



APPLICATION OF FUZZY FAULT TREE ANALYSIS TO IDENTIFY FACTORS INFLUENCING CONSTRUCTION LABOR PRODUCTIVITY: A HIGH-RISE BUILDING CASE STUDY

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Abstract. The aim of this research is to develop a systematic approach to identify and prioritize the most influencing factors on labor productivity in a construction project, with respect to their interrelations, and also investigate different scenarios which can affect it. In the first step, factors influencing construction labor productivity were identified through reviewing previous researches. Applying a group of experts, the most important factors were then determined using their relative importance index in the second step. In the third step, the interrelations among factors were determined through several sessions and interviewing those experts. Finally, the efficiency of the proposed methodology is proved by implementing in a real high rise building construction project. In this step, the selected factors from previous steps were used subsequently for analyzing their impact on labor productivity through fuzzy fault tree analysis. The probability of occurrence of events was determined according to the opinions of four members of the project management team who involved in that project. The most critical causes were also identified using importance analysis. It is believed that using the proposed methodology, appropriate response strategies could be adopted against the identified critical events to enhance the overall productivity of a construction project.

Keywords: construction management, quantitative risk analysis, labor productivity, influential factors, fault tree analysis, fuzzy set theory.

Introduction

The construction sector plays a strategic role in the economic structure of any country (Durdyev & Ismail, 2017; Durdyev, Zavadskas, Thurnell, Banaitis, & Ihtiyar, 2018; Alkay, Watkins, & Keskin, 2018; Ma, Liu, & Reed, 2017). It attracts a large amount of investments from both public and private sectors. Therefore, construction productivity has a major impact on the efficiency of organizations and the overall economy of one country. Low productivity of construction projects is a common problem in many countries (Fulford & Standing, 2014; Durdyev & Mbachu, 2018; Hiyassat, Hiyari, & Sweis, 2016; Alaghbari, Al-Sakkaf, & Sultan, 2019; Jarkas, Al Balushi, & Raveendranath, 2015). Labor productivity is a complex function of many factors which can increase and decrease project performance (Karimi, Taylor, & Goodrum, 2017). In general, the term “productivity” connects outputs to inputs (Borcherding & Liou, 1986). Durdyev, Ismail, and

Kandymov (2018) define productivity as an effective resource (input) utilization to achieve to achieve a set of objectives (output), which can also be expressed as “the ratio of output divided by input”. Output and input vary from industry to industry. In the construction sector, productivity can be measured using two commonly formula (Jarkas & Bitar, 2012). The first measure of productivity is the Total Factor Productivity (TFP). This measure has direct relation with total output and reverse relation with the summation of inputs. Input resources usually include labor, equipment, materials, energy and capital. TFP can be calculated using Eqn (1):

$$TFP = \frac{\text{Total output}}{\sum(\text{labor} + \text{equipment} + \text{materials} + \text{energy} + \text{capital})} \quad (1)$$

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The second measure of productivity is the Partial Factor Productivity (PFP). This measure has also direct relation with the outputs and reverse relation with a single or selected set of inputs. Labor productivity is one of the most commonly used PFP measures in the construction industry. It is defined as the ratio of output to labor input; the output depends on the installing quantities, and labor input depends on the labor work-hours. Therefore, labor productivity is expressed as follows:

$$\text{Labor productivity} = \frac{\text{Output quantity}}{\text{Labor hours}}. \quad (2)$$

Labor is the main component of any construction project and on-site labor costs contribute between 33% to 50% of total project costs (Fayek, 2011). Therefore, it can be argued that the construction sector is a labor sensitive sector and its productivity is dependent on labor productivity (Jarkas, 2012; Gündüz & Kaya, 2017). In the construction sector, productivity was defined as a ratio between earned work hours and expended work hours, or work hours used (Hanna, Taylor, & Sullivan, 2005). Labor productivity has also been defined as the ratio of the units of work completed (as the output of labor) to the hours of work (that is, input for the labor) (Enshassi, Mohamed, Mayer, & Abed, 2007; Ghoddousi & Hosseini, 2012; Hwang, Zhao, & Do, 2014). Therefore, hourly outputs are widely used to measure labor productivity and these are common in construction research. Investigating the factors influencing labor productivity more deeply, can provide guidance for construction project managers to more efficiently utilize their labor force, develop a system to motivate labor force and enhance laborers' commitment to productivity improvement (Nasirzadeh & Nojedehi, 2013). Knowing what labors need and what influences their performance is important for improving their productivity (Dai, Goodrum, & Maloney, 2009; Oglesby, Parker, & Howell, 1989). Improving construction productivity can eliminate variances from primary plan and keeps the projects on time and within budget (Kaming, Holt, Kometa, & Olomolaiye, 1998).

Based on the conducted study by Yi and Chan (2014) six major areas on Construction Labor Productivity (CLP) research interests can be assumed, such as factors influencing CLP, methods and technologies for CLP improvement, CLP trends and comparisons, CLP modeling and evaluation, effect of changes/variations on CLP and baseline/benchmarking CLP.

This research with the aim of recognizing the most influencing factors on labor productivity in a particular construction project, concerning their interrelations, can be placed in the CLP modeling and evaluation category. In the previous research, several modeling methods have been applied to investigate the relations between influential factors and construction labor productivity. These methods include: the expectancy model, statistical and regression models, action response model, expert systems, system dynamics and ANN (Heravi & Eslamdoost, 2015).

However, despite these numerous research efforts, there are some limitations in the existing models include:

- Proposed approaches are unable to consider subjective data for evaluation of influential factors;
- Considerable data sets are required for model development and testing. In practice, historical data for influencing factors on labor productivity are scarce;
- A systematic approach to rank factors concerning their interactions was not identified.

In other words, factors influencing CLP are often interconnected, some factors may happen due to an identical cause, or one factor may result in happening of other ones (Dai, Goodrum, Maloney, & Srinivasan, 2009). Therefore, considering the internal interactions of these factors whilst analyzing their impact on labor productivity, is necessary.

- Most of the methods are unable to take the multiple influence of factors into account.

In order to fill the existing gap, the aim of this study is to develop a systematic approach to identify and rank the most influencing factors on labor productivity, with respect to their interrelations and also investigate different scenarios which can affect it.

For this purpose, in this research a fuzzy fault tree based approach is proposed for modeling and identifying various factors contributing to the reduction of CLP. Using this method we are able to apply subjective knowledge of experts to identify the critical factors considering their interactions. Furthermore, multiple influences of factors on labor productivity can be analyzed.

The proposed research methodology for the study is presented in Figure 1. As shown in this figure, in the first step, causes of reduction in labor productivity are identified through reviewing previous research. The most influencing ones are also identified using their relative importance index. In the second step, the interrelations among factors were determined through several sessions and interviewing relative experts. Also, based on the discussed relations, the fault tree structure of different basic events leading to reduction in CLP is constructed. The probability of occurrence of events are then determined according to the subjective opinions of the project management team, in the third step. An importance analysis using the proposed fuzzy fault tree based approach is finally performed to identify critical factors and propose recommendations. The remainder of this paper was designed as follows. In the first section, different factors causing reduction of labor productivity are recognized through conducting a literature review. In the second section, the structure and principles of fault tree analysis are briefly reviewed and applied methods for identification of factors and definition of causal relations are discussed. In the third section, the efficiency of the proposed method is proved by implementing in a real building construction project case. The model results are also presented in this section. The fourth section presents a brief discussion and provides some recommendations. Finally, the last section concludes the paper and indicates limitations and paths for further research.

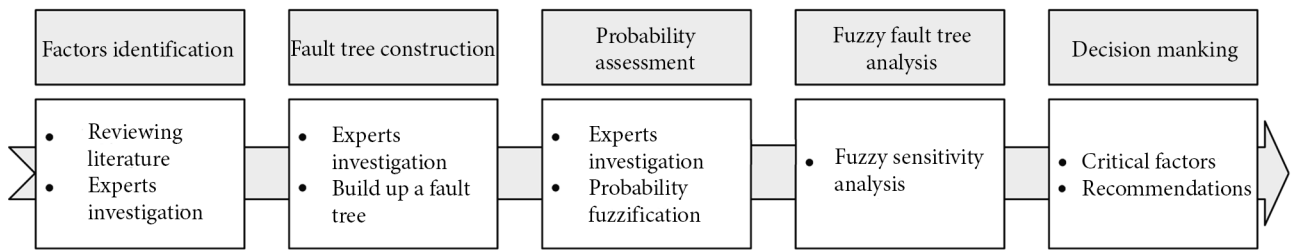


Figure 1. The flow of the research methodology: stages and techniques

1. Literature review

Since in the remainder of this study we want to identify and rank the most influencing factors on labor productivity, using Fuzzy Fault Tree Analysis (FFTA), in this section, the authors reviewed research which have been conducted in different countries concerning factors influencing CLP. Table 1 shows a brief description of these studies and the list of critical identified factors based on their importance.

As depicted in Table 1, because of the significant impact of CLP on project performance, it has been well studied in various countries. According to the reviewed previous research, the identified factors were from five major groups including labor, material and equipment, management and organizational, technical and external related factors.

2. Research methodology

The principles of the proposed fuzzy fault tree method and factors identification method are explained briefly below.

2.1. Fault tree analysis

2.1.1. Fault tree analysis structure

Fault tree analysis (FTA) was developed in 1962 and is frequently used in the fields of safety engineering and reliability engineering (Shoar, Zarandi, Nasirzadeh, & Cheshmikhani, 2017). FTA is employed in almost every engineering discipline and it provides a framework, using that the defects and weaknesses of a system can be

analyzed qualitatively or quantitatively (Lindhe, Rosen, Norberg, & Bergstedt, 2009; Kales, 2006; O'Connor, 2002). Fault tree is a structured logic diagram which is capable to show the cause and effect relationships among events in systems. Fault tree analysis begins with a “top event” to be analyzed that generally is displayed with a rectangle and related events based on logical relations with the top event that are drawn below, branching downward as in a tree (Iverson, Kerkering, Coleman, & Spokane, 2001). The top event defines the failure mode of the system or its function, which is then analyzed in terms of failure modes of its components and influencing factors. FTA begins with the aim of identifying the causes of an undesired event namely top event and with a treelike structure proceeds to their root causes until all possible basic events are reached. After the identification of the top event, intermediate events should be defined. An intermediate event is any event except the top event that could be broken into events could cause it. This process continues until all root causes namely basic events and gate events which show the lowest level in a fault-tree structure are identified. The relationships between events including top event, intermediate event and basic event are described and presented by logical gates including AND gate, OR gate, Inhibit gate and other logic gates (Franke, Flores, & Johnson, 2009). AND gate indicates that if all lower events occur, the upper event will occur. OR gate indicates that the occurrence of any of the lower events would result in the occurrence of the upper event.

Table 1. Summary of previous research in different countries on factors influencing CLP

Country	Source	Brief description of the study	Data analysis approach	Major factors influencing CLP
Uganda	Alinaitwe, Mwakali, and Hansson (2007)	Using a total of 36 selected factors, reported the most important factors influencing CLP perceived by project managers of building projects	Relative importance index	Top 10 factors influencing CLP: (1) incompetent supervisors, (2) lack of skills from the workers, (3) rework, (4) shortage of tools/equipment, (5) poor construction methods, (6) poor communication, (7) stoppages because of work being rejected by consultants, (8) political insecurity, (9) breakdown of tools/equipment, (10) harsh weather conditions
Gaza Strip	Enshassi, Mohamed, Abu Mustafa, and Mayer (2007)	Using a total of 45 selected factors, identified factors negatively influencing CLP within building projects from a contractor’s viewpoint	Relative importance index	Top 5 factors influencing CLP: (1) shortages of materials, (2) lack of labor experiences, (3) lack of labor surveillance, (4) misunderstanding between labor and superintendents, (5) alteration of drawings and specifications during execution

Country	Source	Brief description of the study	Data analysis approach	Major factors influencing CLP
Egypt	Hafez, Aziz, Morgan, Abdullah, and Ahmed (2014)	Using a questionnaire survey comprised 27 productivity factors identified the main factors influencing CLP in the Egyptian construction context	Relative importance index	Top 10 factors influencing CLP: (1) payment delay, (2) skills of labor, (3) shortage of experienced labor, (4) lack of labor supervision, (5) motivation of labor, (6) working overtime, (7) lack of leadership of construction managers, (8) high humidity, (9) clarity of technical specification, (10) high/low temperature
Nigeria	Fagbenle, Ogunde, and Owolabi (2011)	Identified factors have a negative effect on CLP, using a structured questionnaires from the perspective of contractors and labor (operatives) on 40 construction sites	Relative importance index	Top 7 factors influencing CLP: (1) unfair wages, (2) negative influencing factors, (3) lack of motivation, (4) lack of training and retraining, (5) poor communication (6) inclement weather, (7) dearth of investment in research and development
Zimbabwe	Chigara and Moyo (2014)	A structured questionnaires, which included 40 pre-selected factors, were utilized for identifying factors influencing CLP from the perspective of consultants and building contractors	Spearman's rank correlation, mean response, relative importance index	Top 5 factors influencing CLP: (1) materials unavailability, (2) late payment of salaries and wages, (3) plant and equipment suitability/ adequacy, (4) supervisory incompetence, (5) lack of manpower skills
Spain	Robles, Stifi, Ponz-Tienda, and Gentes (2014)	Using a set of 35 selected factors, a structured questionnaire survey was used to collect data from companies for identifying factors influencing labor productivity	Relative importance index	Top 5 factors influencing CLP: (1) late supply or shortage of materials, (2) clarity of the drawings and project documents, (3) clear and daily task assignment, (4) shortages of tools or equipment, (5) level of skill and experience of laborers
Yemen	Alaghbari, Al-Sakkaf, and Sultan (2019)	Using a questionnaire comprised 52 predefined factors identified the main factors influencing CLP from the perspective of architectural and structural engineers	Relative importance index	Top 5 factors influencing CLP: (1) experience and skills of labours, (2) availability of materials in site, (3) leadership and efficiency in site management, (4) availability of materials in the market, (5) political and security situation
Bahrain	Jarkas (2015)	Using a structured questionnaire survey, which included 37 productivity factors, identified the main factors influencing CLP from the perspective of contractors	Relative importance index	Top 10 factors influencing CLP: (1) skills of labour, (2) design disciplines coordination, (3) lack of labour supervision, (4) design drawings errors and omissions, (5) delay in responding to requests for information, (6) rework, (7) stringent inspection by the engineer, (8) working overtime, (9) lack of incentive scheme, (10) inclement weather
Oman	Jarkas, Al Balushi, and Raveendranath (2015)	Using a structured questionnaire survey comprising 33 productivity factors identified the main factors influencing CLP from the perspective of contractors	Relative importance index	Top 10 factors influencing CLP: (1) design drawings errors and omissions, (2) change in orders during execution, (3) delay in responding to requests for information, (4) lack of labour supervision, (5) project specifications clarity, (6) design disciplines coordination, (7) working overtime, (8) rework, (9) inclement weather, (10) physical fatigue of labours
Iran	Ghoddousi and Hosseini (2012)	Using a total of 31 selected factors, a structured questionnaire survey was used to identify the factors and grounds influencing subcontractors productivity and to assess their overall negative side effects on project productivity	Relative importance index	Top 7 factors influencing CLP: (1) materials/tools, (2) construction technologies and methods, (3) planning, (4) supervision system, (5) reworks, (6) weather, (7) jobsite condition

2.1.2. Fuzzy FTA

Fuzzy set theory was first introduced by Zadeh (1965) in order to deal with uncertainty due to imprecision and vagueness. A fuzzy set defined on a universe of discourse (U) is characterized by a membership function, $\mu(x)$, which takes values from the interval $[0, 1]$. A membership function provides a measure of the degree of similarity of an element in U to the fuzzy subset. Fuzzy FTA approach can be applied when sufficient and reliable database is not available. In other words, using this approach, subjective expert opinions can be employed to deal with lack of data in basic events. In general, fuzzy set theory uses triangular, trapezoidal and gaussian fuzzy numbers, which convert the uncertain numbers into fuzzy numbers (Abbasbandy & Hajjari, 2010). In this research, triangular fuzzy numbers are utilized to provide more precise descriptions and to obtain more accurate solutions. $P = (a, b, c)$ is a triangular fuzzy variable when a, b and c represents the minimum, most likely and maximum values, respectively. Tanaka, Fan, Lai, and Toguchi (1983) proposed and applied fuzzy FTA for the first time. This concept has been applied by several researchers in several industries.

Therefore, P_{TE}^- of the n inputs connected by an OR gate or AND gate can be defined by Eqns (3) and (4), respectively.

$$P_{TE}^{OR} = 1 - \left[(1 - P_{E1}^-) \otimes (1 - P_{E2}^-) \otimes \dots \otimes (1 - P_{En}^-) \right]; \quad (3)$$

$$P_{TE}^{AND} = P_{E1}^- \otimes P_{E2}^- \otimes \dots \otimes P_{En}^- . \quad (4)$$

2.1.3. Fuzzy importance analysis

Having determined the probability of different basic events, an importance analysis is performed to rank them. The purpose of the events importance measure is to facilitate identification of the events that should be improved. The event importance measure may be used in the operational phase to dedicate inspection and maintenance resources to the most important event (Hoyland & Rausand, 2004). In other words, the importance analysis helps to identify model inputs that have a significant effect on the output and it helps to understand how to evaluate the effectiveness of the adopted corrective strategies.

In this research, since the probability of the top event is a fuzzy number, the fuzzy importance measures (FIM) (Abdelgawad & Fayek, 2011) is applied to assess the contribution of each basic event to the probability of occurrence of top event. FIM considers the fact that an event may lead to the system failure without being critical. The event leads to system failure when a minimal cut set, including that event is failed. The results of the importance analysis performed for each basic event according to Eqn (5) is presented in Table 3.

$$FIM_i = \frac{TE_1 - TE_2}{TE_1} \times 100\% , \quad (5)$$

where: FIM_i is the fuzzy importance index of i^{th} basic event; TE_2 is the probability of occurrence of the top

event by setting the probability of i^{th} basic event to 0, and TE_1 is the probability of occurrence of the top event.

2.2. Applied methods for identification of factors and definition of causal relations

In order to identify the most influencing factors on CLP, which are in fact the basic events of fault tree structure, a panel of experts is applied. This group consisted of 15 experts from the contracting team professionals of tall and medium height building construction comprising project managers, site managers and technical office engineers. These experts were applied for identification of factors and constructing causal relations among them on the basis of the FTA principles. For this purpose, all the selected experts had at least 10 years of experience and were highly reliable. It was also assured that they were familiar with the mechanism of reduction in labor productivity and had significant information about this field.

In the following, the applied methods for extracting the opinions of the mentioned experts regarding the most influencing factors and also their causal relations are presented in detail.

2.2.1. Defining basic events

The relative importance index method was applied to determine the relative importance of the various factors influencing CLP which had been reported in literature. The 5-point Likert scale ranged from 1 (least important) to 5 (extremely important) was adopted and transformed to relative importance indices (RII) for each factor as follows:

$$RII = \frac{\sum w}{A \times N} , \quad (6)$$

where: W is the weight given to each factor by respondents, ranging from 1 to 5; A is the highest weight = 5, and N is the total number of respondents.

A combination of identified factors in section one was exposed to panel of experts. Owing to the fact that these factors may be different in each country, this opportunity was also given to experts to add or remove factors from the preliminary list. After reaching a consensus on factors by experts through several meeting, the obtained factors were analyzed. The questionnaire which was designed for this purpose included 27 factors. The respondents were requested to choose one degree of severity which was ranged from 1 to 5. The questionnaire was distributed to the mentioned group of experts and they were requested to evaluate each factor. This opportunity was also given to experts to add or remove factors from the preliminary list.

Ranking of factors on the basis of their RII are provided in Table 2. The factors are arranged in descending order from the smallest to the largest value of RII. Factor with highest RII value indicates that it has the maximum impact on CLP while the factor with lowest RII value indicates that it has the least impact on CLP. On the basis of consensus of the respondents factors which have RII value more than 0.7 were chosen for next step. Consequently 18 factors out of 27 factors were chosen based on their RI in-

Table 2. Ranking of factors on the basis of their RII

Category	Factor	Source	RII	Rank
Management and organizational related factors	Unrealistic schedule	Ghoddousi and Hosseini (2012)	0.950	1
Management and organizational related factors	Excessive number of laborer	Added by experts	0.950	2
Technical related factor	Rework	Alinaitwe, Mwakali, and Hansson (2007)	0.900	3
Management and organizational related factors	Delay in salary payment	Hafez, Aziz, Morgan, Abdullah, and Ahmed (2014)	0.900	4
Management and organizational related factors	Workforce overtime	Jarkas, Al Balushi, and Raveendranath (2015)	0.850	5
Management and organizational related factors	Delay	Added by experts	0.850	6
External related factor	Extreme weather condition	Jarkas, Al Balushi, and Raveendranath (2015)	0.800	7
Management and organizational related factors	Inflation in cost of execution	Added by experts	0.800	8
Management and organizational related factors	Improper project financing	Hafez, Aziz, Morgan, Abdullah, and Ahmed (2014)	0.800	9
Labor related factors	Fatigue	Jarkas, Al Balushi, and Raveendranath (2015)	0.800	10
Material and equipment related factors	Lack of equipment	Ghoddousi and Hosseini (2012)	0.750	11
Management and organizational related factors	Improper site layout	Ghoddousi and Hosseini (2012)	0.750	12
Labor related factors	Lack of experience	Robles, Stifi, Ponz-Tienda, and Gentes (2014)	0.750	13
Management and organizational related factors	Schedule pressure	Ghoddousi and Hosseini (2012)	0.750	14
Management and organizational related factors	Client order	Jarkas, Al Balushi, and Raveendranath (2015)	0.750	15
Labor related factors	Lack of training	Fagbenle, Ogunde, and Owolabi (2011)	0.700	16
Labor related factors	Lack of occupational safety	Added by experts	0.700	17
Labor related factors	Lack of motivation	Fagbenle, Ogunde, and Owolabi (2011)	0.700	18
Technical related factor	Incompetent supervisors	Chigara and Moyo (2014)	0.650	19
Technical related factor	Poor construction methods	Ghoddousi and Hosseini (2012)	0.600	20
Management and organizational related factors	Poor communication	Alinaitwe, Mwakali, and Hansson (2007)	0.450	21
Technical related factor	Alteration of drawings and specifications during execution	Enshassi, Mohamed, Abu Mustafa, and Mayer (2007)	0.450	22
Management and organizational related factors	Misunderstanding between labor and superintendents	Enshassi, Mohamed, Abu Mustafa, and Mayer (2007)	0.350	23
Management and organizational related factors	Construction managers lack of leadership	Hafez, Aziz, Morgan, Abdullah, and Ahmed (2014)	0.300	24
External related factor	Political insecurity	Alaghbari, Al-Sakkaf, and Sultan (2019)	0.250	25
Technical related factor	Clarity of technical specification	Hafez, Aziz, Morgan, Abdullah, and Ahmed (2014)	0.250	26
Technical related factor	Clarity of the drawings and project documents	Jarkas, Al Balushi, and Raveendranath (2015)	0.250	27

dex for assessing their contribution to reduce CLP with respect to their interrelationships.

It is worth saying that the reliability of factors is also tested. The Cronbach's alpha coefficient, the measure of internal consistency of the questionnaire, was 0.795 and Cronbach's alpha based on standardized items, was 0.817 - indicating good consistency (Field, 2009).

2.2.2. Defining interrelationships among events

Through several deep interviews with each of the experts, the interrelationships among the factors were defined. The

list of 18 factors which was resulted from previous step was used in this step. The average duration of the interviews with each of the experts was approximately 2 hours. All conversations were tape recorded and then transcribed for further investigations. The resulted and approved relations among factors on the basis of conducting interviews are briefly described as follows.

Relation 1

Contractors for reducing their costs are not careful in employing laborers and as a result, their staff does not have

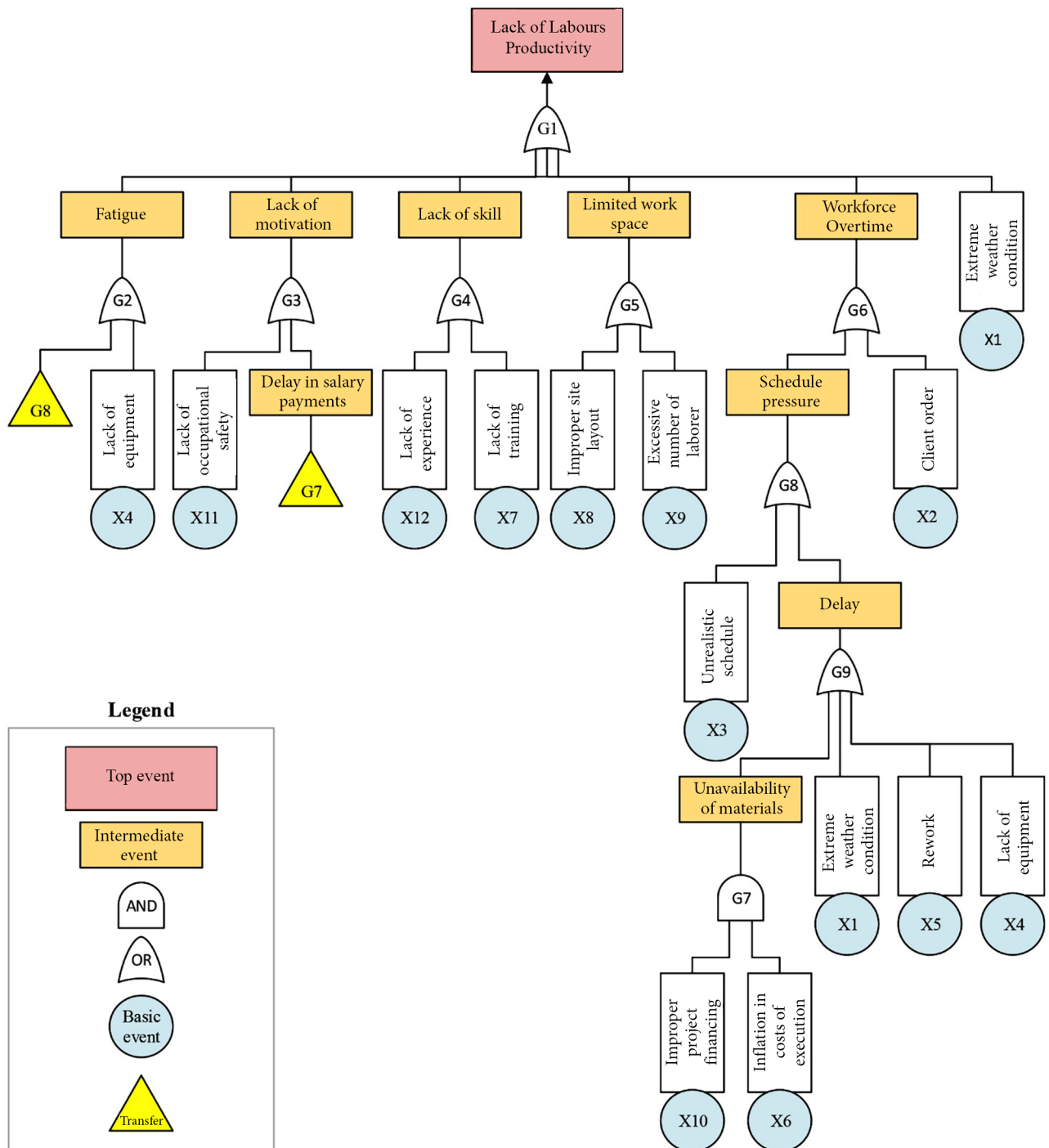


Figure 2. The fault tree structure of different events leading to the lack of labor productivity

the qualifications and skills. Their incompetence results in negligence that this issue decreases their productivity.

Relation 2

Lack of timely payment of laborers' wages accompanied by other factors such as lack of job security decrease laborers' motivation and ultimately reduce their productivity.

Relation 3

Increasing schedule pressure and delay along with other factors such as lack of equipment intensify fatigue among laborers which reduce their productivity.

Relation 4

Contractor's inability to finance project leads to lack of equipment and materials required to perform the work (Parchami Jalal & Shoar, 2017). Shortage of equipment and materials cause schedule pressure and delay and as a result intensify overtime. This factor reduces laborers productivity.

Relation 5

Improper site layout planning made by the contractor along with other factors such as excessive number of laborers result in limitations in workspace and decrease the labor productivity.

On the basis of the discussed relations, the fault tree structure of different basic events which causes reduction in CLP is depicted in Figure 2. It should be considered that, due to the complicated relations among causes, each cause can lead to occurring of different intermediate events. Therefore a basic event may appear in different parts of a tree and as a main cause of different intermediate events.

3. Model application

3.1. Case study description

To justify the validity of the proposed method for identifying the most influencing factors and selecting mitigation strategies, it is implemented in a real building construction project. The project cost is \$7.3 million and the project duration is 29 months. This case is a commercial office building which is located in Tehran and includes 25 floors on ground and 7 floors underground. The project was performed in a Design Bid Build delivery system.

3.2. Model development

For analyzing influencing factors on CLP first of all, we need to identify basic events and define causal relations among them. In this section, the factors and FT structure which were resulted in previous section were considered as input in this section. It is worth saying that these factors can be different from project to project and it mainly depends on the construction sector environment under consideration as discussed in literature review. In the following, the other steps of the FTA are presented.

3.3. Aggregating fuzzy numbers assigned by different experts

Figure 3 represents the membership function values for the variation of the probability of basic events. As shown, the experts can choose the probability of a fuzzy factor from one of the 7 given intervals. It should be stated that the variations in the probability of basic events was divided into 7 intervals (Zhang, Skibniewski, Wu, Chen, & Deng, 2014). To achieve more precise results and obtain smaller probability span, this number of divisions was considered (Shoar & Nazari, 2018). More division depends on the extent of basic events' uncertainty and experts' opinions.

In this research, the probability of fuzzy factors is determined in accordance with the opinion of four experts involved in the project. Due to the fact that the members of project management team are always involved in the project (case study project) the only experts who are able and reliable to assess each event are these people. Absolutely, in other projects on the grounds of project's specific features, assessment of each event by its project management team and the overall outcome can be different.

The limitation of expert's knowledge and experiences may result in different perceptions about the same events and consequently provide different assessment (Chin, Wang, Poon, & Yang, 2009). Therefore, it is necessary to aggregate expert's opinion to reach a consensus.

Assigning a weight factor was therefore recommended for each expert to distinguish their relative importance. However, in this study, since the experts have the same qualification, the importance of experts against each other is not considered. In the other situation it is worthwhile considering the importance weight of each expert using some defined evaluation criteria such as educational level and working experience (Lavasani, Ramzali, Sabzalipour, & Akyuz, 2015).

Table 3 represents the opinions of four experts regarding the probability of different basic events. The opinions of four experts are finally aggregated using Eqn (7):

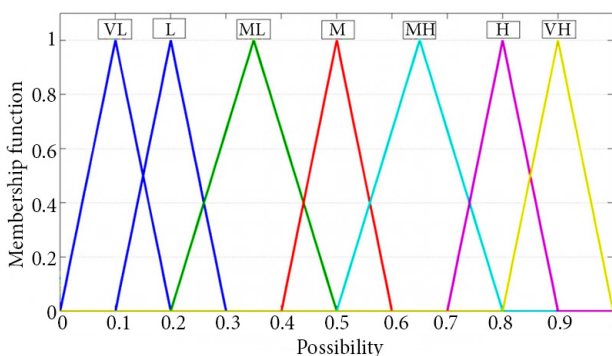


Figure 3. The membership function graphs for determining the probability of basic events

$$P_i = \begin{bmatrix} p_i^{e_1} & p_i^{e_2} & p_i^{e_3} & \dots & p_i^{e_j} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \cdot \\ \cdot \\ w_j \end{bmatrix}, \tag{7}$$

where: P_i is the aggregated fuzzy number of BE_i ; $p_i^{e_j}$ is the fuzzy number of probability interval assigned by expert e_j ; j is the number of experts and w_j is the weighting factor of the expert e_j (as mentioned earlier in this study an equal weight was considered for each expert).

4. Model results

Having determined the probability of different basic events, an importance analysis is performed to rank them. The importance analysis helps to identify model inputs that have a significant effect on the output and it helps to understand how to evaluate the effect of the adopted corrective strategies.

According to the results of importance analysis, X6 (Inflation in cost of execution) and X10 (Improper project financing) are selected as the most critical basic events (Table 3). It is therefore expected that by eliminating of these factors, the CLP will be more improved in comparison to mitigate the other basic events. In other words, the results allow us to make the appropriate decisions to improve CLP. In terms of the factor groups, the top crucial basic events belong to the management and organizational related factors. Therefore, at least in this project, we had reasons to claim that proper and in detail planning before execution and, management decisions during execution have a significant effect on CLP. It is worthwhile mentioning that the obtained results are specific to this project and

in other projects on the grounds of project’s specific features; assessment of each event by its project management team and the overall outcome can be different. The reliability of the proposed method was also assessed through several meeting with project management team. They finally acknowledged that the intended method can be a useful decision support tool in their practical work.

5. Discussion and recommendations

In this section, the top five influencing factors on CLP which were shown in Table 3 are briefly discussed and some recommendations are also presented.

Improper project financing – improper project financing is one of the main latent causes which can directly lead to delay in salary payment and unavailability of materials. The importance and the negative effect of these factors on labor productivity have been previously mentioned by several researchers like Chigara and Moyo (2014), who ranked unavailability of materials and delay in salary payment first and second, respectively, among 40 factors. This factor can be investigated from the client and contractor point of view. From the client perspective, not allocating sufficient time to prepare feasibility study and from the contractor perspective, not developing a comprehensive financial plan and cash flow, and not ensuring the availability of necessary funds, can be the main reasons that intensify improper project financing. Also, there are some external factors such as imposed sanctions and bad economic conditions owing to the high rate of inflation that along with the other mentioned factors can result in improper project financing. Even if, enough attention will be paid to prepare feasibility study and develop cash flow plan, the mentioned external factors can impose difficulties for both contractor and client to gain intended funds. On the basis of these facts, apart from allocating enough time to feasibility study and developing cash flow plan,

Table 3. Determining the probability of different basic events and the importance analysis using fuzzy importance measures

Code	Factor	Experts				Aggregation results	FIM	Rank
		1	2	3	4			
X1	Extreme weather condition	L	ML	L	L	(0.35–0.2375–0.125)	0.3018%	5
X2	Client order	L	L	ML	L	(0.35–0.2375–0.125)	0.1006%	7
X3	Unrealistic schedule	M	ML	M	M	(0.575–0.4625–0.35)	0.8350%	3
X4	Lack of equipment	L	L	ML	L	(0.35–0.2375–0.125)	0.3018%	5
X5	Rework	M	M	M	MH	(0.65–0.5375–0.425)	1.2274%	2
X6	Inflation in cost of execution	H	MH	H	MH	(0.85–0.725–0.6)	1.4085%	1
X7	Lack of training	M	MH	M	M	(0.65–0.5375–0.425)	0.4527%	4
X8	Improper site layout	L	L	ML	L	(0.35–0.2375–0.125)	0.0905%	8
X9	Excessive number of laborer	L	L	L	L	(0.3–0.2–0.1)	0.0704%	9
X10	Improper project financing	MH	MH	H	MH	(0.825–0.6875–0.55)	1.4085%	1
X11	Lack of occupational safety	ML	L	L	ML	(0.4–0.275–0.15)	0.1107%	6
X12	Lack of experience	L	L	VL	VL	(0.25–0.15–0.05)	0.0302%	10

other recommendations include considering contingency budget by clients, applying planning efforts to complete project on time in order not to deal with inflation in prices due to delay, and considering appropriate items in contract.

Unrealistic schedule – unrealistic schedule is mainly determined by the skills and experience of the management team in planning and scheduling. Hickson and Ellis (2014) ranked unrealistic scheduling second among 42 factors explored in the Trinidad and Tobago. The importance of planning is also confirmed by Ghoddousi and Hosseini (2012) in Iranian construction projects. Accurate scheduling can be achieved by hiring experienced personnel to do planning, and using the historical data of similar projects to make an accurate estimation of the required time for each activity.

Inflation in cost of execution – increasing cost of execution as a result of sanction can affect project profitability. Therefore, ability of the contractor to pay salaries timely and on time procurement of the required materials and equipment are the most important factors that can be influenced by this factor. Therefore, considering contingency budget is essential in this regard. There is no doubt that passing of time will reinforce the negative effect of inflation. Therefore, controlling and avoiding delay is another solution to cope with this problem. In other words developing a realistic schedule and doing in accordance with it plays an important role in mitigating high rate of inflation.

Rework – rework is ranked second in this study. It was also ranked third by Alinaitwe et al. (2007) and fifth by Ghoddousi and Hosseini (2012). This factor is mostly caused by failure to follow specifications. Sometimes this factor occurs because of several changes in drawings and documents by consultant or client and sometimes it occurs because of the incompetency of site managers to manage and supervise workers. These factors can be handled by establishing appropriate management tools and procedures.

Extreme weather conditions – extreme weather conditions is one of the factors that can have a negative effect on CLP. It depends generally on the geography, location of the country and location of the construction project within the country. Tehran is generally among the hot and dry cities with high temperature days. In other countries with similar weather condition, previous research indicate that this factor can have a great impact on labor productivity. For example, El-Gohary and Aziz (2014) ranked weather effect third within the industry category and twelfth among thirty factors identified in Egypt. Therefore, considering fewer working hours for hot summer days is recommended for enhancing labor productivity.

Lack of training – lack of experience and training are the most influencing factors on laborer skillfulness. There are governmental institutes for vocational education and training for construction laborers in Iran. However, contracting companies in order to reduce their costs are unwilling to employ laborers with vocational certificate and as a result, most of the laborers are also unwilling to register for these courses and to take certificate. Therefore, it

is recommended that more relevant laws should be established by governmental authorities to force contractors to employ laborers with vocational certificate.

Lack of equipment – the importance of this factor was previously proved by Alinaitwe et al. (2007) who ranked lack of equipment fourth in Uganda. Furthermore, this factor was also ranked fourth by Robles et al. (2014) in Spain. Obviously, without a minimum number of tools and equipment work cannot be accomplished effectively by laborers. If there is lack of equipment and/or tools, productivity will decrease. Again, it is worthwhile mentioning that this result is justified in this case, as some of the equipment used in construction of high rise buildings are special and most of the equipment which is used by contractors is old. Equipment breakdown as a result of unavailability of spares, which leads to lack of equipment, is also prevalent. Therefore, planning periodic and regular maintenance measures for critical equipment is recommended.

Conclusions

In this research a fuzzy fault tree based approach was proposed for modeling and identifying various factors influencing on labor productivity in a particular project, with respect to their interrelations. Causes of reduction in labor productivity were identified through reviewing previous research. The interrelations among factors were determined through several sessions and interviewing relative experts. Based on the discussed relations, the fault tree structure of different basic events leading to reduction in CLP was constructed. The probability of occurrence of events were then determined according to the opinions of the project management team. An importance analysis using the proposed fuzzy fault tree based approach was finally performed to evaluate the contribution of factors to the reduction of CLP. Generally, the advantages of the proposed framework can be summarized as follows:

1. It does not depend on historical data;
2. It is possible to use linguistic terms to evaluate the probability of factors that impact CLP;
3. It is possible to rank factors by considering their interactions and taking the multiple influences of factors into account.

The case study results indicated that the important factors influencing CLP were inflation in cost of execution and improper project financing. Also, from the perspective of factor groups, results indicated the top sensitive basic events belonged to the management and organizational related factors. Therefore, at least in this building construction project, we had reasons to claim that proper and in detail planning before execution and management decisions during execution have a significant effect on CLP. Discussing the model results with participants, they finally confirmed that the model indeed can provide an appropriate decision support for their practical work and provide them reasonable results.

It should be noted that there exist limitations of applying the proposed methodology in practice. First, the membership functions of the probability of basic events were developed using triangular membership function. Future work might be conducted to consider other shapes of the membership functions and test their validity. Second, more research should be conducted to compare the outputs of the proposed methodology with other methodologies applied in previous research. Third, in this research the causes of reduction in CLP were investigated in a high-rise building construction project. Future research could be done to investigate the causes in other construction projects.

Author contributions

Shahab Shoar conceived the study and was responsible for the design and development of the data analysis and writing the first draft of the article. Audrius Banaitis was responsible for supervising this article and checking and developing the final draft of the article.

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