ASSESSMENT OF CRITICALITY OF MATERIALS IN A CONSTRUCTION PROJECT

Santu Kar[1] and Kumar Neeraj Jha

Department of Civil Engineering, Indian Institute of Technology Delhi, New Delhi, 110016, India

Material management is a key process for the success of a construction project. Typically, in a construction project, material accounts for 50-60% of the total project cost. Non-availability of material when required, potentially impact a construction project causing time overrun, cost overrun, and loss of productivity. Due to the complex nature of construction projects, it is difficult to measure the impact of non-availability of materials. It is essential to prioritise materials for procurement based on the impact of their non-availability, especially in the budget constraint situation. However, in practice criticality of materials in procurement has not been considered and also very few studies have been reported in this area. We propose, the total criticality (TC) of material for prioritisation of materials for procurement in budget constraint situation and as a measure of the impact of non-availability of materials. The TC of materials has been determined based on material criticality (MC) and activity criticality (AC). The AC has been obtained based on the float available for the activity. The MC has been determined using an integrated ANP-TOPSIS (analytic network process and technique for order preference by similarity to an ideal solution) approach which is a novel approach. This approach is employed with the additional criteria of MC such as environmental implication and volatility in price of materials along with the other reported criteria in literature such as percentage contribution, flexibility, lead time, customer's specificity, and buyer's dependence on suppliers. The ANP has been employed for determining the weight of the criteria by considering their interdependencies and pairwise comparison as obtained based on a questionnaire survey within a group of experts while for the TOPSIS, inputs from an institutional building project have been utilised. The reported study will help in timely and budgeted completion of construction projects.

Keywords: ANP, criticality, material management, prioritisation, TOPSIS

INTRODUCTION

The construction industry is a fast-growing sector, and its contribution to the global economy will increase to about 15% of the global GDP by 2020 (Schilling, 2013). The construction spending of the global market is expected to reach USD 14 trillion in 2025 (Statista, 2017). Countries likely to undergo substantial growth include China, India, Russia, Brazil, Poland, and the US. The growth of the construction industry leads to large consumption of materials in construction projects. Moreover, materials account for 50-60% of the total project cost of a construction project and influence 80% of the construction schedule (Caldas *et al.,* 2014). Hence, greater importance is required to be given to effectively managing the materials. Typically, a limited budget is allocated for procurement of materials for a certain period in a construction

[1] santu.iitd.11@gmail.com

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project, which restricts procurement of all materials at once. Project network characteristic needs to be considered for procurement of materials. Besides, managers desire to store materials which have other important criteria such as high volatility in price, high percentage contribution, long lead time, more buyer dependency, etc. Therefore, materials need to be prioritised for procurement to avail the right materials at the right time in construction projects, especially in a budget constraint situation (Dixit *et al.,* 2013).

Non-availability of materials when required, incur a penalty in the form of time overrun, cost overrun, and loss of productivity (Koushki and Kartam, 2004). The penalty can be minimised or avoided if materials are prioritised for procurement considering their criticality values. Criticality of a material indicates the relative quantitative measure of the penalty due to their non-availability. Although it is essential to determine the criticality of materials and to prioritise them for procurement, very few studies are reported in this area in literature. Also, no prior study has been reported in the literature demonstrating the methodology for determining the criticality of construction materials that have both multiple criteria and interdependence property.

In this study, the above need is addressed by assessing total criticality (TC) of materials based on material criticality (MC) and activity criticality (AC). MC is the criticality of material concerning the activity whereas, TC is the criticality of materials concerning the overall project as it integrates the project network by assessing AC. The MC values of materials are calculated based on some criteria using ANP (analytic network process) - TOPSIS (technique of order preference by similarity to ideal solution) method. Specifically, we demonstrate how an integrated ANP-TOPSIS method can be used for determining MC values by considering interdependence among criteria. An institutional building project is considered as a case project for calculating TC values of materials. Higher TC value indicates the higher penalty due to the non-availability of materials. Greater follow-up and coordination with suppliers need to be adopted for highly critical materials. Procurement of materials by prioritising them based on the TC values can reduce the penalty incurred due to the non-availability of materials and will assist in timely and budgeted completion of the construction projects. Furthermore, TC values can be adopted as the shortage cost coefficients in the inventory model as it incorporates both material perspective and project perspective. This study contributes to the body of knowledge by integrating material management with the construction schedule and demonstrating a systematic approach for prioritisations of materials through the assessment of their criticality values.

LITERATURE REVIEW

The penalty incurred due to non-availability of materials were described by Huiskonen (2001) defining two dimensions: (1) process criticality which is related to the penalties due to loss of work and (2) control criticality which is related to the supply uncertainty of items. Dixit *et al.,* (2013) addressed the integration of material management with project management. The researchers adopted the criteria such as percentage contribution, flexibility, buyer's dependence, customer specificity, and lead time to determine criticality values of materials. They adopted fuzzy inference system (FIS) in the study. Overall criticality (OC) of material was determined based on material criticality (MC) and activity criticality (AC) values. OC was treated as the prioritisation measure of materials. However, they did not consider the interdependencies among criteria and the study was in the context of manufacturing of complex products. Criticality of materials in infrastructure projects was introduced by Purnell *et al.,* (2013). They described that disruption of the supply of critical materials could be affected by geological reserves, geopolitics, and increasing demand. However, in this study, the criticality of materials was demonstrated in the context of raw materials and project network characteristic was not considered. Lapko *et al.,* (2016) described the materials that are said to be critical due to their high supply constraints and high economic importance.

The above studies did not incorporate sustainability aspects for the assessment of material criticality. Hallstedt and Isaksson (2017) explained that sustainability aspects had an impact on criticality and introduced it for assessing the criticality of alloy materials. Knoeri *et al.,* (2013) described the importance of environmental implication for assessing the criticality of raw materials. Researchers mentioned that environmental implication could restrict the material supply. Glöser *et al.,* (2015) addressed the criticality of raw materials considering supply risk, vulnerability, and environmental implication. Lloyd *et al.,* (2012) considered that environmental limitation would cause stricter legislation and hence will restrict the supply of materials. Environmental aspects of criticality have been considered by researchers in many terms such as environmental restrictions, environmental performance, environmental impacts, and environmental implications (Nieto *et al.,* 2013; Knoeri *et al.,* 2013; Ku *et al.,* 2018). However, for this research, environmental implication will be used as the criteria from sustainable aspects to determine the MC values.

A comprehensive literature review has revealed that no prior study is reported for assessment of criticality of construction materials. Although it is important to incorporate project network characteristic for assessing criticality, very few studies considered this. Also, interdependencies among criteria are not considered while determining criticality. Therefore, it is essential to assess the criticality of construction materials considering sustainable aspects, interdependencies among criteria, and incorporating project network characteristic.

RESEARCH METHODOLOGY

The research was carried out focusing on the construction industry. The criteria governing the MC values were identified from the literature. The criteria were reviewed by a group of experts who have extensive experience and knowledge of material management in construction. Twelve professionals from the leading construction companies, working as project manager, planning engineers, store engineers, and procurement engineers were selected as experts. The professionals have a work experience of ten to thirty-five years in material management. A questionnaire survey was conducted among the group of experts to identify the interrelationship between the criteria. The experts were asked to rate the effect of one criterion on to the other criteria on a Likert scale of 1-5. Here, 1 represents 'very less effect' and 5 represents 'very high effect.' The mean values of the responses were calculated and based on it the interrelationship between criteria were drawn. Another questionnaire survey was carried out to obtain the relative importance of criteria by comparing them pairwise considering their interrelationships. The ratings were obtained on 1 - 9 scale. Here, 1 represents 'equal importance,' and 9 represents 'extreme importance' when comparing one criterion over another (Saaty, 1990). Subsequently, using the ANP technique in the Super Decisions 2.10 (SD) software, the weights of the criteria were determined. Consistencies of the collected responses were also computed using the software. The ANP technique was adopted for obtaining the precise weights of criteria as it considers collective effort from a group of experts, and gives a better structure for decision support, and also considers interdependencies among the criteria.

Further, the MC values of materials in an institutional building project was calculated using the TOPSIS method considering the weights of the criteria and input for the specific materials given by the three project professionals who are involved in the material management process in the project. Input on percentage contribution (PC) and lead time (LT) was captured in percentage and days respectively. Flexibility (FE), customers' specificity (CS), and buyer's dependence on suppliers (BD) were taken as input on a 1-5 scale where 1 represents very low, and 5 represents very high. Environmental implication (EI) was taken as tons of carbon dioxide emission for production of 1 ton of material and volatility in price of material (VP) as the ratio of maximum price to minimum price for the 5 years. The criteria of MC include both positive and negative criteria. The TOPSIS method was adopted because it can incorporate both positive and negative criteria in the analysis. Positive criteria and negative criteria are the criteria which have a direct relationship and inverse relationship with MC respectively. The MC value increases with the increase of the positive criteria value of the material whereas, the MC value decreases with the increase of the negative criteria value of the material. The, AC values of materials were obtained based on the float available for the activities to which they are involved according to the construction schedule of the institutional building project. Further, TC values of materials were determined by combining MC values with AC values of respective materials.

Determination of material criticality

Criteria of material criticality
To determine the material criticality (MC), the first step is to identify the criteria that influence the MC. The six criteria of MC were identified after reviewing the literature. The criteria were reviewed by the group of experts and an additional criterion termed 'volatility in price of materials' was identified from the discussion with experts. The criteria with their description and relationship with the MC are provided in Table 1.

Interrelationship between criteria
To determine the interrelationship among criteria forming a network structure is the most important step of ANP. For this, we collected responses from a group of experts based on a questionnaire survey. The effect of one criterion to others was captured on a 1-5 scale and the mean value of the responses was calculated. It was considered that a particular criterion affects another criterion if the mean value obtained was more than 3 (Ahuja *et al.,* 2009). For example, the mean value of the effect of percentage contribution (PC) on flexibility (FE) was obtained as 3.8. However, the mean value of the effect of FE on PC was 2.6. Therefore, PC affects FE, but FE does not affect PC. The resulting network structure is shown in Figure 1.

From Figure 1, it can be seen that environmental implication (EI) has no relationship with other criteria of MC, because EI does not affect any criterion and no criterion affects EI. However, other criteria are interrelated as shown in Figure 1.

Determination of the weight of criteria using ANP method
Another questionnaire survey was carried out to obtain the relative importance of criteria by comparing them pairwise. The questionnaire was developed based on the

interrelationship among criteria. In the first section of the questionnaire, the experts were asked to evaluate the criteria with respect to MC without assuming their interdependencies. To compare the criteria pairwise, it was asked which criterion is more important and how much more important on a 1-9 scale. Pairwise comparison matrices of the individual responses were developed. Consistency ratios (CR) of the individual responses were calculated using the SD software. To combine the individual responses, an overall pairwise comparison matrix was determined using the Eq. (1) as reported by Wakchaure and Jha (2012).

Table 1: Criteria and their relationship with MC

S. N	Criteria	Description	Relationship with the material criticality (MC)
1	Percentage contribution (PC)	It is the percentage contribution of material for completion of the activity.	A material with higher PC leads to higher penalty due to its non-availability. Thus, PC is directly related to MC.
2	Flexibility (FE)	It is the likelihood to carry out an activity adopting other ways or using other alternative materials, in case the material is not available.	A material with lower FE will cause higher penalty as the possibility to carry out the associated activity is lesser. Thus, FE is inversely related to MC.
3	Lead time (LT)	It is the time to deliver a material to the construction site after placing the order to the supplier.	A material with higher LT has high supply risk and requires more follow-ups, causing higher expediting cost. Thus, LT is directly related to MC.
4	Customers' specificity (CS)	It is the uniqueness of the material which demands technical expertise.	A specialised supplier is required for a material with higher CS value. Higher level of communication is required for its procurement. Therefore, CS is directly related to MC.
5	Buyer's dependence on suppliers (BD)	It is the degree to which the buyer needs a particular supplier to procure the material.	BD is directly related to MC.
6	Environmental implication (EI)	It is the measure of environmental performance associated with material production/manufacturing.	If the emission of carbon dioxide is high, then EI is high. This may increase the supply risk of material due to a stricter legislation policy decision. Therefore, EI is directly related to MC.
7	Volatility in price of material (VP)	It is the degree of variation of material price over time.	If the VP is high, the risk in purchasing the materials are high as the price of materials may increase to a high amount. Therefore, VP is directly related to MC.

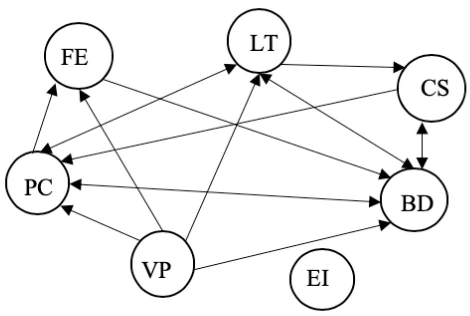

Figure 1. Interrelationship between criteria

For combining, the responses were weighted based on their consistencies on a prorate basis (see Eq. 1). For example, a response with a higher consistency was given a higher weight in comparison to the response with a lower consistency.

$$y_{ij} = [x_{1ij}^{w1} \times x_{2ij}^{w2} \times .... \times x_{nij}^{w_n}]^{\frac{1}{w_1+w_2+\cdots+w_n}} \quad (1)$$

Here, y_{ij} is the cell entry of the combined pairwise comparison matrix and x_{nij} is the cell entry of the pairwise comparison matrix of the nth respondent. w_n is the weight assigned to the nth respondent which is equal to (1 - CRn) and CRn is the consistency ratio for the nth respondent. The weight of the criteria (w_1) without considering interdependencies was determined based on the combined pairwise comparison matrix of criteria with respect to MC as provided in Table 2. The CR value of the combined matrix was obtained as 0.036 which is less than 0.1 and assures the consistency of the responses

Table 2: Weight of the criteria without considering its interdependencies

	PC	FE	LT	CS	BD	EI	VP
Weight (w_1)	0.122	0.110	0.190	0.179	0.095	0.090	0.214

In the second section of the questionnaire, the experts were asked to evaluate the criteria considering their interrelationship. For example, LT, CS, BD, and VP affect PC as shown in Figure 1. Therefore, it was asked to evaluate LT, CS, BD, and VP by comparing them pairwise with respect to PC. Similarly, it was asked to evaluate criteria with respect to FE, LT, CS, and BD. However, no criteria affect EI and VP. Pairwise comparison matrices were developed based on the individual responses and were combined using Eq. (1). The priority vectors of the matrices were obtained. Combining the priority vectors, the interdependence matrix of criteria (w_2) was determined as shown in Table 3. Zero was assigned to the eigenvector of criteria which are independent. The CR values of the matrices were obtained as less than 0.1 that confirm the consistency of the responses.

Table 3: Interdependence matrix of criteria

w_2	PC	FE	LT	CS	BD	EI	VP
PC	0.500	0.263	0.166	0.353	0.100	0.000	0.000
FE	0.000	0.500	0.000	0.000	0.032	0.000	0.000
LT	0.158	0.000	0.500	0.000	0.112	0.000	0.000
CS	0.108	0.000	0.000	0.500	0.099	0.000	0.000
BD	0.092	0.000	0.095	0.000	0.500	0.000	0.000
EI	0.000	0.000	0.000	0.000	0.000	1.000	0.000
VP	0.142	0.237	0.239	0.147	0.157	0.000	1.000

By synthesizing the above results weight of the criteria (w_3) with interdependencies were obtained as given in Table 4 using Eq. (2). Considering interdependencies, the weight of the criteria of MC has changed significantly which reveals the novelty of the ANP method.

$$w_3 = w_2 \times w_1 \quad (2)$$

Table 4: Weight of the criteria considering its interdependencies

	PC	FE	LT	CS	BD	EI	VP
Weight (w_3)	0.194	0.058	0.125	0.112	0.077	0.090	0.344

Determination of MC values using TOPSIS method

TOPSIS technique determines the preference of alternatives based on the distance from the positive ideal solution and the negative ideal solution. The best alternative has the shortest distance from the positive ideal solution and farthest from the negative ideal solution. To calculate MC values adopting TOPSIS method, a total of 5 materials (representing alternatives) required in the building project were considered. The project professionals were asked to evaluate materials under each individual criterion. A decision matrix was established calculating the geometric mean of the individual responses. A normalised decision matrix was developed using Eq. (3). Further, a weighted normalised decision matrix was developed using Eq. (4) as shown in Table 5.

$$r_{ij} = x_{ij} / \sqrt{\sum_{i=1}^{5} (x_{ij})^2} \quad (3)$$

$$v_{ij} = w_j \times r_{ij} \quad (4)$$

i = 1, 2… 5 and j = 1, 2….7

Here, x_{ij} is the original score of material i with respect to criteria j, and r_{ij} is its normalised score. v_{ij} is the weighted normalised score of material i with respect to criteria j, and w_j is the weight of the criteria j.

Table 5: Weighted normalised decision matrix

Material	PC	FE	LT	CS	BD	EI	VP
Cement	0.063	0.012	0.064	0.047	0.034	0.030	0.144
Reinforcement bar	0.135	0.012	0.054	0.041	0.038	0.069	0.143
AAC blocks	0.092	0.040	0.073	0.054	0.038	0.002	0.181
Coarse aggregate	0.042	0.015	0.043	0.054	0.034	0.002	0.142
Tiles	0.072	0.036	0.038	0.052	0.026	0.050	0.156

The next step in TOPSIS method is to determine the ideal solution. The positive ideal solution and the negative ideal solution were obtained using Eqs. (5) and (6) respectively. Here, positive criteria are PC, LT, CS, BD, EI, and VP as they have a direct relationship with MC whereas, FE is the negative criteria as it has an inverse relationship with MC.

$$A^* = \{(\max(v_{ij}) | j \in J); (\min(v_{ij}) | j \in J')\} = \{v_1^*, \dots v_n^*\} \quad (5)$$

$$A' = \{(\min(v_{ij}) | j \in J); (\max(v_{ij}) | j \in J')\} = \{v_1', \dots, v_n'\} \quad (6)$$

Here, J is the set of positive criteria whereas, J' is the set of negative criteria. For example, the weighted normalised scores of reinforcement bar (0.012) and AAC blocks (0.073) represent the positive ideal solution for FE and LT respectively while the weighted normalised scores of AAC blocks (0.040) and tiles (0.038) represent the negative ideal solution for FE and LT respectively. In the next step, separation measure from the positive ideal solution and negative ideal solution were calculated using Eqs. (7) and (8) respectively. Further, relative closeness to the positive ideal solution was determined using Eq. (9) as given in Table 6. This represents the MC values of materials which lies between 0 and 1.

$$S_i^* = [\sum_{j=1}^{n} (v_j^* - v_{ij})^2]^{1/2} \quad (7)$$

$$S_i' = [\sum_{j=1}^{n} (v_j' - v_{ij})^2]^{1/2} \quad (8)$$

$$C_i^* = \frac{S_i'}{(S_i^* + S_i')} \quad (9)$$

Table 6: Material criticality (MC) values of materials

Material	Cement	Reinforcement bar	AAC blocks	Coarse aggregate	Tiles
C_i^* (MC)	0.365	0.730	0.468	0.189	0.419

Determination of total criticality

Traditionally, in the critical path method, a critical activity is the activity which has zero float duration. Criticality increases as the float decreases. Based on this, Eq. (10) is developed for calculation of activity criticality (AC) of materials.

$$AC_k = 1 - \frac{f_k}{\sum f_k} \quad (10)$$

Here, AC_k is the activity criticality value of material associated with activity k and f_k is float duration of the activity. Using Eq. (10), AC values of materials were calculated as shown in Table 7. Finally, total critically (TC) of materials were determined by combining MC and AC values as shown in Table 7. Materials are ranked based on the TC values where higher TC value indicates a higher priority of material for procurement.

Table 7: Activity criticality (AC) values of materials

Material	Associated activity	Float (days)	AC	MC	TC	Rank
Cement	Slab concreting	0	1.0	0.365	0.365	2
Reinforcement bar	Slab reinforcement fixing	0	1.0	0.730	0.730	1
AAC blocks	External Wall	10	0.6	0.468	0.281	3
Coarse aggregate	Slab concreting	0	1.0	0.189	0.189	4
Tiles	Flooring	15	0.4	0.419	0.168	5

DISCUSSION

An activity may need several materials. However, criticality of the materials may not be the same. It depends on the inherent characteristics of materials and the supply environment. Cement and coarse aggregate are required for the same activity (slab concreting). It can be seen from Table 7 that cement (TC=0.365) is more critical than coarse aggregate (TC=0.189). This is because of the higher percentage contribution (PC), higher lead time (LT), higher volatility in price of material (VP), and lesser flexibility (FE) values of cement than coarse aggregate. Thus, penalty due to non-availability of cement will be more than that due to coarse aggregate.

It can be further seen that cement (TC=0.365) is more critical than AAC blocks (TC=0.281). Even though the material criticality (MC) value is lower for cement, it will be used for slab concreting which is a critical activity. However, AAC blocks will be used for a noncritical activity. This leads to higher activity criticality (AC) values of cement compared to that of AAC blocks. It is implied that penalty due to non-availability of material can be greater for the material which has higher AC value. Therefore, it is important to incorporate AC values in material procurement decision. As shown in Table 7, it can be observed that the reinforcement bar is most critical with TC=0.730 due to its highest MC values and highest AC values. Hence in a budget constraint situation, procurement manager should give the highest priority to reinforcement bar followed by cement, AAC blocks, coarse aggregate, and tiles for procurement. Although, materials like cement, reinforcement bar, and coarse aggregate are ranked based on their TC values, these being key elements of reinforced cement concrete, an appropriate procurement strategy and supply chain decision needs to be taken for their procurement in addition to the assessment of their criticality.

CONCLUSIONS

Material management process in a construction project requires an extensive effort due to its complex nature and limited budget availability. The process can be effective if procurement is carried out by prioritising the materials based on their inherent characteristics, supply environment, and project network. Seven interdependent criteria are identified that represents the characteristics of materials and the supply environment. The material manager can directly use the weight of the criteria for evaluation of MC values in any construction project. Further, based on the inputs for the material on the given scale under each criteria, managers can determine MC values of materials in a construction project. By calculating AC values based on activity float and combining it with MC values, TC values can be calculated. The TC value represents the quantitative measure of the penalty due to the non-availability of a material. Materials with higher TC values needs greater attention from materials managers and extensive coordination with suppliers. It can be used to prioritise the material for procurement especially, in the budget constraint situation in a construction project. Prioritising materials based on it will ensure the availability of materials on time and reducing the penalty in terms of time and cost overrun.

Furthermore, penalty due to non-availability of materials or shortage cost is very difficult to quantify in a construction project and also there is no well-defined method for its quantification in the organization. However, it is an essential component for an inventory model. Therefore, TC values are proposed to be used as shortage cost coefficients of materials in the inventory model as it incorporates both material characteristics and project characteristics. To validate the model, it is planned to be implemented in an ongoing building construction project by comparing it with the existing procurement strategy in an organization. This is the part of the authors' intended comprehensive research plan. Further research is also suggested to conduct sensitivity analysis for the mentioned criteria. Even though due care was taken to select the respondents in an unbiased manner, the selection of criteria and assessment of their weights through the questionnaire survey involve subjectivity such as deficiency of conscientious responses and differences in understanding.

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