	R4: Wastewater treatment/reuse rate	%	100	50	40
	R5: Material availability, serviceability & durability	%	100	80	80
	R6: Generative material use rate	%	20	5	0
	R7: Construction & demolition waste generating rate	%	1.0	5.0	8.5
	R8: Waste reuse & recycling rate	%	90	30	35
	R9: Equipment requirement in construction	h	216k	256k	264k
	R10: Workforce requirement in construction	h	496k	544k	600k
	R11: Required skills on workforce	%	80	60	60
Nature	N1: Temperature difference risk in life cycle	%	10.0	8.9	8.7
	N2: Windstorm risk in life cycle	%	2.0	1.8	1.8
	N3: Rainfalls risk in life cycle	%	1.0	1.1	1.1
	N4: Flood risk in life cycle	%	0.15	0.25	0.25
	N5: Earthquake risk in life cycle	%	0.01	0.01	0.01
	N6: Landslip risk in life cycle	%	0.0	0.1	0.2
	N7: Settlement risk in life cycle	%	1.5	2.5	3.0
	N8: Corrosion risk in life cycle	%	1.0	1.0	2.0
	N9: Disturbance risk to geo-environment	%	1.0	5.0	6.0
Society	S1: Public health risk in life cycle	%	10	20	25
	S2: Public safety risk in life cycle	%	0.10	0.21	0.28
	S3: Landfill burden (waste disposal) during construction	Million $	0.12	0.30	0.35
	S4: Public traffic disruptions during construction	h	320	480	560
	S5: Cargo transportation burden during construction	tn mile	550k	600k	650k
	S6: Legal & responsibility risk	%	0.05	0.20	0.30
	S7: Neighborhood disturbance in construction	h	260	320	360

Note: k=1000.

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Table 2. Indicators for Measuring Past Experience

Criteria clusters	Related indicators
Engineering	Suitability of the design & the construction cleaner technologies & automation ratio
Management	ISO EMS accreditation ISO QMS accreditation Qualification in design & construction Experience in similar project
Time	Interference possibility in design & construction Delay risk in design & construction Overrun risk in design & construction Responsivity in design & construction
Cost	Variation possibility in design & construction Overrun risk in design & construction Financial risk in the project's life cycle Emergency risk
Resources	Wastewater treatment/reuse rate Generative material use rate Construction & demolition waste generating rate Waste reuse & recycling rate Required skills on workforce
Nature	Landslip risk in life cycle Settlement risk in life cycle Corrosion risk in life cycle
Society	Public health risk in life cycle Public safety risk in lifecycle Landfill burden (waste disposal) during construction Public traffic disruptions during construction Legal & responsibility risk Neighborhood disturbance in construction
Knowledge	(*several*) (see Table 3)

data collected from different tenders. For example, there are 19 indicators for risks measurd from the clusters of management (2), time (3), cost (3), nature (9), and society (3) (see Table 1). As shown in Table 1, these risks are measured by percentage according to decision makers subjective judgments, which is the same as what is done by the rating method (Kashiwagi 2004). However, the writers are still working on a more effective method to allow decision makers evaluate these risks based on objective statistics.

Two specific issues related to these criteria need to be addressed. The first one is cost criterion. As the cost is normally changed during construction, the cost criterion focuses on two issues, including actual bid and related risks. The "life-cycle cost of the project" (see Table 1) is an ideal item whenever there is such a value; in practice, the bid may be the only data that can be used. This may depend on the requirements made by the clients. Another one is experience criterion. The "past performance information" has been dispersed into different clusters. For example, some related measures are listed in Table 2. To effectively measure all these indicators, subjective judgments, i.e., percentages, are adopted at this stage. Objective measures to these indicators are also still under research.

Assuming there are three vendors (tender alternatives), including Vendor A, Vendor B, and Vendor C, the KANP.BID criteria are then quantified in regard to details of different tender alternatives (see Table 1). So far the three lists of quantified indicators are ready to be accumulated into the proposed KANP.BID model. In other words, the KANP.BID model is required to be set up, before running for final decision, by using the group of KANP.BID criteria and values of indicators in terms of details from different vendors.

KANP Approach

Regarding multicriteria decision-making methods, the AHP put forward by Saaty (1994) is known as a powerful and flexible decision-making approach that supports decision-makers when setting priorities and making the best decision when both qualitative and quantitative aspects of a decision need to be considered, and it has been utilized in various areas of research and practice since the late 1970s (Zeeger and Rizenbergs 1979), including project appraisal at the planning stage (Dey et al. 1996; Rogers 2001). In this regard, the AHP method is recommended by many researchers and practitioners as a useful multicriteria assessment tool for its stronger mathematical foundation, its capacity to gauge consistency of judgments, and its flexibility in the choice of ranges at the sub-criteria level (Khasnabis et al. 2002; Expert Choice 2005).

However, a notable limitation of AHP is that it does not deal with interconnections among factors at the same level as an AHP model is structured in a hierarchy system in which no horizontal links are defined. In addition, Kashiwagi (2004) indicated that the AHP is not a suitable method to deal with assessment problems in construction procurement due to other reasons (see the section "Discussion and Recommendation"). In fact, these weaknesses can be overcome by using a senior multicriteria analytical technique known as ANP. The ANP is more powerful in modeling complex decision systems than AHP because it can be used to model very sophisticated decisions involving a variety of interactions and dependencies (Meade and Sarkis 1999). These advantages are embodied in many examples of applications of the ANP (Srisoepardani 1996; Saaty 2005). For example, Saaty (1996) recommended that the ANP be used in cases where the most thorough and systematic analysis of influences needs to be made. In addition, the ANP method has been successfully applied to the strategic evaluations of environmental practices and programs in both manufacturing and business to help in analyzing various project, technological, or business decision alternatives, and it also has been proven to be useful in modeling dynamic strategies and systemic influences on managerial decision related to environmental management (Meade and Sarkis 1999; Chen and Li 2006). As a result, the ANP is selected to evaluate vendors (contractor candidates) with regard to the criteria focusing on sustainable construction and other general issues related to vendors evaluation at the project procurement stage.

The KANP approach is a philosophical development of the general application of the ANP by means of embedding a knowledge frame such as a standard industrial classification directly related to a specific decision-making problem into the formal ANP procedure. As defined by Saaty (1996), 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, which 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. There is a coupling of two parts in the ANP, including a control network of criteria and subcriteria that control the interactions including in-

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Table 3. Knowledge Framework Based on ANZSIC (ABS 2004)

ANZSIC items	Code of indicators for knowledge cluster
Subdivision 41: General construction	
411: Building construction	
4111 House construction	K1
4112 Residential building construction n.e.c.	K2
4113 Nonresidential building construction	K3
412: Nonbuilding construction	
4121 Road and bridge construction	K4
4122 Nonbuilding construction n.e.c.	K5
Subdivision 42: Construction trade services	
421: Site preparation services	
4210 Site preparation services	K6
422: Building structure services	
4221 Concreting services	K7
4222 Bricklaying services	K8
4223 Roofing services	K9
4224 Structural steel erection services	K10
423: Installation trade services	
4231 Plumbing services	K11
4232 Electrical services	K12
4233 Air conditioning and heating services	K13
4234 Fire and security system services	K14
424: Building completion services	
4241 Plastering and ceiling services	K15
4242 Carpentry services	K16
4243 Tiling and carpeting services	K17
4244 Painting and decorating services	K18
4245 Glazing services	K19
425: Other construction services	
4251 Landscaping services	K20
4259 Construction services n.e.c.	K21

terdependencies and feedback, and a network of influences among the nodes and clusters. The criteria are used to compare the components of a system, and the subcriteria are used to compare the elements of a component. Regarding the proposed ANP-based decision making in construction procurement, the classification of the construction division (Chapter 2, Division E) of the ANZSIC (ABS 2004) (see Table 3) is adopted as the knowledge classification structure.

The procedure of using the ANP approach in decision making can be summarized by means of four steps, including the following:

- Model construction;
- Pairwise comparisons;
- Supermatrix calculation; and
- Selection.

Below is a step-by-step description using data for an experimental case study (see Table 1), and the process to evaluate construction vendors is conducted through following four steps:

Step 1: KANP.BID Model Construction

This step aims to define a set of clusters with their nodes and to define the interrelations between pair clusters and pair nodes of the same clusters and the different clusters. The KANP model provides descriptions in abstract to a module or cluster of construction knowledge classification structures from different construction sectors, which can be adopted to facilitate vendor evaluation under a construction knowledge framework. The purpose of integrating a cluster of construction knowledge into a normal ANP model is to provide a wider range of evaluation criteria that can cover the issues of sustainable construction from the height of the whole built environment. In this pilot research, all indicators for the construction knowledge cluster are defined by using the construction specification from the ANZSIC (ABS 2004), which comprises two main groups of titles with seven subgroups of titles and their 21 codes (see Table 3). All 21 codes are then assembled into a new group called the construction knowledge cluster which is integrated into the KANP.BID model as nodes of the cluster with the same name (see Fig. 2).

Regarding other clusters and their nodes selected for the KANP.BID model, this paper provides a whole list of these indicators in Table 1, and all those indicators are collected based on an extensive literature review and the writers industrial experiences. As different applications may need different groups of clusters, the writers will explore different applications in terms of using different evaluation criteria in further research. In this pilot research, the writers collected a group of clusters from previous publications that provide the most used indicators for vendors evaluation purposes according to Chua and Li (2000), Hampton (1994), Lo et al. (1998), Palaneeswaran and Kumaraswamy (2000), Alhazmi and McCaffer (2000), and Brown et al. (2001); and the list of current selected indicators is given in Table 1. Further to the definition of these clusters and their nodes for the KANP.BID model, the interconnections among pair clusters on the cluster level and among pair nodes on the node level are then modeled by two-way and looped arrows to describe all possible interdependences that exist (see Fig. 3).

The KANP.BID model illustrated in Fig. 3 is comprised of an exterior and an internal environments. In the exterior KANP.BID environment, the downward arrow indicates the process of transferring required data, while the upward arrow indicates the feedback process of evaluation results, and the feedback process or the loop of tender alternatives indicates a circulating pipe for sustainable priority evaluation of tender alternatives. In the internal KANP.BID environment, connections among nine clusters and 79 nodes are modeled by one-way or two-way and looped arrows to describe the interdependences that exist. The nine clusters are tender alternatives, construction knowledge, engineering, management, time, cost, resource, nature, and society. Corresponding to the nine clusters, there are 79 nodes including three nodes in the cluster of tender alternatives, 21 nodes in the cluster of construction knowledge, seven nodes in the cluster of engineering, ten nodes in the cluster of management, six nodes in the cluster of time, five nodes in the cluster of cost, 11 nodes in the cluster of resource, nine nodes in the cluster of nature, and seven nodes in the cluster of society.

Fig. 3 illustrates the KANP.BID model implemented using ANP with all interior clusters and nodes, and exterior related participators. Concerning the interdependences between any pair clusters and any pair nodes, the KANP.BID model presented 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, i.e., sustainable construction, with respect to which all judgments (pairwise comparisons) are made in setting up the KANP.BID model. For example, when comparing the cluster engineering to the cluster management, no one is obviously more important in terms of sustainable construction; there-

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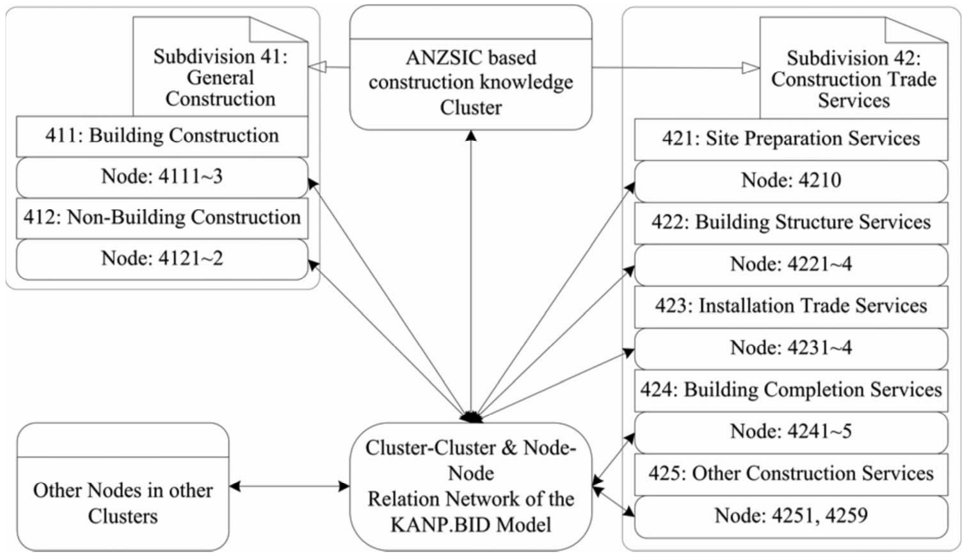

Fig. 2. Cluster of construction knowledge and its nodes (adapted from ABS 2004)

fore they are equal in pairwise comparison. After the cluster comparisons are made, the relative importance of all pair nodes can be decided in the same way. For example, in the pairwise comparison between the node E2 (reliability of the design) from the engineering cluster node S2 (public safety risk in life cycle) from the society cluster, it was thought that no one is obviously more important in terms of sustainable construction; therefore they are equal in pairwise comparison.

Step 2: Pairwise Comparisons

The purpose of this step is to perform pairwise comparisons among the clusters and their nodes within the KANP.BID model. On completing the pairwise comparisons, the relative importance of the weight of interdependence is determined by using a scale of pairwise judgments, where the relative importance weight is valued from one to nine (see Table 4) (Saaty 1996, 2005) and the judging criteria are different from case to case.

Pairwise comparisons have been modified in this research based on two considerations, including to maximize knowledge reuse for increasing benefits and to minimize knowledge retrieval for reducing time use. During the research with the IDCOP consortium (see "Acknowledgements"), Professor Keith Jones from the University of Greenwich once mentioned that the ANP can be used for knowledge reuse. In this regard, the writers have further paid attention to details in terms of how to reuse experts knowledge in ANP modeling. On the other hand, it is an effective way to ask experts to do pairwise comparisons for all pair indicators through a questionnaire survey; however, the pair-wise comparison mechanism makes it very difficult to use on projects with large numbers of contractors and criteria (Kashiwagi 2004). For example, there are 76 indicators selected by the writers to evaluate vendors (contractor candidates) in this research; and there will be thousands of pairwise comparisons in setting up an ANP

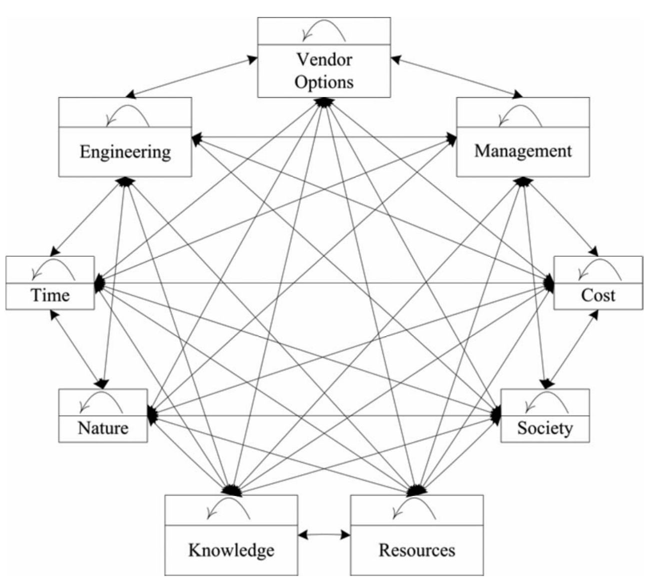

Fig. 3. KANP.BID decision-making model

Table 4. Fundamental Scale of Pairwise Judgment and PairWiser Criteria

Scales of pairwise judgment	Comparisons of pair indicator scores[a]
1 = equal	1:1
2 = equally to moderately dominant	2:1, 3:2, 4:3, 5:4, 6:5, 7:6, 8:7, 9:8
3 = moderately dominant	3:1, 4:2, 5:3, 6:4, 7:5, 8:6, 9:7
4 = moderately to strongly dominant	4:1, 5:2, 6:3, 7:4, 8:5, 9:6
5 = strongly dominant	5:1, 6:2, 7:3, 8:4, 9:5
6 = strongly to very strongly dominant	6:1, 7:2, 8:3, 9:4
7 = very strongly dominant	7:1, 8:2, 9:3
8 = very strongly to extremely dominant	8:1, 9:2
9 = Extremely dominant	9:1

[a]Scores for indicators based on questionnaire survey; scales for scoring each indicator: 1 = not important; 2 = not to moderately important; 3 = moderately important; 4 = moderately to strongly important; 5 = strongly important; 6 = strongly to very strongly important; 7 = very strongly important; 8 = very strongly to extremely important; 9 = extremely important.

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model. There should be no problem for research purposes, but practitioners may not accept it. Based on these considerations, a PairWiser tool is developed and is presented in Table 4.

The PairWiser is a solution to the bottleneck problem of using ANP for models with a large number of assessment criteria (Kashiwagi 2004), which means it is designed to significantly decrease the times of pairwise comparison. A table called Pairwise Questionnaire Table is used to collect data from experts, and those data will then be compiled according to the 9 scales of pairwise judgement given in Table 4. This process is regarded as knowledge retrieval, and the use a finalized ANP model for decision-making support is regarded as knowledge reuse. In this study, a two-page questionnaire table is adopted in a questionnaire survey, and it is presented in the "Appendix." The Delphi method (Linstone and Turoff 1975) is recommended to collect experts' knowledge related to all indicators. To finally accumulate experts knowledge retrieved from the questionnaire survey, the PairWiser criteria (see the second column of Table 4) are used to input all data into the ANP model.

It should be noted that the adoption of the PairWiser tool reduces burden the of experts in answering questionnaires, allowing them to concentrate on the importance rate of each indicator instead of boundless pairwise comparisons. On the other hand, there should be a person who deals with data input based on survey results. According to the writers experience, the use of PairWiser criteria has significantly accelerated the process of data input. In this regard, the PairWiser tool is adopted in this research.

Super-matrix

$$W = \begin{bmatrix} W_{11} & W_{12} & W_{13} & W_{14} & W_{15} & W_{16} & W_{17} & W_{18} & W_{19} \\ W_{21} & W_{22} & W_{23} & W_{24} & W_{25} & W_{26} & W_{27} & W_{28} & W_{29} \\ W_{31} & W_{32} & W_{33} & W_{34} & W_{35} & W_{36} & W_{37} & W_{38} & W_{39} \\ W_{41} & W_{42} & W_{43} & W_{44} & W_{45} & W_{46} & W_{47} & W_{48} & W_{49} \\ W_{51} & W_{52} & W_{53} & W_{54} & W_{55} & W_{56} & W_{57} & W_{58} & W_{59} \\ W_{61} & W_{62} & W_{63} & W_{64} & W_{65} & W_{66} & W_{67} & W_{68} & W_{69} \\ W_{71} & W_{72} & W_{73} & W_{74} & W_{75} & W_{76} & W_{77} & W_{78} & W_{79} \\ W_{81} & W_{82} & W_{83} & W_{84} & W_{85} & W_{86} & W_{87} & W_{88} & W_{89} \\ W_{91} & W_{92} & W_{93} & W_{94} & W_{95} & W_{96} & W_{97} & W_{98} & W_{99} \end{bmatrix}$$

$$\begin{array}{lccccccccc} \textit{Clusters}: & C_1 & C_2 & C_3 & C_4 & C_5 & C_6 & C_7 & C_8 & C_9 \\ \textit{Nodes}: & N_1^{(3)} & N_2^{(7)} & N_3^{(10)} & N_4^{(6)} & N_5^{(5)} & N_6^{(11)} & N_7^{(9)} & N_8^{(7)} & N_9^{(21)} \end{array}$$

Sub-matrix

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

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 ($I, J \in (1, 2, \ldots, 79)$), n_I is the total number of nodes in Cluster I, n is the total number of columns in Cluster I. Thus a 79×79 supermatrix is formed.

Fig. 4. Formulation of supermatrix and its submatrix

Step 3: Supermatrix Computation

This step aims to form a synthesized supermatrix to allow for the resolution of the effects of the interdependences that exist between the nodes of clusters of the KANP.BID model following three substeps which transform an initial supermatrix to a weighted supermatrix, and then to a synthesized supermatrix. There are two routes to conduct the computation. First, decision makers can use the MATLAB program for the supermatrix computation by using data collected from Microsoft Excel. Alternatively, they can utilize the Super Decisions program for the supermatrix computation by using data collected from the software itself. Data collected from different routes can be reused by manual operation, and can be automatically reused after data transform from storage. In this research, the Super Decisions program is adopted in supermatrix computation.

At first, an initial supermatrix of the KANP.BID model is created. The initial supermatrix consists of local priority vectors obtained from pairwise comparisons among 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 Eq. (1) (Saaty 1996)

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

where w_i=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 to reflect the relative importance weight of interdependence. The initial supermatrix is constructed by substituting the submatrices into the supermatrix as indicated in Fig. 4. After the formation of the initial supermatrix, a weighted supermatrix is then transformed. This process is to multiply every node in a cluster of the initial supermatrix by the weight of the cluster, which has been established by pairwise comparison among the four clusters. In the weighted supermatrix, each column is stochastic, i.e., the sum of the column amounts to 1 (Saaty 1996). The last substep is to compose a limiting supermatrix, which is to raise the weighted supermatrix to powers until it converges or 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 a limiting supermatrix is repeatedly to take 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 should be employed in a software environment to facilitate the formation of the limiting supermatrix.

Step 4: Evaluation

The purpose of this step is to rank tender alternatives by using the results from the computation to the KANP.BID model, and to facilitate selecting the most appropriate tender alternative for evaluation purposes. The process of evaluation is based on the computation results from the limiting supermatrix of the KANP.BID model. As the main results from the computations are the overall priorities of each alternative which are obtained by synthesizing the priorities of individual case alternative against different knowledge indicators (knowledge indicators are the nodes of the construction knowledge cluster in the KANP.BID model) and other assistant indicators from other clusters, the pro-

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cesses of evaluation and selection of alternatives, which have the different knowledge priority, can be conducted by a limiting priority weight.

In brief, the KANP approach is to provide a knowledge-framed ANP procedure for evaluation purposes within a multicriteria decision-making environment. As the knowledge frame for the KANP model is built based on the ANZSIC construction division in this paper, the model is therefore a construction knowledge-framed multicriteria decision making model, and has its inherent potentials and capability for multicriteria decision-making in all construction related problems wherever the ANZSIC can be applied. In other words, the KANP approach has its inherent potentials and capability for multicriteria decision making in any special areas related to the knowledge frame it is built on.

Experimental Case Study

There are 79 nodes, including 76 indicators and three alternatives, which can be regarded as assessment criteria adopted by the ANP model. To collect this group of indicators, which is critical in selecting appropriate contractors in construction procurement, the writers have paid attention to related literature and recalled their experiences directly and indirectly gained from construction projects across the world. The writers believe that these criteria could be modified later during further research and development. However, it may not be a problem to use these criteria in current experimental case study, which aims to demonstrate the effectiveness of the ANP model.

As given in Table 1, there are three tender alternatives including Vendors A, B, and C. The experimental study is thus conducted to demonstrate the effectiveness of the KANP.BID model, which is to select the most appropriate tender among different alternatives for environmental-friendly construction purposes (refer to Table 1). For the KANP.BID model presented in Fig. 3, in order to complete the pairwise comparisons, the relative importance weight of interdependence is determined by using a scale of pairwise judgment, where the relative importance weight is valued from one to nine (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 updated on professional experience and knowledge in the application area. In this study, it is determined by the writers that the objective of this study is mainly to demonstrate the usefulness of the KANP.BID model in evaluating the sustainability of the proposed construction project for carrying out procurement.

For a particular tender alternative, weights for all interdependences are then aggregated into a series of submatrices; the series of submatrices are then aggregated into a supermatrix; and the supermatrix is then used to derive an initial supermatrix. In order to obtain useful information for tender selection, calculation of the supermatrix is to be conducted following three substeps which transform an initial supermatrix to a weighted supermatrix (see Fig. 4), and then to a synthesized supermatrix. After the limiting supermatrix is set up, the following procedure is adopted to select the most appropriate tender by using results from the limiting supermatrix (Saaty 1996, 2005).

The main results of the KANP.BID model computations are the overall priorities of tender alternatives, which can be obtained by synthesizing the priorities of individual tender alternatives against different KANP.BID indicators. The selection of the most appropriate tender that has the highest sustainability priority can be conducted by a limiting priority weight, which is defined in Eq. (2) below

$$w_i = w_{\lim,i}/w_{\lim} = w_{\lim,i}/(w_{\lim,1} + \cdots + w_{\lim,n_T}) \tag{2}$$

where w_i=synthesized priority weight of tender alternative t ($t=1,\ldots,n_T$) (n_T=total number of tender alternatives, n_T=3 in this study); and $w_{\lim,i}$=limited weight of tender alternative t in the limiting supermatrix. Because the $w_{\lim,i}$ is transformed from pairwise judgments, it is reasonable to regard as it the priority of the tender alternative t and thus to be used in Eq. (1). According to the computation results in the limiting supermatrix in the experimental study, $[w_{\lim,i}]=[0.283, 0.057, 0.032]$, so the $[w_i]=[0.761, 0.153, 0.086]$. Since the synthesized priority weight of tender A=highest among the three alternatives, the most appropriate tender is tender A (refer to Table 5).

Table 5. Selection of Most Appropriate Vendor

ANP model	Number of nodes	Synthesized priority weight w_i Vendor A	Vendor B	Vendor C	Selection
KANP.BID	79	0.761	0.153	0.086	Vendor A

According to the attributes of tender alternatives listed in Table 1, comparison results based on the synthesized priority weight also imply that the most preferable tender in sustainable procurement is the one that regulates the construction practice with lowest life-cycle cost, lowest risk, least consumption, lowest waste, and maximum material recycle and reuse, etc. These consistencies indicate that the KANP.BID model presented can provide a quite reasonable comparison result for the purpose of environmental-friendly construction during procurement and thus can be applied into construction tendering practice.

Discussions and Recommendations

This paper has been being prepared based on the writers their own research initiative, which is to apply ANP in selecting contractors. According to the writers literature review, there has been much research in this area using multicriteria decision making (MCDM); however, an ANP application has note emerged from the writers search frame (as illustrated in Fig. 1), in the area of construction procurement. To follow up the reviewer's comments, the writers have further read some publications from the performance based studies research group (PBSRG) at the Arizona State University, and noticed that Kashiwagi (2004) mentioned that ANP is one of the decision-making methods, but did not recommend it for one or more of the following reasons:

1. It is very complex (requires an "expert" to run the model);
2. It requires someone to translate numbers;
3. It cannot compare objective and subjective data;
4. It allows user bias and subjectivity;
5. It uses pairwise comparison between alternatives and attributes, which makes it very difficult to use on projects with a large number of contractors and criteria;
6. It cannot prioritize a list of contractors;
7. It cannot select the best value efficiently (in a fast and cost effective manner); and

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8. It requires extensive programming and "learning."

According to their experience in using ANP (Chen 2007), the authors would like to give the following explanations with regard to the eight reasons listed above:

1. Expert or expert worker or knowledge worker is required in order to achieve a high level decision; on the other hand, it allows reusing experts knowledge, which is valuable in construction procurement;
2. The ANP model can be developed in a research center and packaged for commercial use;
3. The ANP model can be used to compare objective and subjective data depending on the specification of indicators;
4. The human decision-making process may not ignore subjective opinions. The ANP model can effectively combine objectivity and subjectivity to increasingly use subjective experts knowledge;
5. An innovative tool called PairWiser has been developed to deal with a large number of pairwise comparison issue, and a description has been added in the revised paper;
6. This may not apply to ANP as those eight reasons are all for the nine "decision-making models," including the arithmetic average matrix, AHP, linear programming, neural network, cluster analysis, ANP, data envelopment analysis, factor analysis, and expert systems;
7. There has been some software that can be used for AHP/ANP modeling, and new versions can be expected based on theoretical development; and
8. Refer to explanations 1 and 7.

This paper describes an ANP model to support decision making in selecting an appropriate contractor for a specific project. The writers have significantly reduced the description of ANP theory, because it is assumed that most readers may not have enough knowledge of ANP and some basic information has to be delivered. Furthermore, according to the theory of ANP, it may not be a complicated MCDM method for practitioners to grasp in their work, especially when there is professional software to facilitate the applications. To evaluate whether ANP can be applied in construction procurement, the most important issue may be whether an ANP model can bring real value to a client in selecting the most appropriate contractor for a construction project. If this is the case, practitioners may use this approach in improving their techniques.

The ANP model is designed for use by clients' decision-making panels. Therefore, the clients may need to put all necessary effort into data collection and assembly by themselves. Alternatively, they can ask for services provided by a third party. In order to apply the KANP.BID model in practice, it is recommended to follow the following steps:

1. Assess tender alternatives (vendors) according to the list of KANP.BID indicators using Table 1;
2. Carry out pairwise comparisons among all KANP.BID indicators, using the Delphi method (Linstone and Turoff 1975) to collect data from experts through a questionnaire survey with the two-page PairWiser questionnaire table (see Appendix), and PairWiser tool to accelerate data accumulation into ANP software;
3. Conduct supermatrix calculation following the three substeps to transform an initial supermatrix into a limiting supermatrix using ANP software;
4. Calculate synthesized priority weight of each tender alternative (vendors) using the calculation results from the limiting supermatrix, and then to get the ANP result regarding the most appropriate vendor as contractor; and
5. If none of the tender alternatives (vendors) meets the requirements on sustainability, adjustments to tenders are necessary and reevaluation of the tender alternatives is recommended by repeating the above procedure.

The process of the first four steps has been described in the context, which aims to demonstrate the effectiveness of the ANP model in terms of vendor selection in project procurement. Regarding the fifth step, this paper does not provide a demonstration to explain how it works. However, as a recommended step, the writers would like to think that clients may need to specify some requirements in advance in regard to the assessment criteria as given in Table 1, and this may facilitate getting satisfactory results at the end of the fourth step. The fifth step is a guarantee that clients will get ideal tenders before making final decisions. In this regard, the fifth step is not a must in using ANP to select the most appropriate vendor; and it may be beyond the scope of this paper to further demonstrate how to conduct Step 5 in the experimental case study.

There is an experimental case study to demonstrate the effectiveness of the proposed ANP model, and further case studies are still in progress. The writers are looking forward to more collaboration with both academics and professionals in terms of applying ANP to support decision making in construction procurement. Regarding what is required of the computing alternatives to get benefits from using ANP, the writers have recommended a procedure in the "Discussion and Recommendation" section. ANP modeling can support decision making and the paper suggests a procedure to be followed that can reduce the subjectivity of client decision makers. However it should be noted that the model does not totally replace the decision maker.

In this experimental case study, the writers use Super Decisions software designed by Bill Adams and the Creative Decisions Foundation in Pittsburgh. In this software, a consistency check and inconsistency improvements are always done from the matrix mode. In our experimental case study, the software gave satisfied results regarding a consistency check in pairwise comparisons. Consequently, the writers are satisfied that the pairwise comparisons are robust and do not explore consistency issue in detail in this paper. Readers who are interested may further use the Super Decisions software and review texts by Saaty (1994; 2005) for inconsistency improvement in their ANP modeling. In a discussion of the results with practitioners, they took the view that ANP is a new technique and expressed a need for such decision support tools. Therefore, the writers would like to recommend the use of the Super Decisions software at present, and explore consistency issues by users themselves in using such function integrated in the software.

The discussion of the value that a MCDM model would give is beyond the scope of this paper. However, as ANP is one MCDM method the writers would recommend that it could be used by practitioners to deal with a number of decision making problems in the construction domain. The beauty of ANP is that it provides more reliable decision-making support by quantitatively measuring all possible interrelations among indicators based on reuse of the experts' knowledge.

Conclusions

This paper presents a multicriteria decision-making model called KANP.BID for the assessment of contractor candidates in open competitions of project procurement. The model is developed

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based on a proposed knowledge-framed ANP approach using criteria related to sustainable construction. The KANP.BID model is comprised of nine clusters and 79 nodes consisting, of the cluster of tender alternatives (vendors) and its three options for experimental case study purposse. The KANP.BID model contains feedback and self-loops among the clusters (see Fig. 3), but with no control model. However, there is an implicit control criterion with respect to which all judgments in pairwise comparison are made for setting up the model, and it is the sustainability in construction or the sustainable construction, which is defined in the first paragraph in the “Introduction” section. The Super Decisions software is recommended to build up the decision-making model and to conduct super-matrix computations for the overall priorities of tender alternatives. Finally, the synthesized priority weight of each vendor is used to distinguish the most appropriate vendor who may be chosen as the contractor for the construction project.

An experimental case study is conducted to demonstrate the procedure of using the KANP.BID model in vendor evaluation. This case study is designed for potential interest from both practitioners and researchers. From the practitioners' points of view, they may need a practical tool rather than understanding of the theory. In this regard, the writers did not explore more theories on ANP and KANP according to current technical levels among practitioners. Instead this paper provides a practical procedure that practitioners can follow repeatedly in their daily work. On the other hand, from the researchers' points of view, they may have more interest in theories, applications, and further research. In this regard, the writers did not explore many details about how to use the KANP.BID model in construction procurements. As a result, this paper compromises these possibilities by providing opportunities for both sides to further explore relevant applications and research, and the writers expect that this may be the most appropriate way to introduce the work to the audiences of the Journal.

However, problems also exist in the current KANP.BID model. For example, the reliability of clusters and their nodes has not been quantitatively measured, and subjective interrelation judgments in pairwise comparison between pair clusters and nodes can influence the accuracy of calculation results. Further studies are therefore needed to explore these issues.

Regarding the indicators selected for the KANP.BID model in this paper, there was no quantitative evaluation processes conducted to identify the relevant rates of those indicators (see Table 1), although the quantitative evaluation of indicators for ANP modeling is recommended (Chen 2007). Alternatively, a search frame as illustrated in Fig. 1 provides an appropriate way for choosing those indicators from relevant works being conducted by practitioners and researchers previously, including references mentioned in the section of “Step 1: KANP.BID Model Construction” because all those relevant works are valuable to support current research into ANP modeling. For further study, there is also a potential to develop a quantitative approach to selecting a group of the most appropriate indicators under different conditions, which could be more flexible for use in practice, to facilitate the application of the KANP.BID model in construction procurements. Moreover, adaptations among different standard industrial classifications as a knowledge frame for the KANP method requires further experimental study in terms of various situations in different construction industries.

Regarding how practitioners can use ANP in their daily work, the writers would like to consider two options. The first one is to repeat the writers' experience, which means they must put effort into data collection and input to set up all possible interrelations among all indicators and their clusters. This is useful to set up specific models based on individual preference based on experience from their own projects; but they also need to spend much time at the very beginning. The second one is to use an ANP model developed by researchers or other practitioners, which means they can save time but have to trust that the commercial model is reliable. However, under any circumstance, it is important to have an ANP model that can effectively support the clients' decision-making process in vendors evaluation. This paper is only one attempt to explore the possibility of using ANP based on knowledge reuse to deal with one complicated problems in construction procurement with regard to the increasing need for sustainable construction.

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Appendix

PairWiser Questionnaire Table: Importance Scores of Indicators and Their Clusters (Page 1).

Clusters of indicators			Indicators to evaluate contractor candidates		
No.	Name of cluster	Score[a] of cluster	Number	Name of indicator	Score[a] of indicator
6	Nature		6.1	N1:Temperature difference risk in life cycle	
			6.2	N2:Windstorm risk in life cycle	
			6.3	N3:Rainfalls risk in life cycle	
			6.4	N4:Flood risk in life cycle	
			6.5	N5:Earthquake risk in life cycle	
			6.6	N6:Landslip risk in life cycle	
			6.7	N7:Settlement risk in life cycle	
			6.8	N8:Corrosion risk in life cycle	
			6.9	N9:Disturbance risk to geoenvironment	
7	Society		7.1	S1:Public health risk in life cycle	
			7.2	S2:Public safety risk in life cycle	
			7.3	S3:Landfill burden (waste disposal) during construction	
			7.4	S4:Public traffic disruptions during construction	
			7.5	S5:Cargo transportation burden during construction	
			7.6	S6:Legal & responsibility risk	
			7.7	S7:Neighborhood disturbance in construction	
8	Knowledge		8.1	4111 House construction	
			8.2	4112 Residential building construction n.e.c.	
			8.3	4113 Nonresidential building construction	
			8.4	4121 Road and bridge construction	
			8.5	4122 Nonbuilding construction n.e.c.	
			8.6	4210 Site preparation services	
			8.7	4221 Concreting services	
			8.8	4222 Bricklaying services	
			8.9	4223 Roofing services	
			8.10	4224 Structural steel erection services	
			8.11	4231 Plumbing services	
			8.12	4232 Electrical services	
			8.13	4233 Air conditioning and heating services	
			8.14	4234 Fire and security system services	
			8.15	4241 Plastering and ceiling services	
			8.16	4242 Carpentry services	
			8.17	4243 Tiling and carpeting services	
			8.18	4244 Painting and decorating services	
			8.19	4245 Glazing services	
			8.20	4251 Landscaping services	
			8.21	4259 Construction services n.e.c.	

[a] Note: Below please find scales for scoring with regard to sustainable (environmental, social and economic) issues relevant to construction projects: 1=not important, 2=not to moderately important, 3=moderately important, 4=moderately to strongly important, 5=strongly important, 6=strongly to very strongly important, 7=very strongly important, 8=very strongly to extremely important, 9=extremely important.

Notation

The following symbols are used in this paper:

I,J = I=index number of rows; J=index number of columns; both I and J correspond to number of cluster and their nodes ($I,J \in (1,2,\ldots,79)$);

$N_I^{(n_I)}$ = node belongs to cluster I and total number of nodes in cluster I is n_I;

n = total number of columns in cluster I;

n_I = total number of nodes in cluster I;

n_T = total number of tender alternatives (n_T=3 in this study);

t = tender number ($t=1,\ldots,n_T$);

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W_{IJ} = submatrix of supermatrix;
w_t = synthesized priority weight of tender alternative t;
$w_i|_{I,J}$ = weighted/derived priority of node i at row I and column J, $i \in (1,2,\ldots,n_I)$;
$w_{\lim}$ = sum of limited weight of all tender alternatives in limiting supermatrix;
$w_{\lim,t}$ = limited weight of tender alternative t in limiting supermatrix; and
α_{ij} = matrix value assigned to interdependence relationship of node i to node j to reflect relative importance weight of interdependence.

References

Addis, B., and Talbot, R. (2001). *Sustainable construction procurement: A guide to delivering environmentally responsible projects*, CIRIA publication C571, Construction Industry Research and Information Association (CIRIA), London.

Alhazmi, T., and McCaffer, R. (2000). "Project procurement system selection model." *J. Constr. Eng. Manage.*, 126(3), 176–184.

Al-Tabtabai, H. M. (2002). "Construction procurement strategy selection using analytical hierarchy process." *J. Constr. Procure.*, 8(2), 117–132.

Ashworth, A. (2006). *Contractual procedures in the construction industry*, 5th Ed., Pearson Education Limited, Harlow, U.K.

Australian Bureau of Statistics (ABS). (2004). *ANZSIC review: Construction division paper*, The Australian Bureau of Statistics (ABS), Belconnen, Australia.

Australian Government Department of the Environment and Heritage (DEH). (2004). *National Australian built environment rating system (NABERS) project*, Industry Partnerships Section, Environment Protection Branch, Australia, ⟨http://www.deh.gov.au/industry/construction/nabers/index.html⟩ (Nov. 23, 2004).

Avila, E. A. (1997). "Demystifying the local agency procurement and selection process for professional engineering consultant services." *J. Manage. Eng.*, 13(2), 92–95.

Brown, D. C., Ashleigh, M. J., Riley, M. J., and Shaw, R. D. (2001). "New project procurement process." *J. Manage. Eng.*, 17(4), 192–201.

Chen, Z. (2007). *Multicriteria decision-making for the sustainable built environment*, The University of Reading, Reading, U.K., ⟨http://www.ibrg.rdg.ac.uk/Publications.htm⟩ (June 10, 2008).

Chen, Z., and Li, H. (2006). *Environmental Management in Construction*, Taylor & Francis, London.

Chen, Z., Li, H., Hong, J., and Xu, Q. (2004). "An integrative analytical system for environmental management in construction projects." *Autom. Constr.*, 13(5), 621–628.

Chen, Z., Li, H., and Wong, C. T. C. (2000). "Environmental management of urban construction projects in China." *J. Constr. Eng. Manage.*, 126(4), 320–324.

Chen, Z., and Li, H., and Wong, C. T. C. (2005). "Environal Planning: An analytic network process model for environmentally conscious, construction planning." *J. Constr. Eng. Manage.*, 131(1), 92–101.

Cheung, S. O., Lam, T. I., and Wan, W. Y. (2001). "Improving objectivity in procurement selection." *J. Manage. Eng.*, 17(3), 132–139.

Chua, D. K. H., and Li, D. (2000). "Key factors in bid reasoning model." *J. Constr. Eng. Manage.*, 126(5), 349–357.

Crowley, L. G., and Hancher, D. E. (1995). "Risk assessment of competitive procurement." *J. Constr. Eng. Manage.*, 121(2), 230–237.

Department for Environment, Food and Rural Affairs. (2006). "What is sustainable development? The sustainable development unit (SDU)." U.K., ⟨http://www.sustainable-development.gov.uk/what/index.htm⟩ (June 10, 2008).

Dey, P. K., Tabucanon, M. T., and Ogunlana, S. O. (1996). "Petroleum pipeline construction planning: a conceptual framework." *Int. J. Proj. Manage.*, 14(4), 231–240.

Elfvengren, K., Kengpol, A., Varis, J., and Tuominen, M. (2004). "Alliance partner selection using a group support system and the analytic network process." *Proc., 13th Int. Working Seminar on Production Economics*, Igls, Innsbruck, Austria, 73–84.

El Wardani M. M. A., Messner J. I., and Horman, M. J. (2006). "Comparing procurement methods for design-build projects." *J. Constr. Eng. Manage.*, 132(3), 230–238.

Emap Construction Network. (2008). *Construction plus: Knowledge for construction*, Emap Construction Network, London, ⟨http://www.constructionplus.co.uk/⟩ (October 10, 2008).

Expert Choice. (2005). "Client list." Expert Choice, Inc., USA, ⟨http://www.expertchoice.com⟩ (May 12, 2007).

Gransberg, D. G., and Molenaar, D. (2003). "A synthesis of design-builder selection methods for public infrastructure projects." *J. Constr. Procure.*, 9(2), 40–51.

Hackett, M., Robinson, I., and Statham, G. (2006). *The Aqua Group guide to procurement, tendering and contract administration*, Blackwell Publishing, Oxford U.K..

Hampton, D. (1994). "Procurement issues." *J. Manage. Eng.*, 10(6), 45–49.

Kashiwagi, D. T. (2004). *Best value procurement*, 2nd Ed., Performance Based Studies Research Group (PBSRG), Arizona State University Press, Tempe, Ariz.

Kashiwagi, D. T., and Byfield, R. (2002a). "State of Utah performance information procurement system tests." *J. Constr. Eng. Manage.*, 128(4), 338–347.

Kashiwagi, D. T., and Byfield, R. (2002b). "Testing of minimization of subjectivity in best value procurement by using artificial intelligence systems in state of Utah procurement." *J. Constr. Eng. Manage.*, 128(6), 496–502.

Khasnabis, S., Alsaidi, E., Liu, L., and Ellis, R. D. (2002). "Comparative study of two techniques of transit performance assessment." *J. Transp. Eng.*, 128(6), 499–508.

Linstone, H. A., and Turoff, M. (1975). *The Delphi method: Techniques and applications*, Addison-Wesley Publishing Company, Reading, Mass.

Lo, W., Chao, C. H., Hadavi, A., and Krizek, R. J. (1998). "Contractor selection process for Taipei mass rapid transit system." *J. Manage. Eng.*, 14(3), 57–65.

McGraw-Hill. (2008). *Construction, building, and engineering news: ENR*, The McGraw-Hill Companies, Inc., New York, ⟨http://enr.construction.com/Default.asp⟩ (October 10, 2008).

Meade, L. M., and Sarkis, J. (1999). "Analyzing organizational project alternatives for agile manufacturing processes." *Int. J. Prod. Res.*, 37(2), 241–261.

Morledge, R., Smith, A., and Kashiwagi, D. T. (2006). *Building procurement*. RICS Research and Blackwell Science, Oxford, U.K.

Muya, M., Price, A. D. F., Thorpe, A., and Edum-Fotwe, F. (1999). "Application of analytic hierarchy process to the evaluation of logistics factors and their contribution to improvements in construction materials supply." *J. Constr. Procure.*, 5(2), 99–117.

National Academy of Engineering (NAE). (1999). *Industrial environmental performance metrics: Challenges and opportunities*, Committee on Industrial Environmental Performance Metrics, National Research Council, Washington, D.C..

National Academy of Sciences (NAS). (2005). *Decision making for the environment: Social and behavioral science research priorities*, Committee on the Human Dimensions of Global Change (HDGC), and Center for Economic, Governance, and International Studies (CEGIS), Washington, D.C.

O'Connor, J. T., Rusch, S. E., and Schulz, M. J. (1987). "Constructibility concepts for engineering and procurement." *J. Constr. Eng. Manage.*, 113(2), 235–248.

Ogunlana, S. O., ed. (1999). *Profitable partnering in construction procurement*, E&FN Spon, London.

Palaneeswaran, E., and Kumaraswamy, M. M. (2000). "Contractor selec-

J. Constr. Eng. Manage., 2008, 134(12): 928-941

tion for design/build projects." *J. Constr. Eng. Manage.*, 126(5), 331–339.

Pryke, S. D. (2006). "Legal issues associated with emergent actor roles in innovative U.K. procurement: Prime contracting cast study." *J. Profl. Issues Eng. Educ. Pract.*, 132(1), 67–76.

RMIT. (2004). *Greening the building life cycle: Life cycle assessment tools in the building and construction*, Centre for Design, Australia, ⟨http://buildlca.rmit.edu.au/menu1.html⟩ (June 10, 2008).

Rogers, M. (2001). *Engineering project appraisal*, Blackwell Publishing, Oxford, U.K.

Rowlinson, S., and McDermott, P., eds., (1999). *Procurement systems: A guide to best practice in construction*, E & FN Spon, London.

Saaty, T. L. (1994). *The fundamentals of decision making and priority theory with the analytic hierarchy process*, RWS Publications, Pittsburgh.

Saaty, T. L. (1996). *Decision making with dependence and feedback: The analytic network process*, RWS Publications, Pittsburgh.

Saaty, T. L. (2005). *Theory and applications of the analytic network process*, RWS Publications, Pittsburgh.

Srisoepardani, K. P. (1996). "The possibility theorem for group decision making: The analytic hierarchy process." Ph.D. dissertation, Katz Graduate School of Business, Univ. of Pittsburgh, Pittsburgh.

UK Government Department of Trade and Industry (UK DTI). (2004). *Sustainable construction brief 2*, Sustainable construction team (DTI), London, ⟨http://www.dti.gov.uk/construction/sustain/⟩ (Nov. 23, 2004).

UK Office for National Statistics (2003). *United Kingdom standard industrial classification (UK SIC) of economic activities 2003*, statistics-.gov. uk, ⟨http://www.statistics.gov.uk/statbase/Product.asp?vlnk=9769⟩ (Nov. 23, 2004).

U.S. Census Bureau (2002). *2002 NAICS codes and titles*, census. gov, ⟨http://www.census.gov/epcd/naics02/naicod02.htm⟩ (Nov. 23, 2004).

Zeeger, C. V., and Rizenbergs, R. L. (1979). "Priority programming for highway reconstruction." Transportation Research Board and Washington, D.C., *Transportation Research Record*. *698*, 15–23.

J. Constr. Eng. Manage., 2008, 134(12): 928-941