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Development of Simulation-Based Fuzzy Logic System for Measuring and Improving Performance of Construction Operations

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الملخص:

تظل عملية قياس وتحسين الإنتاجية من الأهداف المهمة بصناعة التشييد لزيادة القدرة التنافسية والوصول بزمن وتكلفة المشروعات للحد الأدني فتحقيق المزيد من الوحدات المنتجة كمخرجات مع تقليل مدخلات الإنتاج هو المبدأ الرئيسى للإنتاجية. وتمثل عملية قياس الإنتاجية بصناعة التشييد تحدى كبير نظراً لصعوبة وضع معايير قياسية ثابتة لمدخلات عملية الإنتاج من عمالة وتمويل وتكنولوجيا الإنتاج وظروف العمل وما إلى ذلك بالأضافة إلى صعوبة توصيف تلك المدخلات بشكل محدد وذو مصداقية عالية. وهو مادفع الباحثيين إلى التعامل مع اللايقين المحيط بعملية قياس وتحسين الإنتاجية من خلال النظم والنماذج القائمة على أساس المحاكاة والتى ينتمى معظمها إلى نظم المحاكاة التقيليدية ذات الأحداث المنفصلة التى تعتمد على سجل وافر من المعلومات والبيانات التاريخية التى تستخدم لتحليل العوامل المؤثرة على عمليات التشييد المختلفة وتقدير إنتاجية تلك العمليات. وبما ان المعلومات والبيانات التاريخية عادةً ماتكون محدودة للغاية أو غير موجودة على الأطلاق بمعظم شركات التشييد فان هذا البحث يتبنى استخدام نظم المنطق الضبابى المعتمد على مبادىء المحاكاة لأستخدام المصطلحات النوعية اللغوية بدلاً من المعلومات والبيانات الدقيقة المحدود توافرها. يهدف هذا البحث إلى اقتراح نظام شامل يدعم إتخاذ القرار لقياس وتحسين أداء عمليات التشييد حيث يدمج النظام المقترح المحاكاة مع المنطق الضبابى للتغلب على عدم توفر بيانات ومعلومات دقيقة ومحددة. يدعم النظام المطور قياس الإنتاجية والتعبير عنها من حيث مخرجات عمليات التشييد لكل وحدة زمنية وكذلك لكل وحدة نقدية. تم التحقق من صحة النظام المقدم فى هذا البحث من خلال دراسة حالة بإستخدام بيانات خاصة لمشروع فعلى حيث تظهر النتائج ان النظام المقترح يساهم بشكل فعال فى قياس وتحسين الإنتاجية بالرغم من محدودية البيانات التاريخية.

Abstract:

The measurement and improvement of productivity remain important goals for the construction industry in the race to increase time and tender price competitiveness. The basic tenet of productivity is making more with less. The measurement of productivity is challenging. Challenges in measuring productivity arise from constructing standardized measures of the value of primary factors of production: labor, capital, technology, work conditions and … etc. The most data on primary factors of productivity are not reliable so, simulation-based approaches are effective to deal with the uncertainty involved in productivity measurements and improvements. Traditional discrete-event simulation models use historical data to analyze the factors influencing the productivity of construction operations and to estimate the effect of such factors on the productivity. As historical data are usually very limited or nonexistent in construction organizations, this research adopts the simulation-based fuzzy logic approach to use linguistic qualitative terms instead of limited explicit information. The aim of this paper is to propose a comprehensive system that supports decision making to measure and improve the performance of construction operations. The proposed system integrates simulation with fuzzy logic thereby overcoming the unavailability of precise historical data. The developed system supports measuring and expressing productivity in terms of operations outputs per time units and also per monetary units. The system introduced in this research was validated by a case study using data acquired from a real project. Results show that the proposed system contributes positively towards measuring and improving productivity despite limited historical data.

KEYWORDS: Construction Industry, Productivity Measuring, Productivity Improvement, Simulation, Fuzzy Logic, Fuzzy Operations, Quality Factors.

1- Introduction:

Productivity is the most important factor affecting the overall performance of the construction operations. Every construction project is influenced by a wide range of factors with a significant impact on productivity. There have been decades of previous efforts in seeking a causal link between factors and productivity through quantifying factors and measuring their impacts on productivity. Building components, building design, the role of planning, site factors, material, equipment, site management, personnel management, skills training and qualifications, work time and regulations are examples of primary factors that have a significant impact on productivity (Chan and Kaka 2007). Enshassi et al. (2009) indicated that the average delay because of material shortage was the most important performance factor as it has the first rank among all factors from the perspectives of owners, consultants, and contractors in Gaza Strip. On the other hand, Enshassi et al. (2010) identified the factors affecting labor productivity in building projects and the rank of these according to their relative importance from the contractor's viewpoint within the Palestinian construction industry. The results indicated that the main 10 factors negatively affecting labor productivity are: material shortage, lack of labor experiences, lack of labor surveillance, misunderstanding between labor and superintendents, drawings and specifications alteration during execution, payment delay, labor disloyalty, inspection delay, working seven days per week without holiday and tool / equipment shortage. On the other hand, Attar et al. (2013) identified the groups of factors which were highly effective were: supervision, material, execution plan, and design. Moreover, for large companies, equipment factors were highly effective, while in small and medium companies, owner/consultant factors need special attention because they have a high effect too. The health and safety factors have not been a concern of small and medium companies and have some effect, while in large companies, these factors have a better concern but not as a major concern and have an average effect. In addition, Gundecha (2012) investigated all probable factors affecting labor productivity in building construction. A structured questionnaire was administrated all over the USA to investigate all possible factors. Total of 255 questionnaires were distributed to project managers, project engineers, architectures, schedulers, and estimators. Forty factors considered for the study were categorized in five different groups: manpower, external, communication, resources and miscellaneous. The survey results were subjected to analysis and the ranking of factors was calculated using a relative important index. Furthermore, Lamka et al. (2014) assessed the factors which affect labor productivity and evaluate various management strategies on labor productivity and on labor-intensive construction sites in Nairobi County. They identified critical factors in total from the literature review and ranked them in accordance with their levels of impact based on the views of project managers, contractors and developers. These factors are lack of training/skills, work planning and scheduling, incompetent supervisors, late deliveries of material, and motivation.

In general terms, construction productivity can be simply illustrated by an association between an output and an input. However, since productivity on construction sites is dynamic, it is challenging to develop sufficiently reliable construction plans. Each construction project is unique and complex as it includes numerous risks and uncertainty (Mao and Zhang 2008). Accordingly, modeling and simulation tools are used to assist decision-makers to predict essential parameters such as completion duration, total cost and a productivity rate of construction operations associated with a certain degree of confidence. Song et al. (2008) presented an approach to measuring productivity, collecting historical data and developing productivity models using such data. The collected productivity data were used to develop labor productivity models using such techniques as artificial neural network and discrete-event simulation. These productivity models were developed and validated using actual data collected from a steel fabrication company. On the other hand, Birgisson (2009) presented how discrete-event simulation can be used in the planning of construction-related productions systems. A model was developed which simulates on-site construction activities considering uncertainty factors such as prevailing weather conditions. In addition, Shahandashti et al. (2010) created several different earthmoving scenarios. These scenarios were created based on the factors that affect earthmoving productivity. These scenarios were simulated and the required information items were identified. On the other hand, Alzraiee et al. (2013) used two approaches: process simulation and system simulation. They presented an assessment to simulated project completion duration and productivity rate under traditional Discrete Event Simulation and modified traditional simulation technique. The results, generated from simulation models that were developed based on the process approach, generates ideal outcomes of the process or operation being simulated. This is because it tends to neglect the effects of influential factors as the adverse effects of weather, rework, and schedule pressure that surround construction operations. Consequently, it provides misleading results and can’t be relied upon in the decision-making process. In order to address this problem, a simulation approach called system modeling was considered to circumvent such limitations. It modeled the factors believed to affect process simulation model and injected their influence in the model. In addition, AbdelRazig and Ghanem (2016) used computer simulation to identify potential improvement to reduce the duration in construction projects. On the other hand, Han et al. (2017) developed a framework for the validation of simulation-based productivity analysis. This approach enabled the simulated productivity to be statistically close to the measured productivity in construction site.

Despite the ability of the simulation models to present a real picture of the actual status of construction operations, the main question that arises is about the credibility of the data used. Simulation models require explicit information while there are obvious limitations of quantity and scope of such information in construction companies. This limitation arises from the fact that the surrounding conditions of each project are different than other projects. Also, some projects are unprecedented and unique and the use of historical data is limited in the management of such projects. The use of linguistic values to express subjective judgment in construction is paramount. A construction expert's opinion can be used to provide a subjective judgment on different issues. Data that include linguistic terms is best analyzed through the use of the fuzzy set concept. Fuzzy sets can be employed to transform linguistic expressions such as unlikely, likely and very likely into quantitative terms. Fuzzy set analysis has been widely used in the construction engineering area. Birgun and Kahraman (2010) used the fuzzy set theory for productivity measurement. Productivity measurement was realized under vague and incomplete information. On the other hand, Elwakil et al. (2015) used a fuzzy approach to predict the productivity. Furthermore, Salah et al. (2017) introduced a new fuzzy set-based monitoring system that investigates the effects of productivity variation on cost, schedule and depletion of resources in earthmoving projects based on a set of qualitative and quantitative factors.

Combining the capabilities of simulation, as an effective technique to deal with uncertainty, with fuzzy logic, as a mathematical technique dealing with imprecise data and problems, is a promising approach to measure and improve the productivity of construction operations. Corona-Suarez et al. (2014) presented a methodology that integrates simulation modeling techniques with fuzzy logic-based techniques in order to assess the effect of project quality management on the performance of construction operations. This methodology adopted fuzzy-logic applications for computing the required statistical parameters. These statistical parameters are the inputs to the simulation model from which the productivity estimates of the operation are obtained. Nevertheless, only factors related to project quality management were considered in this modeling approach. In addition, the proposed methodology completely excluded the cost of the analysis.

To improve the study presented by Corona-Suarez et al. (2014), this current research presents a comprehensive system that allows addressing all possible factors affecting the performance of construction operations. Furthermore, the current proposed system takes the costs into consideration in order to support measuring and expressing productivity in terms of operations outputs per monetary units as well as per time units.

2- Objective of the Proposed System:

The objective of the proposed system is to effectively measure and improve the productivity of construction operations by combining the capabilities of simulation technique with fuzzy logic. In this study, measuring and improving productivity are based on disruption analysis that includes investigating the number of disruptions (N) for each activity and the duration of delays (D) of one disruption.

Identifying factors influencing each construction operation and their level of quality (Q) is crucial to effectively measure the effect of such factors on the corresponding operation and consequently on the entire project. The quality level of each influencing factor is presented in a linguistic term such as poor, medium and good. In addition, the frequency of occurrence (F) of the quality level and the adverse consequences (C) on the activity are two important variables for disruption analysis. The linguistic terms used for assessing (F) are unusual, often and usual. On the other hand, the linguistic terms used for assessing (C) are mild, medium and severe. N and D are also presented in linguistic terms such as small, medium and large. In this study, the development of a simulation modeling approach requires estimating the probability mass functions that embody uncertainty associated with the occurrence of disruptions. Accordingly, the modeling of uncertainty considers two variables: N and D.

Determining the statistical parameters (μ, σ) that describe the probability mass functions of both variables N and D is a challenge. This study adopts fuzzy logic to compute the statistical parameters of N and D as inputs to the simulation model in order to finally estimating the effect of the variables Q, F, C, N and D on construction operation productivity, as shown in **Figure (1).**

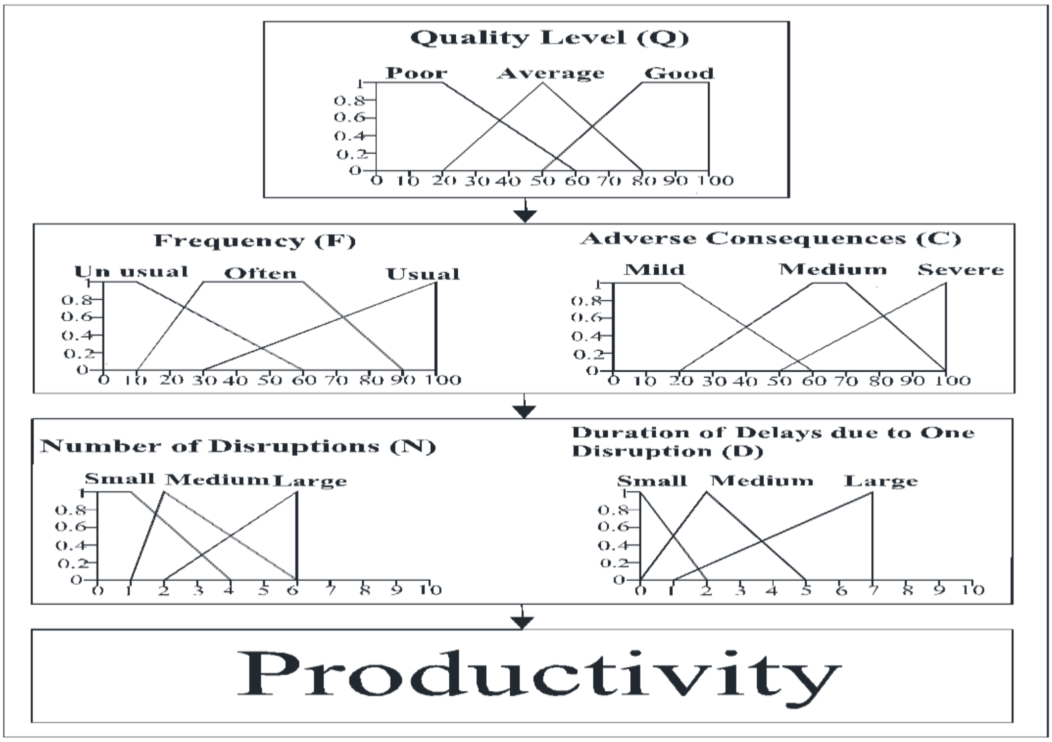


Figure (28): The effect of influencing factors on operation productivity

3- Structure of the Proposed System:

The conceptual framework of the simulation-based fuzzy logic technique serves as the foundation for the development of a comprehensive approach that measures and improves the productivity of construction operation. As shown in **Figure (2)**, the main components of this framework are:

- A database to facilitate data entry.
- Fuzzy logic operations.
- Statistical parameters estimation for N and D.
- CPM-based simulation.
- Providing simulation results.

The following sections will describe each of these components in more details.

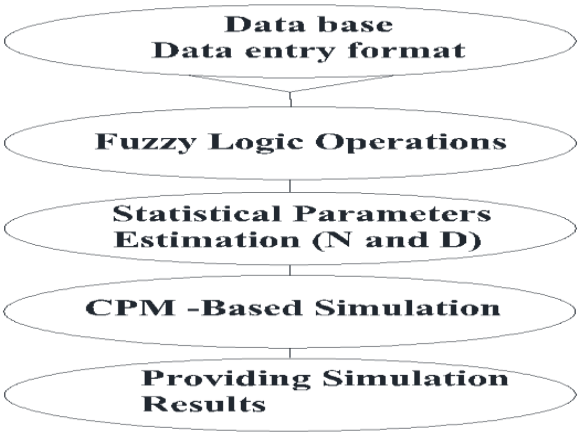


Figure (29): Structure of the proposed system

4- Data Modeling:

Effective storage and processing of data are very important for the functioning of both fuzzy logic and simulation-based techniques. A database is designed for the proposed system to facilitate data entry and to maintain data integrity. The proposed system uses a pre-designed database as data storage. The database is developed in Microsoft Access and it is linked to the proposed system via an administrative tool known as Open Database Connection. The main entities and their attributes defined for the database are listed in **Table (1):**

Entity	Attributes
Activity (Act)	Mean of activity ideal duration (μ), standard deviation of activity ideal duration (σ), predecessors (Pred1, Pred2, Pred3, Pred4 and Pred5), relationship between activities (Rela1, Rela2, Rela3, Rela4 and Rela5) with all types of relationship between activities (fs, ss and ff), lags (Lag1, Lag2, Lag3, Lag4 and Lag5), number of influencing factors (Factor), quantity (Quantity), direct cost (Direct), indirect cost per day (Indirect / day) and name of influencing factors (F1, F2 and F3) .
Influencing factors (Q)	For each influencing factor, quality levels (Q), frequency of occurrence (F) and level of adverse consequences (C) in three statuses (poor, medium and good).
Disruptions	Number of diruptions (N) counted during the performance of the activity and duration of delays (D) due to one disruption.

Table (6): Entities and attributes of the database

Figure (3) shows a screenshot for an example of the tables that represent the entity (activity) and its attributes as defined in the database.

ID	Act	M	S
1	Excavation	7	0.1
2	Replacement (Layer 1)	1	0.01
3	Replacement (Layer 2)	1	0.01
4	Replacement (Layer 3)	1	0.01
5	Formwork PC (Footing + UG Beams)	5	0.1
6	Concrete Pouring PC (Footing + UG Beams)	1	0.01
7	Formwork Removal PC (Footing + UG Beams)	1	0.01

Pred1	Pred2	Pred3	Pred4	Pred5
0	0	0	0	0
Excavation	0	0	0	0
Replacement (Layer 1)	0	0	0	0
Replacement (Layer 2)	0	0	0	0
Replacement (Layer 3)	0	0	0	0
Formwork PC (Footing + UG Beams)	0	0	0	0
Concrete Pouring PC (Footing + UG Beams)	0	0	0	0

Rela1	Rela2	Rela3	Rela4	Rela5	Lag1	Lag2	Lag3	Lag4	Lag5	Factor	Quantity	Direct	Indirect/day
0	0	0	0	0	0	0	0	0	0	123	1223	60749	868
fs	0	0	0	0	0	0	0	0	0	123	167	10334	1034
fs	0	0	0	0	1	0	0	0	0	123	167	10334	1034
fs	0	0	0	0	1	0	0	0	0	123	167	10334	1034
fs	0	0	0	0	0	0	0	0	0	12	53.5	8025	161
fs	0	0	0	0	0	0	0	0	0	123	53.5	37450	3745
fs	0	0	0	0	1	0	0	0	0	1	53.5	1	1

F1	F2	F3
Equipment Breakdown	High Ground Water Level	Inadequate Soil Investigation
High Ground Water Level	Material Shortage	Equipment Breakdown
High Ground Water Level	Material Shortage	Equipment Breakdown
High Ground Water Level	Material Shortage	Equipment Breakdown
Skilled Labor Shortage	Material Shortage	0
Skilled Labor Shortage	Material Shortage	Equipment Breakdown
Skilled Labor Shortage	0	0

Figure (30): The activity and its attributes

Figure (4) illustrates the ER-diagram for the database. The ER diagram involves three entities “Activity, Influencing factors and Disruptions” and a relationship “Cause”.

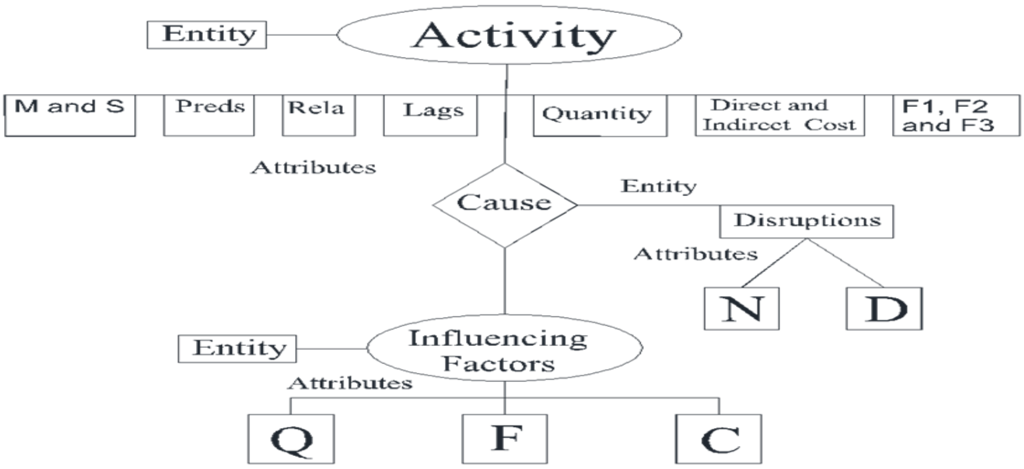
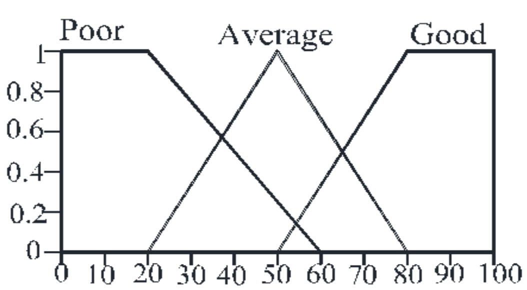


Figure (31): Entities and attributes of the database

Data required for the main variables Q, F, C, N and D are prepared according to the deliverables obtained from pre-designed questionnaires. Experts closely involved with construction operations are consulted to complete such questionnaires. The information contained in the database is encoded as vectors and matrices of variables. Fuzzy sets and membership functions are generated according to the information relevant to the main variables Q, F, C, N and D. Psychometric scales with values ranging from 0 to 100 are utilized for constructing the membership functions of Q, F and C, while natural numbers are more appropriate for the membership functions representing the liquistic values of N and D. **Figures (5 and 6)** show examples of membership functions for Q and N respectively.



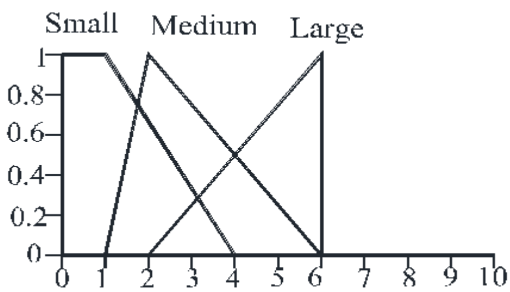


Figure (32): Quality level (Q) **Figure (6): Number of disruptions (N)**

5- Fuzzy Logic Operations:

This section describes the main operations of the theory of fuzzy sets that are used to analyze the combined effect of the influence factors on a given activity as proposed by Corona-Suarez et al. (2014).

The membership functions resulting from the fuzzy relation that combine the membership function of corresponding Q and C values of everyone of the influencing factors affecting the operation can be computed by:

$\boldsymbol{\mu_{Q\times C}(x_i,y_j)}$**=min [** $\boldsymbol{\mu_Q(x_i), \mu_C(y_j)}$**] ………………………………………………..….. (1)**

The values $\boldsymbol{x_i}$ and $\boldsymbol{y_j}$ are values within a psychometric scale from 0 to 100 used for estimating Q and C, respectively, while $\boldsymbol{\mu_Q}$ $(\boldsymbol{x_i})$ and $\boldsymbol{\mu_C}$ $(\boldsymbol{y_j})$ are the respective degrees of membership.

The membership functions $\boldsymbol{T_1}$ representing the total effect or union (∪) of the Q and C values on the construction performance of each activity can be computed by:

$\boldsymbol{T_1} = \cup_{\boldsymbol{i=1}}^{\boldsymbol{n}} [\ \boldsymbol{\mu_{Q\times C}(x_i, y_j)}]$ **………………………………………………………….. (2)**

The membership functions resulting from the fuzzy relations between F and N values of each activity of the project can be computed by:

$\boldsymbol{\mu_{f\times N}(f_j, r_k)}$**=min [**$\boldsymbol{\mu_f(f_j),\ \mu_N(r_k)}$**] ……….……………………….................... (3)**

Where $\boldsymbol{f_j}$ is a value within a psychometric scale from zero to 100 used for assessing F and, $\boldsymbol{r_k}$ is a natural number used for appraising N (i.e., $r_k = 1, 2, 3, \ldots$), while $\boldsymbol{\mu_f}$ $(\boldsymbol{f_j})$ and $\boldsymbol{\mu_N}$ $(\boldsymbol{r_k})$ are the respective degrees of membership.

The membership functions $\boldsymbol{T_2}$ representing the total effect or union (∪) of the F and N values on the construction performance of each activity can be computed by:

$\boldsymbol{T_2} = \cup_{\boldsymbol{i=1}}^{\boldsymbol{n}} [\boldsymbol{\mu_{F\times N}(f_j, r_k)}]$ **…………...……………….………………...……...…... (4)**

The total effect of C on N in a given activity can be computed by:

$\boldsymbol{R_N = (C_1 \times N_1) \cup (C_2 \times N_2) \ldots \cup (C_n \times N_n)}$ **…………...…………………....... (5)**

Where $C_n \times N_n$ are fuzzy relations based on fuzzy condition expressions represented by statements assessing the relation between each possible C value and a corresponding expected N value.

The membership function M resulting from the fuzzy composition relation between T_1 and R_N can be computed by:

$\boldsymbol{M = \mu_{T1 \circ R_N}(x_i, r_k) = max_{\ y_j}}$ **{min [**$\boldsymbol{\mu_{T_1}(x_i, y_j), \mu_{R_N}(y_j, r_k)}$**]} ………..…...……..… (6)**

Where $\mu_{T_1} \circ R_N$ $(x_i,\ r_k)$ is the membership function of the fuzzy composition relation between T_1 and R_N, $\boldsymbol{\mu_{T_1}}$ $(\boldsymbol{x_i, y_j})$ obtained with (2) and $\boldsymbol{\mu_{R_N}(y_j, r_k)}$ is the membership function resulting from the fuzzy relation obtained with (5).

The membership function of the fuzzy joint effect of Q and F on the expected N can be computed by:

$\boldsymbol{\mu_{M,T2}(x_i, y_j)(r_k)}$ **=min [** $\boldsymbol{\mu_M(x_i, r_k), \mu_{T2}(f_j, r_k)}$**] …………………………………... (7)**

Where $\boldsymbol{\mu_M}$ $(\boldsymbol{x_i,\ r_k})$ is the membership function of the effect of the quality levels of influencing factors (Q) on the expected number of disruptions (N), which was obtained with (6), while $\boldsymbol{\mu_{T2}}$ $(\boldsymbol{f_j,\ r_k})$ is the membership function of the effect of F on the expected N in the activity, obtained with (4). This fuzzy joint relationship will produce m number of matrices, each of which corresponds to an element $\boldsymbol{r_k}$ in the subset of possible values of N.

The same procedure should be carried out to compute the membership function of the fuzzy joint effect of Q, F and C on the expected D.

6- Fuzzy Statistical Parameters Estimation:

The most challenging task in creating a simulation model is usually not identifying an appropriate probability distribution and parameters to model the uncertainty of each input variable. This section describes the procedure adopted to calculate the statistical parameters $(\boldsymbol{\mu}, \boldsymbol{\sigma})$ for N and D based on the membership functions of the fuzzy joint effect of Q, F and C on the expected N and D respectively. This procedure is deduced from Ayyub and Haldar (1984). Referring to equation (7), the probability of occurrence of each element $\boldsymbol{r_k}$ within the subset of possible values of N can be computed by:

$$\mathbf{P}\ (\mathbf{N}=\boldsymbol{r_k}) = \frac{\mu_{S_N}(r_k)}{\sum_{k=1}^{m} \mu_{S_N}(r_k)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(8)}$$

Where N is the expected number of disruptions, $\mathrm{P}(N = \mathrm{r_k})$ is the probability of occurrence of N being element r_k, $\mu_{S_N}(\mathrm{r}_k)$ is the membership value of each element r_k in the subset S_N comprising the possible values of N and m is the number of elements in the subset S_N.

Subsequently, the mean value of the number of disruptions $(\boldsymbol{\mu_N})$ and the corresponding standard deviation $(\boldsymbol{\sigma_N})$ can be, respectively, computed by with (9 and 10):

$$\boldsymbol{\mu_N} = \sum_{k=1}^{m} (\boldsymbol{r_k}) \times \boldsymbol{P}\ (\mathbf{N} = \boldsymbol{r_k}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(9)}$$

$$\boldsymbol{\sigma_N} = \sqrt{\left[\sum_{k=1}^{m} (\boldsymbol{r_k})^2 \times \mathbf{P}(\mathbf{N} = \mathbf{r}_k)\right] - (\boldsymbol{\mu_N})^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(10)}$$

This procedure should be carried out to compute the mean and standard deviation of N in each activity in a project. Moreover, it should also be used to estimate the statistics of D in such activities by using the same procedure.

7- Perform Simulation:

Once the statistical parameters (μ, σ) for N and D have been determined, CPM-based simulation is performed to simulate the project by solving (or iterating) it hundreds or thousands of times. Performing simulation has several steps:

- Each run (or iteration) begins by selecting a period ($D\ ideal_i$) for each risky activity at random from its range and probability distribution according to the proposed statistical parameters of activity ideal status (i.e. no influencing factors affect such activity).
- For each run, a random value for N and D $(\boldsymbol{N_i\ and\ D_i})$ according to the statistical parameters (μ, σ), previously computed, is selected and the activity total duration $D\ total_i$ can be computed by :

$$\boldsymbol{D\ total_i} = \boldsymbol{D\ ideal_i} + (\boldsymbol{N_i} \times \boldsymbol{D_i}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(11)}$$

- For each run, the activity total cost ($C\ total_i$) can be computed by:

$$\boldsymbol{C\ total_i} = \textbf{Activity Direct cost} + (\textbf{Activity Indirect cost per day} \times \boldsymbol{D\ total_i}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(12)}$$

- For each run, the productivity of each activity in terms of activity outputs per time units and per monetary units can be computed by (13 and 14) respectively:

$$\boldsymbol{Activity\ Prod_i}\ \textbf{(Per time units)} = \frac{\boldsymbol{Quantity}}{\boldsymbol{D\ total_i}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(13)}$$

$\boldsymbol{Activity\ Prod_i}$ **(Per monetary units)**=$\frac{\boldsymbol{Quantity}}{\boldsymbol{Ctotal_i}}$ **……………..……..………..…….. (14)**

- Using CPM, project completion time and total project cost are determined.
- The project is iterated many times to determine the entire patterns of productivity values for each activity, the project completion date and the project cost values.
- At the end of the entire simulation, all deliverables are arrayed in vectors and matrices.

8- Provide Simulation Results:

After performing the entire simulation, the corresponding results are displayed. These results include:

- The statistical parameters (μ, σ) for N and D.
- The productivity of each activity in terms of activity outputs per time units and per monetary units associated with a certain degree of confidence.
- The statistical parameters (μ, σ) for the duration and the cost of each activity.
- The duration and the cost of each activity associated with the degree of confidence.
- The statistical parameters (μ, σ) for the project completion time and cost.
- The project completion time and the cost associated with a certain degree of confidence.

It should be noted that the user can easily change the state of the main variables Q, F, C, N and D and fuzzy rules to reflect all possible statuses: poor, medium and good.

9- Application:

A real-world project consisting of 59 activities is studied to illustrate the use of the proposed system and demonstrate its capabilities. The project is a three-story residential building (ground + two typical floors + roof) with a building area of 530 m^2. **Table (2)** shows precedence relations and lags for activities of the project under study.

Activity	Predecessor, (Relation) and (Lag)	Activity	Predecessor , (Relation) and (Lag)
1- Excavation	————————	2- Replacement (Layer 1)	1-Excavation, (fs),(0)
3-Replacement (Layer 2)	2-Replacement (Layer1), (fs), (1)	4-Replacement (Layer 3)	3-Replacement (Layer2), (fs),(1)
5-Formwork PC (Footing +UG Beams)	4-Replacement (Layer3), (fs),(0)	6-Concrete Pouring PC (Footing + UG Beams)	5-Formwork PC (Footing + UG Beams), (fs),(0)
7- Formwork Removal PC (Footing + UG Beams)	6- Concrete Pouring PC (Footing + UG Beams), (fs),(1)	8-Formwork RC (Footing + UG Beams)	7- Formwork Removal PC (Footing + UG Beams), (fs),(0)
9- Rebar RC (Footing +UG Beams)	8-Formwork RC (Footing + UG Beams) ,(fs),(0)	10- Concrete Pouring RC (Footing + UG Beams)	9- Rebar RC (Footing + UG Beams), (fs),(0)
11-Formwork Removal RC (Footing + UG Beams)	10-Concrete Pouring RC (Footing + UG Beams), (fs),(1)	12-Formwork Columns of Ground Floor	11-Formwork Removal RC (Footing + UG Beams),(fs),(0)
13-Rebar Columns of Ground Floor	12- Formwork Columns of Ground Floor,(fs),(0)	14- Concrete Pouring Columns of Ground Floor	13- Rebar Columns of Ground Floor ,(fs),(0)

15-Formwork Removal Columns of Ground Floor	14- Concrete Pouring Columns of Ground Floor,(fs),(1)	16- Brickwork Under SOG	15-Formwork Removal Columns of Ground Floor,(fs),(0)
17- Insulation of Footing	16-Brickwork Under SOG,(fs),(5)	18-Backfill	17- Insulation of Footing, (fs),(1)
19- Formwork PC-SOG	18- Backfill,(fs),(0)	20- Concrete Pouring PC-SOG	19- Formwork PC-SOG, (fs),(0)
21-Formwork Removal PC- SOG	20- Concrete Pouring PC- SOG, (fs),(1)	22- Formwork RC-SOG	21-Formwork Removal PC- SOG,(fs),(0)
23- Rebar RC-SOG	22- Formwork RC-SOG, (fs),(0)	24- Concrete Pouring RC- SOG	23- Rebar RC-SOG, (fs),(0)
25-Formwork Removal RC- SOG	24- Concrete Pouring RC-SOG, (fs), (1)	26- Formwork (Slab + Stairs) of Ground Floor	25-Formwork Removal RC- SOG,(fs),(0)
27-Rebar (Slab + Stairs) of Ground Floor	26- Formwork (Slab + Stairs) of Ground Floor, (fs),(0)	28- Concrete Pouring (Slab + Stairs) of Ground Floor	27- Rebar (Slab + Stairs) of Ground Floor, (fs),(0)
29-Formwork Removal (Slab + Stairs) of Ground Floor	28- Concrete Pouring (Slab + Stairs) of Ground Floor ,(fs),(7)	30-Formwork Columns of First Floor	28- Concrete Pouring (Slab + Stairs) of Ground Floor,(fs),(1)
31- Rebar Columns of First Floor	30- Formwork Columns of First Floor ,(fs),(0)	32- Concrete Pouring Columns of First Floor	31- Rebar Columns of First Floor ,(fs),(0)
33-Formwork Removal Columns of First floor	32- Concrete Pouring Columns of First Floor, (fs),(1)	34- Formwork (Slab + Stairs) of First Floor	33-Formwork Removal Columns of First Floor, (fs),(0) 29-Formwork Removal (Slab + Stairs) of Ground Floor,(fs),(0)
35- Rebar (Slab +Stairs) of First Floor	34- Formwork (Slab + Stairs) of First Floor, (fs),(0)	36- Concrete Pouring (Slab + Stairs) of First Floor	35-Rebar (Slab + Stairs) of First Floor, (fs),(0)
37-Formwork Removal (Slab + Stairs) of First Floor	36-Concrete Pouring (Slab + Stairs) of First Floor,(fs),(7)	38-Formwork Columns of Second Floor	36- Concrete Pouring (Slab + Stairs) of First Floor,(fs),(1)
39- Rebar Columns of Second Floor	38- Formwork Columns of Second Floor,(fs),(0)	40- Concrete Pouring Columns of Second Floor	39- Rebar Columns of Second Floor, (fs),(0)
41-Formwork Removal Columns of Second Floor	40- Concrete Pouring Columns of Second Floor,(fs),(1)	42-Formwork (Slab + Stairs) of Second Floor	41- Formwork Removal Columns of Second Floor,(fs),(0) 37- Formwork Removal (Slab + Stairs) of First Floor,(fs),(0)
43-Rebar (Slab + Stairs) of Second Floor	42- Formwork (Slab + Stairs) of Second Floor, (fs),(0)	44-Concrete Pouring (Slab + Stairs) of Second Floor	43- Rebar (Slab + Stairs) f of Second Floor,(fs),(0)
45-Formwork Removal (Slab + Stairs) of Second Floor	44-Concrete Pouring (Slab + Stairs) of Second Floor, (fs),(7)	46-Brickwork (m^3) of Ground Floor	29-Formwork Removal (Slab + Stairs) of Ground Floor,(fs),(0)
47- Brickwork (m^2) of	46-Brickwork (m^3) of	48-Brickwork (m^3) of	37-Formwork Removal

Ground Floor	Ground Floor,(fs),(0)	First floor	(Slab + Stairs) of First Floor,(fs),(0)
49- Brickwork (m^2) of First Floor	48-Brickwork (m^3) of First Floor,(fs),(0)	50-Brickwork (m^3) of Second Floor	45-Formwork Removal (Slab + Stairs) of Second Floor,(fs),(0)
51- Brickwork (m^2) of Second Floor	50- Brickwork (m^3) of Second Floor, (fs),(0)	52- Brickwork (m^3) of Roof Floor	51- Brickwork (m^2) of Second Floor,(fs),(0)
53-Moisture Insulation of Ground Floor	47- Brickwork (m^2) of Ground floor, (fs),(1)	54-Moisture Insulation (Terraces and Bathrooms) of First Floor	49- Brickwork (m^2) of First Floor,(fs),(1)
55- Thermal Insulation (Terraces) of First Floor	54- Moisture Insulation (Terraces and Bathrooms) of First Floor,(fs),(3)	56-Moisture Insulation (Terraces and Bathrooms) of Second Floor	51- Brickwork (m^2) of Second Floor,(fs),(1)
57- Thermal Insulation (Terraces) of Second Floor	56-Moisture Insulation (Terraces and Bathrooms) of second floor,(fs),(3)	58-Moisture Insulation of Roof Floor	52- Brickwork (m^3) of Roof Floor,(fs),(1)
59-Thermal Insulation of Roof Floor	58- Moisture Insulation of Roof Floor, (fs), (3)	________________	________________

Table (7): Precedence relations and lags for activities of the project understudy

Survey questionnaires were designed and several interviews were administrated to five experts working on the project in order to get the knowledge needed for:

- Exploring factors influencing each activity.
- Development of the fuzzy membership functions for the main variables Q, F, C, N and D.
- Identification of fuzzy rules.

Table (3) lists the most important three factors identified by experts influencing a sampling of project activities.

ID	Activity	Factor1	Factor 2	Factor 3
1	Excavation	Excavator Breakdown	High Ground Water Level	Inadequate Soil Investigation
2	Replacement (Layer 1)	High Ground Water Level	Material Shortage	Inadequate Soil Investigation
8	Formwork RC (Footing + UG beams)	Skilled Labor Shortage	Material Shortage	________________
18	Backfill	Skilled Labor Shortage	Material Shortage	Equipment Breakdown
31	Rebar Columns of First Floor	Skilled Labor Shortage	Material Shortage	________________
44	Concrete Pouring (Slab + Stairs) of Second Floor	Skilled Labor Shortage	Material Shortage	Equipment Breakdown
46	Brickwork (m^3) of Ground Floor	Skilled Labor Shortage	Material Shortage	________________
59	Thermal Insulation of Roof Floor	Skilled Labor Shortage	Material Shortage	________________

Table (8): Influencing factors for a sampling of project activities

An example table, presented to experts to identify the quality level (Q) for a certain factor, is provided in **Table (4)**. For example, to identify the quality level for excavator breakdown as an influencing factor of excavation, experts identify the quality of excavator (poor, medium, or good) based on the remaining useful life of such excavator as a percentage of the original value. Remaining useful life is a proper criterion to identify the quality of a piece of equipment as it is directly proportional to its productivity.

Poor Quality										
0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
×	×	×	×							
Medium Quality										
0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
				×	×					
Good Quality										
0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
						×	×	×	×	×

Table (9): Quality level (Q) identification for a certain factor

Opinions of all experts are collected in one table as shown in **Table (5)**. Sum of opinions is standardized by dividing it by the total number of experts as a major step in developing the fuzzy membership functions.

Opinions for poor Quality	**The element within the subjective scale (in %)**										
	0	10	20	30	40	50	60	70	80	90	100
Interviewee A	×	×	×	×							
Interviewee B	×	×	×								
Interviewee C	×	×	×	×	×						
Interviewee D	×	×	×	×	×	×					
Interviewee E	×	×	×	×							
Sum of opinions	5	5	5	4	2	1	0				
Standardized frequency	1	1	1	0.8	0.4	0.2	0				

Table (10): Standardization of expert's opinions to develop the fuzzy membership function

Preliminary membership functions obtained by dividing the sum of expert's opinions by the total number of experts are adjusted in order to obtain triangular and trapezoidal – shaped membership functions as shown in **Table (6)**.

Linguistic terms	**Fuzzy membership functions**											
	0	10	20	30	40	50	60	70	80	90	100	Shape
Poor	1	1	1	0.75	0.5	0.25	0	0	0	0	0	Trapezoidal
Medium	0	0	0	0.33	0.67	1	0.67	0.33	0	0	0	Triangle
Good	0	0	0	0	0	0	0.33	0.67	1	1	1	Trapezoidal

Table (11): Triangular and trapezoidal-shaped membership functions

Going through the same procedures used to develop the fuzzy membership functions for (Q), functions for F, C, N and D are developed. As previously mentioned, psychometric scales with values ranging from 0 to 100 are used for construction the membership functions of Q, F and C, while natural numbers are used for N and D. **Figures (7, 8, 9, 10 and 11)** show examples of the fuzzy membership functions developed and utilized for studying productivity of the project under study.

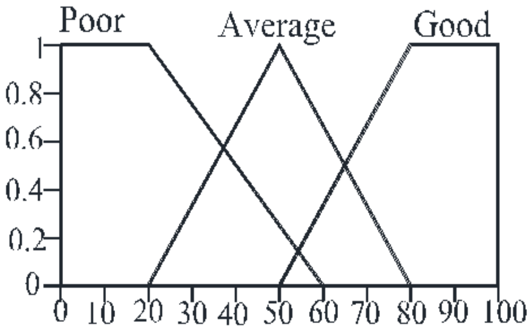


Figure 7: Quality level (Q)

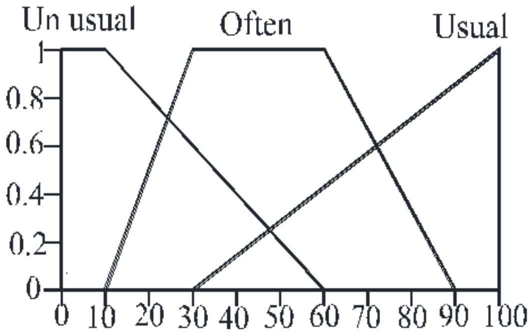


Figure 8: Frequency (F)

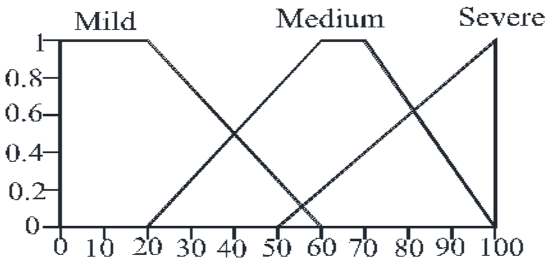


Figure 9: Adverse consequences (C)

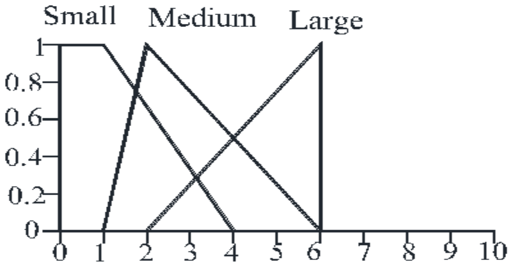


Figure 10: Number of disruptions (N)

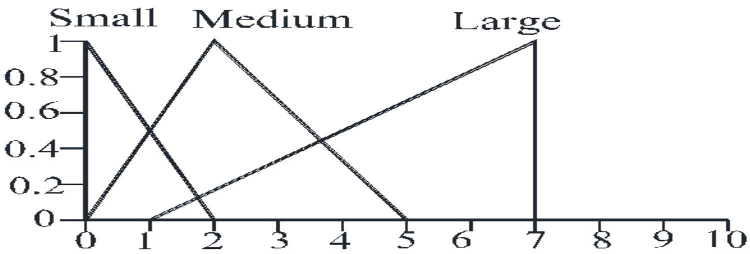


Figure 11: Duration of delays due to one disruption (D)

In addition to sharing their opinions for construction the fuzzy membership functions, experts give their opinions to generate fuzzy rules. **Table 7** is an example of fuzzy control rules applied in the excavation activity.

Q	**F**	**C**	**N**	**D**
Poor	Usual	Severe	Large	Large
Average	Often	Medium	Medium	Medium
Good	Unusual	Mild	Small	Small

Table 12: An example of fuzzy rules applied in the project

Once the fuzzy membership functions and fuzzy rules have been generated, computing the fuzzy joint effect of Q, F and C on both N and D is carried out taking the combined effect of all influencing factors on a given activity into consideration. The deliverables are the statistical parameters (**μ, σ**) for N and D. **Tables (8 and 9)** show the results of the statistical parameters of N and D respectively. Results are presented for some activities of the project in three different statuses (Poor, Medium and Good).

ID	Activity	Poor		Medium		Good	
		μ_N	σ_N	μ_N	σ_N	μ_N	σ_N
1	Excavation	12.1667	2.7639	6.7272	2.1359	3.4203	2.5955
2	Replacement (Layer1)	12.0952	3.0065	7.5556	2.6294	3.5556	2.6294
8	Formwork RC (Footing + UG Beams)	7.2245	1.4814	5.5000	1.7078	1.8889	1.4866
18	Backfill	8.7901	2.5275	6.0000	2.6017	2.1429	1.9949
31	Rebar Columns of First Floor	7.0001	1.7320	4.5000	1.7078	2.3215	1.6269
44	Concrete Pouring (Slab + Stairs) of Second Floor	10.8237	3.6336	6.4444	2.6294	2.5714	2.0603
46	Brickwork (m^3) of Ground Floor	5.7272	1.6007	4.0000	1.4142	2.5000	1.7078
59	Thermal Insulation of Roof Floor	7.0001	1.7320	4.0000	1.4142	1.4347	1.0965

Table 13: Results of the statistical parameters (μ_N, σ_N) for the number of disruptions

ID	Activity	Poor		Medium		Good	
		μ_D (Day)	σ_D (Day)	μ_D (Day)	σ_D (Day)	μ_D (Day)	σ_D (Day)
1	Excavation	4.6470	1.6429	2.3636	1.0679	0.4667	0.4989
2	Replacement (Layer 1)	0.7935	0.1901	0.3750	0.1250	0.1250	0.1250
8	Formwork RC (Footing + UG Beams)	1.8077	0.2433	0.7500	0.2500	0.1923	0.2433
18	Backfill	4.3950	1.2637	2.2857	1.0302	0.3750	0.4841
31	Rebar Columns of First Floor	0.9167	0.1179	0.3750	0.1250	0.1250	0.1250
44	Concrete Pouring (Slab + Stairs) of Second Floor	0.8750	0.1250	0.3750	0.1250	0.1250	0.1250
46	Brickwork (m^3) of Ground Floor	3.6000	1.0832	2.0000	0.8165	0.5000	0.5000
59	Thermal Insulation of Roof Floor	1.6667	0.3727	1.0000	0.4082	0.2500	0.2500

Table 14: Results of the statistical parameters (μ_D, σ_D) for the duration of delays caused by each disruption

The mean (μ) and standard deviation (σ) are the distributional parameters required to construct the probability distributions that represent the main inputs to the simulation model. CPM-based simulation was performed to simulate the project by iterating it 1000 times.

Productivity results in terms of quantity per time units and in quantity per monetary units are shown in **Tables (10 and 11)** respectively. Results are presented in three different statuses: poor, medium and good.

ID	Activity	productivity per unit time ($unit/day$)					
		Poor		Medium		Good	
		μ (unit/ day)	σ (unit /day)	μ (unit /day)	σ (unit /day)	μ (unit /day)	σ (unit /day)
1	Excavation (m^3/day)	28.2367	11.7620	63.2097	28.3443	145.3037	28.8909
2	Replacement (Layer 1) (m^3/day)	20.7150	5.7797	50.4530	20.5179	125.0644	35.2338
8	Formwork RC (Footing + UG Beams) (m^3/day)	2.8335	0.4700	5.0766	0.8701	7.4243	0.5004
18	Backfill (m^3/day)	14.7361	4.7251	29.9621	11.0025	56.5673	5.9370
31	Rebar Columns of First Floor (ton/day)	0.3152	0.0741	0.7144	0.1676	1.1168	0.1477
44	Concrete Pouring (Slab + Stairs) of Second Floor (m^3/day)	3.5523	1.5631	10.0414	4.4511	22.7182	5.4593
46	Brickwork (m^3) of Ground Floor ($m^3 l\ day$)	2.2557	0.9236	4.6782	1.9461	9.5560	2.2598
59	Thermal Insulation of Roof Floor ($m^2 l\ day$)	7.9192	2.9290	22.8075	13.8456	69.0441	17.7663

Table 15: Productivity in terms of quantity per time units

ID	Activity	Productivity per unit monetary (unit / L.E), (L. E / unit)					
		Poor		Medium		Good	
		μ (unit / LE) ,(LE/Unit)	σ (unit / LE) ,(LE/Unit)	μ (unit / LE) ,(LE/Unit)	σ (unit / LE) ,(LE/Unit)	μ (unit / LE) ,(LE/Unit)	σ (unit / LE) ,(LE/Unit)
1	Excavation (m^3/ L. E), (L. E / m^3)	0.0121, (83)	0.0013, (8)	0.0154, (65)	0.0013, (7)	0.0179, (56)	0.0005, (2)
2	Replacement (Layer 1) (m^3/ L. E), (L. E / m^3)	0.0088, (114)	0.0010, (13)	0.0119, (85)	0.0011, (8)	0.0141, (71)	0.0006, (4)
8	Formwork RC (Footing + UG Beams) (m^3/ L. E), (L. E / m^3)	0.0052, (193)	1.8223×10^{-4}, (7)	0.0058, (173)	1.3357×10^{-4}, (5)	0.0060, (167)	4.2664×10^{-5}, (2)

18	Backfill (m^3/ L.E), (L.E / m^3)	0.0355, (29)	0.0027, (3)	0.0415, (25)	0.0028, (2)	0.0461, (22)	0.0006, (1)
31	Rebar Columns of First Floor (ton/ L.E) ,(L.E/ton)	5.6520× 10^{-5}, (17693)	3.4678× 10^{-6}, (1086)	6.7696× 10^{-5}, (14772)	2.4468× 10^{-6}, (536)	7.1723× 10^{-5}, (13943)	1.1442× 10^{-6}, (255)
44	Concrete Pouring (Slab + Stairs) of Second Floor (m^3/ L.E), (L.E / m^3)	0.0007, (1429)	8.6975× 10^{-5}, (148)	0.0010, (1000)	9.1293× 10^{-5}, (95)	0.0012, (834)	4.0943× 10^{-5}, (33)
46	Brickwork (m^3) of Ground Floor (m^3/ L.E), (L.E / m^3)	0.0011, (910)	1.2918× 10^{-4}, (123)	0.0013, (770)	1.0586× 10^{-4}, (72)	0.0015, (667)	5.0583× 10^{-5}, (24)
59	Thermal Insulation of Roof Floor (m^2/ L.E), (L.E / m^2)	0.0130, (77)	0.0022, (14)	0.0194, (52)	0.0027, (8)	0.0251, (40)	0.0010, (2)

Table 16: Productivity in terms of quantity per monetary units

Furthermore, simulation results for the project completion time and total cost (associated with a certain degree of confidence) are presented in **Tables (12 and 13)**.

Total Project duration per day					
Poor		**Medium**		**Good**	
μ (Day)	**σ (Day)**	**μ (Day)**	**σ (Day)**	**μ (Day)**	**σ (Day)**
673	30	309	19	158	6
A degree of Confident (85%)(Day)		**A degree of Confident (85%) (Day)**		**A degree of Confident (85%) (Day)**	
704		326		164	

Table 17: Simulation results of the total project duration

Total Project Cost (L.E)					
Poor		**Medium**		**Good**	
μ(L.E)	**σ (L.E)**	**μ(L.E)**	**σ (L.E)**	**μ(L.E)**	**σ(L.E)**
1.8354×10^6	3.6188×10^4	1.3972×10^6	2.1889×10^4	1.2186×10^6	6.7273×10^3
A degree of Confident (85%) (L.E)		**A degree of Confident (85%) (L.E)**		**A degree of Confident (85%) (L.E)**	
1.8720×10^6		1.4184×10^6		1.2258×10^6	

Table 18: Simulation results of the total project cost

Conclusion:

As advancements in the area of productivity research are very much constrained by data quality and availability, this study presents a comprehensive system that integrates discrete-event simulation with fuzzy logic technique to overcome the limited availability of information. The use of fuzzy logic technique permits dealing with imprecise data and problems via relying on linguistic terms rather than limited or nonexistent historical data. The proposed system assesses the effect of all possible influencing factors on the performance of construction operations. In fact, this methodology adopts fuzzy-logic operations for computing the required statistical parameters. These statistical parameters are the inputs to the simulation model from which the productivity estimates of the construction operation are obtained. The outcomes of the simulation model are activities and entire project duration, activities and entire project cost and productivity of each activity in terms of operations outputs per monetary units as well as per time units. These outcomes could be predicted considering all operational level of influencing factors.

The applicability and performance of the proposed system were assessed by implementing it in a real-world project. The proposed system clarified how the value of productivity could be effectively predicted. The results revealed how productivity was affected by the different operational level of influencing factors such as poor, medium and good status. The proposed system may present a robust approach to measure and improve construction operations.

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