Design of an innovative construction model for supply chain management by measuring agility and cost of quality: An empirical study

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Abstract. This paper aims to present a model for an agile supply chain network in construction enterprises with performance evaluation of suppliers and contractors. Management and selection of suppliers and contractors play an important role in the process of constructions since contractors are as corner stones of construction projects. Additionally, contractors are the main factor in converting resources to final products. Traditionally, contractor selection in construction projects is on the basis of the lowest proposed price. However, there are various qualitative and quantitative criteria with different priorities associated in this regard in order to make the best decision. In this paper, a hybrid method of DEA/AHP/FDEMATEL is used. First, important and effective evaluation criteria are selected through an FDEMATEL method. Then, the DEA/AHP method is implemented in order to evaluate and prioritize the selected indicators as well as to incorporate them in a supply chain. Furthermore, agility is involved in the considered supply chain network. Furthermore, in this paper, for the first time in Iran, a supply chain model is studied and designed for civil companies.

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1. Introduction

Efficiency and effectiveness of each organization is obtained through management performance and its supply chain structure. The key to success of today’s organizations is laid in perception and recognition of customers’ requirements and providing a quick response to them. This results from investigations and developments in a Supply Chain (SC). Supply Chain Management (SCM) is a set of approaches towards collaboration of suppliers, manufacturers, warehouses, and retailers so that products are delivered to customers in a right amount, time, and location, in which the total cost of the system is minimized through satisfaction of a determined service level [1]. In fact, SCM is managing a set of interrelated issues that are in line with customers' satisfaction [2]. The total aim of SCM is to integrate organizational units and coordinate material flow, information, and money in a way that competency of an SC can be improved [3-5].

Supply chain management in construction projects is defined as follows: management of information flow, actions, activities, and processes including
various networks of independent organizations and their communication paths (upstream and downstream) that create value in the form of a project for the owner [6]. Upstream activities in an SC of construction projects from the main contractor’s point of view include the project owner and engineering/design group that prepare the process of construction. Downstream activities, including material suppliers and secondary contractors that stay in touch with the primary contractors, require high levels of cooperation among beneficiaries of the project. In today’s competitive environment, construction organizations have to be connected with the best suppliers and secondary contractors in order to keep their competency advantageous. Often, construction organizations are not expert in determining their suppliers’ capabilities and commonly make decisions based on their perceptions. This integrated concern, i.e. process of supplier selection, should melt in supply chain environment in a way that ensures material availability [6]. In Appendix A, two models, i.e. horizontal and vertical, are presented for SCM of construction projects. In this paper, we apply the first pattern for the SC design [6].

Supplier and contractor selection is basically a Multi-Criteria Decision Making (MCDM) problem. However, most organizations deal with this issue from a strategic point of view. The essence of this kind of decisions is highly complex without having a certain structure. Therefore, by applying management tools, e.g. MCDM methods, we can solve them. Regarding the proposed problem and the related literature, a new model is presented in this paper for SCM of construction projects along with supplier and contractor evaluations.

Various models are available in the literature, which are concerned with the supplier selection problem. Wind and Robinson [7] proposed a linear weighting method for rating different vendors in an experimental environment. Also, some studies considered their goals under budget constraints for evaluation of different vendors. For example, goal programming formulation was used for obtaining the goals related to price and quality under different constraints [8,9]. There have been several methods used for a supplier selection problem during the past years [10-19]; however, Data Envelopment Analysis (DEA), Analytical Hierarchy Process (AHP), and the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) are the most popular methods for the vendor (or supplier) selection problem.


In this paper, superiorities of the AHP/DEA hybrid method presented by Stern et al. [41] in AHP and DEA methods are studied in case of decision making units’ performance evaluation. Also, AHP/DEA is employed for evaluation of decision making units [42]. Many quantitative methods have been presented for performance evaluation and prioritizing of decision-making units so far. These methods are Delphi, AHP, ANP, MCDM, DEA, etc. Due to comprehensiveness and efficiency of the AHP/DEA, this method is employed in this study.
2. AHP/DEA/FDEMATEL hybrid approach framework

Supply chains in manufacturing systems are multi-
echelon networks consisting of suppliers, manufactur-
ers, wholesalers, retailers, and warehouses. In these
supply chains, manufacturers or warehouses are fixed,
whereas they are not fixed in construction projects. To
be more explicit, whenever a project is completed, the
workshop, i.e. virtual warehouse, is removed. Hence,
warehouses in construction projects can be defined as
virtual workshops. The supply chain network proposed
in this paper is considered to be agile and virtual
once a project, in which this network is applicable,
is completed. In this network, a hybrid multi-criteria
model is applied. First, this model selects the most
favorable influential criteria for supplier and contractor
evaluation. Afterwards, it prioritizes them through
the hybrid AHP/DEA method. Then, with regard
to Figure 1 and inserting the chosen suppliers and
contractors in the network, construction supply chain
networks are constituted. In this paper, a real case is
implemented in the P.G. Company.

P.G. Corporation has remarkable experiences
when it comes to dam building, implementation of
irrigation and drainage networks, road construction,
tunnel drilling, hydraulic heavy concrete and steel
construction, marine structures, massive constructions,
and design and construction of manufacturing firms.
This corporation is licensed grade one under the super-
vision of president’s Strategic Planning and Monitoring
Deputy and under the supervision of Iranian Ministry
of Housing and Urban Development. The grades of this
corporation are as follows:
- Grade one in the fields of water, industry, and
mining; roads and transportation; buildings and
monuments; facilities and equipment; and massive
construction management;
- Grade two in oil and gas industry, and design and
construction of buildings and monuments;
- Grade three in the field of power.

P.G. Construction and Industrial Corporation
has managed to receive the following licenses since
2003: Integrated Management System (IMS) certified
by DQS of Germany, IQNet, Environmental Manage-
ment System (ISO 14001; 2004), Quality Management
System (ISO 9001; 2008), Occupational Health &
Safety Advisory Services (OHSAS 18001; 2007), Risk
Management System (ISO 31000: 2009). Customer Satis-
faction, and Complaints Handling (DIN ISO 10002;
2005). Furthermore, this corporation is awarded a
5star acknowledgement of EFQM.

3. Determining performance evaluation
criteria by an FDEMATEL method

In order to evaluate performance of decision-making
units, first, it is necessary to determine and study their
indicators. In this paper, the FDEMATEL method is
employed for supplier/contractor performance evalua-
tion. Finally, regarding specific features of construction
companies, important criteria are obtained for both
suppliers and contractors.

Fontela and Gabus [43] presented DEMATEL,
which was based on paired comparisons. To bene-
fit from experts’ judgments in extracting a system’s
indicators and putting them in a structure through
a graph theory, a hierarchical structure with logical
relations is acquired [44,45]. The severity of these
relations is stated as numerical rates. The DEMATEL
method is used for determining and studying mutual
relations among criteria and for mapping them onto
the network. Since directed graphs can better present
the relations among components of a system, the
DEMATEL method is on the basis of some diagrams
that define the involved components into cause and
effects. Also, it draws their relations in an intelligible
structural model. It is often used for global complex
problems and similarly, for structuring a sequence
of given information. Subsequently, the severity of
relations is studied as numerical scores; the feedbacks
are searched along with their importance, and the
indefensible relations are accepted. The main steps of
the DEMATEL method are as:

![Diagram](attachment:figure_1.png)
Considering interrelations: This method has an edge over ANP; it has clarity and transparency in mirroring the interrelations among the large sum of components so that experts can express their points of view dominantly towards the effects (direction and effect intensity) among criteria. It is remarkable that, in fact, the occasioned matrix in DEMATEL method (interrelated matrix) constitutes a part of a super-matrix. In other words, DEMATEL acts indirectly and as a subsystem of a larger system such as ANP.

Structuring complex criteria in the form of cause and effect groups: This issue is one of the most frequently used functions and one of the most important factors in the process of problem solving. In this case, a wide range of complex criteria is divided into smaller subsets in the form of cause and effect groups so that decision maker can perceive the relations more appropriately. This matter leads to better understanding of the position of criteria and their role in mutual effects.

3.1. Steps of the DEMATEL method

Establishing direct relation matrix: The paired comparisons are recognized by experts. Thus, the direct relation matrix $A$, with $n \times n$ dimensions ($n$ is the number of criteria), is established and $a_{ij}$ is a number which shows effect of criterion $i$ on criterion $j$.

Normalizing direct relation matrix: The primary normal matrix can be calculated through Eqs. (1) and (2) as follows:

$$X = k \times A. \quad (1)$$

$$k = 1 / \max \sum_{j=1}^{n} a_{ij} \quad 1 \leq i \leq n. \quad (2)$$

Obtaining the general relations matrix: The general relations matrix ($T$) is represented through Eq. (3). $I$ is an identity matrix:

$$T = X \times (1 - X)^{-1}. \quad (3)$$

Cause and effect diagram establishment: Summation of the rows ($D$) and summation of the columns ($R$) in matrix $T$ are obtained by Eqs. (4)- (6):

$$T = [t_{ij}]_{n \times n} \quad i, j = 1, 2, \ldots, n. \quad (4)$$

$$R = \left[ \sum_{i=1}^{n} t_{ij} \right]_{1 \times n} = [r_{ij}]_{1 \times n} \quad i, j = 1, 2, \ldots, n. \quad (5)$$

$$D = \left[ \sum_{i=1}^{n} t_{ij} \right]_{n \times 1} = [d_{ij}]_{n \times 1} \quad i, j = 1, 2, \ldots, n. \quad (6)$$

Table 1. Linguistic scales for the importance weight of criteria.

<table>
<thead>
<tr>
<th>Linguistic terms</th>
<th>Triangular fuzzy numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>No influence</td>
<td>(0.1, 0.1, 0.3)</td>
</tr>
<tr>
<td>Very low influence</td>
<td>(0.1, 0.3, 0.3)</td>
</tr>
<tr>
<td>Low influence</td>
<td>(0.3, 0.5, 0.7)</td>
</tr>
<tr>
<td>High influence</td>
<td>(0.5, 0.7, 0.9)</td>
</tr>
<tr>
<td>Very high influence</td>
<td>(0.7, 0.9, 1)</td>
</tr>
</tbody>
</table>

The horizontal vector of cause and effect diagram ($D + R$) is called superiority vector, which shows the relative importance of each criterion. The vertical axis ($D - R$) is named relative vector. If the value of this vector is positive, the corresponding criteria belong to causes and otherwise the corresponding criteria belong to effects.

Obtaining internal dependency matrix: In this step, summation of the elements of each column in general matrix equals 1 through normalizing method and the internal dependency matrix can be obtained.

Chang et al. [46] and Wu and Lee [47] investigated implementing of a fuzzy DEMATEL. The considered group consisted of 50 experts and specialists (project managers), experienced enough in the field of supplier evaluation in a wide range of projects. They were asked to fill out the questionnaires. The group of experts included 20 experts (project managers), specialists in supplier evaluation. They were asked to express their opinion through filling out the questionnaires. Table 1 shows the linguistic scales for the importance weight of criteria used by specialists.

Regarding the outcome of the DEMATEL method in Tables 2 and 3, the most important and influential indicators are chosen for suppliers and contractors of the corresponding company. The selected indicators are CR 9, CR 20, CR 14, CR 13, and CR 19 for suppliers and CR 20, CR 14, CR 13, CR 19, CR 16, CR 17, and CR 2 for contractors. The names of these indicator are shown in Appendix B. To measure the reliability of the questionnaire, the Cronbach’s alpha is used in SPSS 21 software. The product of this method for our questionnaire is 0.85, which means the questionnaire is reliable enough. Appendix B shows the normalized input and output indicators related to each supplier and contractor. Due to importance of quality as one of the main evaluation criteria for performance of suppliers in civil projects, we decide on the cost of quality recognition and analysis.

3.2. Analysis of cost of quality indicators in construction projects

The concept of quality cost in construction projects was introduced in early 1980s, when organizations had
focused on boosting quality of construction projects. Quality costs are assumed to be total cost of compliances and non-compliances. The cost of compliances or reaching a certain level of quality is that spent to prevent a low level of quality and non-compliances or quality failure; low quality is imposed by defective product or service. A classification model of prevention, inspection, failure is commonly used to define and classify the cost of quality. Regarding the research conducted in construction projects, a non-compliance cost can be reduced from 2 to 10% through spending more 1% in a prevention phase. Minimizing the cost of quality to the lowest possible amount is one of the goals of a quality cost system. The basic assumption of P.A.F is that focusing on prevention and inspection will reduce failure cost. In fact, in this paper, we also design a systematic framework for the cost of quality, in which the optimum interval is obtained for the mentioned costs. Quality costs are structured based on the P.A.F model. This approach is achieved by recent studies [48-51] and the experiences of experts as shown in Figure 2. Since the quality cost of suppliers is crucial in construction projects and in the P.G. Company, the suppliers and contractors with the least possible amount of quality costs are selected.

4. AHP/DEA method

The DEA method divides the considered units into two efficient and inefficient groups. The units which score 1 in efficiency are defined as efficient and the others, with efficiency less than 1, are named inefficient ones. The main problem is to rank and prioritize the efficient while the inefficient units are ranked spontaneously. The presented hybrid DEA/AHP method is to rank decision making units [41]. In this method, a DEA model is initially implemented for each pair of units regardless of other units. Afterwards, using the outcomes of solving DEA models, a paired comparison matrix is formed. Then, the AHP method is implemented in level 1 to fully rank the units.

The proposed method has some major advantages. The inconsistency resulted from mental judgments in a paired comparison matrix of the AHP is removed. The constraints of enterprises are relaxed towards inputs and outputs. Since in the DEA method, the number of enterprises in comparison with the number of inputs and outputs is relatively high, it leads to a situation that most enterprises score one in efficiency. As a consequence, prioritizing them can be difficult. In this method, each enterprise is compared with others and its efficiency score is calculated. Therefore, the

| Table 2. Prominence and relation axes for the cause and effect group for suppliers. |
|---------------------------------|--------|--------|--------|--------|
| Criteria | $R + D$ | $R - D$ | $D$   | $R$   |
| CR 20    | 50.3325 | -0.66  | 25.49625 | 24.83625 |
| CR 14    | 43.9965 | 11.93  | 16.04175 | 27.95475 |
| CR 19    | 40.96125 | -2.00725 | 21.48425 | 19.477 |
| CR 16    | 41.4425 | 1.903  | 19.76975 | 21.67275 |
| CR 17    | 42.36075 | 2.05475 | 20.153  | 22.20775 |
| CR 2     | 42.234  | 5.853  | 18.1905  | 24.0435 |
| CR 10    | 39.0045 | 7.5885 | 15.708  | 23.2965 |
| CR 18    | 37.23375 | -0.23025 | 18.732  | 18.50175 |
| CR 1     | 36.98025 | -3.59925 | 20.28975 | 16.6905 |
| CR 3     | 36.46425 | -9.06075 | 18.7125  | 17.75175 |
| CR 4     | 35.8395 | -5.382  | 20.61075 | 15.28275 |
| CR 12    | 35.697  | -2.3395 | 19.02825 | 16.68675 |
| CR 15    | 33.579  | 7.9635  | 12.80775 | 20.77125 |
| CR 9     | 32.817  | -11.0085 | 21.91275 | 10.90425 |
| CR 8     | 30.74175 | 6.04175  | 12.348  | 18.39375 |
| CR 6     | 27.66375 | 0.86775  | 13.398  | 14.26575 |
| CR 7     | 27.294  | -1.515  | 14.4045  | 12.8895 |
| CR 11    | 22.89  | 0.6555  | 11.11725 | 11.7725 |
| CR 5     | 22.02675 | 3.86025  | 9.08325  | 12.9435 |

| Table 3. Prominence and relation axes for the cause and effect group for contractors. |
|---------------------------------|--------|--------|--------|--------|
| Criteria | $R + D$ | $R - D$ | $D$   | $R$   |
| CR 9     | 42.35687 | -5.81787 | 24.07873 | 18.2935 |
| CR 20    | 30.1555 | 2.9595  | 13.598  | 16.5575 |
| CR 14    | 33.36155 | 4.01145  | 14.62035 | 18.6365 |
| CR 13    | 28.52445 | -0.06945 | 14.26095 | 14.2725 |
| CR 10    | 23.14058 | 7.92146  | 7.60084  | 15.531 |
| CR 17    | 23.0201 | -2.7431  | 12.8816  | 10.1385 |
| CR 12    | 22.5945 | -0.30445 | 11.41065 | 11.1215 |
| CR 18    | 22.3249 | 2.3441  | 9.9004  | 12.3345 |
| CR 3     | 19.3195 | 4.3495  | 7.485  | 11.8345 |
| CR 1     | 19.2429 | 3.0111  | 8.1159  | 11.127 |
| CR 4     | 18.3968 | 1.9082  | 8.2433  | 10.1525 |
| CR 8     | 17.2017 | 7.3233  | 4.9922  | 12.3265 |
| CR 6     | 14.8697 | 4.1513  | 5.3592  | 9.5105 |
| CR 11    | 14.51885 | 1.17815  | 6.67035  | 7.8485 |
| CR 7     | 14.3548 | 2.8312  | 5.7618  | 8.303 |
| CR 5     | 12.2623 | 4.9957  | 3.6333  | 8.629 |
Figure 2. Recognition framework cost of quality in construction projects.

5. Supply chain design in construction projects

In this study, an innovative dynamic supply chain for a real case study in a construction project is presented. The case study is considered in a civil enterprise, namely, P.G. Company. In this hybrid method, suppliers and contractors are first selected through the hybrid AHP/DEA/FDEMATEL method. While implementing the project, the project management office and quality assurance unit are in touch with a contractor and continuously assess the project; also, in case of disruption and failure, the main contractor will be summoned. In the next step, some new indicators are defined and combined with the first introduced ones to evaluate suppliers and contractors when the project is finished by project managers. This process is again based on the hybrid DEA/AHP method and the best ones are selected to establish a rich database for the upcoming projects. In fact, the continuous evaluation of projects before initialization, during the execution, and after completion is an agile approach (it is noteworthy that agility is matched with EFQM 2013 and PMBOK, Fifth Edition) to supplier and contractor evaluation in construction projects’ SCM. This model is shown in Figure 4.

5.1. Measuring agility in Construction Supply Chain Model (CSCM)

In this paper, due to importance and novelty of agility in civil projects, we decided to measure the agility in civil projects through Yield Process method:

\[
\text{Agility} = \text{Yield Process}_{\text{overall}} = f \left( \text{Yield Process}_{\text{circle}_1} + \text{Yield Process}_{\text{circle}_2} + \text{Yield Process}_{\text{circle}_3} \right),
\]

(7)

\[
\text{Yield Process}_{\text{circle}_n} = A \times x_n.
\]

(8)

where \( A \) shows the importance rate of each circle in total Yield Process and \( x_n \) defines each Yield Process in its circle. Therefore, regarding Eqs. (7) and (8), the main equation is as follows:

\[
YP_{\text{overall}} = Ax_{\text{circle}_1} + Bx_{\text{circle}_2} + Cx_{\text{circle}_3} + Dx_{\text{circle}_4}.
\]

(9)

With respect to Figures 3 and 4, each circle is calculated; for instance, circle3 and circle4 show CSI (Customer Satisfaction Index) and CSI2. To boost the agility in the supply chain of civil projects, it is necessary to obtain large values for Yield Process. Hence, the total quality cost, mentioned in Section 3.2, will be optimized.

5.2. Ranking suppliers/contractors using a hybrid method

Tables 4 and 5 show the rankings for suppliers and contractors according to the hybrid DEA/AHP method.
Due to some confidential issues, instead of unit names, we use the DMU to show suppliers and contractors. It is worth mentioning that supplier and contractor evaluation in the P.G. Company is conducted just for a specific project. The AHP method is done via Excel VBA and the resulted rankings are executed through the DEA method in GAMS 24.1.2 software on a Pentium 4 system with 2.3 GHz and 4GB RAM.

6. Conclusions and future studies

In this paper, for the first time in Iran, we have studied and designed a supply chain for civil companies. A hybrid AHP/DEA/FDEA method has been proposed and used to evaluate and prioritize the suppliers and contractors in the network. First, the most influential indicators have been chosen by a fuzzy DEMATEL method. Afterwards, suppliers and contractors have been evaluated according to the DEA method and the selected indicators. However, regarding inefficiency of most units, we have applied a hybrid DEA/AHP method. Furthermore, in this study, we have focused on agility of a supply chain. In addition to agility,
Figure 4. Construction supply chain management agility mode.
it is dynamic and virtual; thus, it is applicable for different projects. Quality costs have been optimized through applying a yield process approach to agility of the supply chain. For future research, it is worthwhile to contribute portfolio management into the proposed model.

References


Appendix A
Figures A.1 and A.2. show the representation of the vertical and horizontal supply chains in construction projects, respectively.

Appendix B
Tables B.1 and B.2 show the supplier and contractor’s criteria scores, respectively.
Figure A.1. Representation of supply chain in vertical construction projects in private and public sections.

Figure A.2. Representation of horizontal supply chain and large-scale construction projects in public sections.

Table B.1. Criteria scores of suppliers.

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Cost of quality</th>
<th>Guarantee and warranty</th>
<th>Waste and damages</th>
<th>Equipment</th>
<th>Delivery</th>
<th>Supplier</th>
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Table B.2. Criteria scores of contractors.

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<th>Ability technical and planning</th>
<th>Native</th>
<th>Rework costs</th>
<th>Financial</th>
<th>Reliability</th>
<th>History</th>
<th>Experience</th>
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Biographies

Yaser Rahimi is a PhD student of Industrial Engineering in the College of Engineering at University of Tehran, Iran. He received his MSc degree in Industrial Engineering from University of Tehran, Iran, in 2014 and his BSc degree in Industrial Engineering from University of Kurdistan, Iran, in 2011. His research interests include hub location, transportation, operations research, meta-heuristic methods, exact optimization methods, and supply chain management. Yaser Rahimi published 12 papers related to hub location problems and supply chain in journals.

Reza Tavakkoli-Moghaddam is Professor of Industrial Engineering in the College of Engineering at University of Tehran, Iran. He obtained his BSc, MSc, and PhD degrees from Iran University of Science and Technology, Tehran, in 1989; University of Melbourne, Melbourne, in 1994; and Swinburne University of Technology, Melbourne, in 1998, respectively. He serves as the Editor-in-Chief of two journals and the Editorial Board Member of five journals. He was the recipient of the 2009 and 2011 Distinguished Researcher Awards as well as the 2010 and 2014 Distinguished Applied Research Awards by University of Tehran in Iran. He was also selected as National Iranian Distinguished Researcher in 2008 and 2010 by the Ministry of Science, Research and Technology (MSRT) in Iran. He obtained the outstanding rank of being among the top 1% scientists and researchers in the world elite group, reported by Thomson Reuters in 2014. Professor Tavakkoli-Moghaddam has published 4 books, 17 book chapters, and more than 700 papers in reputable academic journals and conferences.

Sirous Shojaie received his MSc degree in Industrial Engineering at Iran University of Science and Technology in Iran (2014). He obtained his BSc degree in Industrial Engineering from the Imam Hossein Comprehensive University in Tehran, Iran, in 2001. His research interests include location, transportation, quality management system, six-sigma, and total quality management.

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