Fuzzy Modus Ponens Deduction Technique for Construction Scheduling

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Abstract: This paper presents a new method to estimate the duration of construction activities. A model, Activity Duration Decision Support System (ADDSS), was developed. This model employs the fuzzy modus ponens deduction (FMPD) technique to evaluate the impact of different factors on activity duration. The linguistic values of these factors are represented by angular fuzzy set models. The technique described in this paper allows a scheduler to partially match an evidence with a rule. The use of angular models demonstrates the use of a single and relatively simple fuzzy logic formula. The technique we developed does not require the scheduler to understand the underlying concept of fuzzy logic. In fact, one needs only to input an assessment of factors that may affect the completion of an activity. At this stage, ADDSS interfaces with the CA-SuperProject scheduling package. ADDSS was also developed to export and import data to and from the CA-SuperProject. Both the logic operations and angular models of ADDSS are elaborated. A step-by-step procedure using ADDSS is presented, followed by case studies demonstrating the implementation of ADDSS in hypothetical and real construction projects. These cases show the practicality and applicability of ADDSS.

Introduction

Of the many causes that can delay a construction project, a primary one is the failure to correctly estimate the duration of one or several critical activities in the scheduling process. An overly optimistic activity duration (even if it is noncritical) could result in a project not being completed within its scheduled time. On the other hand, an overly pessimistic activity duration could produce idleness of resources, increases in overhead expenses, and other problems.

Scheduling methods are designed based on the assumption that the duration of each activity is correctly estimated. However, it is often difficult to estimate activity duration. Among a few methods which can help schedulers to estimate the duration of activities, program evaluation and review technique (PERT) uses weighted values of pessimistic, optimistic, and most likely duration to estimate the mean and variance of the duration's distribution, which is often assumed to be a beta distribution. In the past 10 years, several studies have been conducted to include consideration of factors affecting the activity durations. Crandall and Woolery (1982) used the result of Monte Carlo simulation to estimate the node point distribution, which was assumed to be a beta distribution. Levitt and Kunz (1985) included the past experience of project managers to update a project's schedule. Hendrickson et al. (1987) employed a rule-based expert system to

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estimate the productivity of mason works. These studies suggest that uncertainties in a construction project should be considered when establishing an activity duration.

Frequently, the duration of activities are determined by a scheduler's experience in performing such activities. These durations, however, are often used and reused for other projects whose characteristics differ from the original project. In other words, the variability of the projects, such as site condition, equipment performance, labor performance, ând so forth, are sometimes excluded. Thus, a more accurate method is necessary to obtain the pessimistic and optimistic durations to substitute for the often-used unfounded values.

A project is usually characterized by many conditional, climatic, and resource factors that may have an impact on the productivity of its activities. The impact of these factors, which are usually expressed in linguistic values, rather than numerical values, is difficult to assess and evaluate. Ayyub and Haldar (1984) pioneered the use of fuzzy set theory to evaluate the impact of these factors on duration parameters. Their paper emphasizes primarily the assessment of the mean, variance, and covariance of activity durations.

In this paper, the writers introduce a model, the Activity Duration Decision Support System (ADDSS), that employs the fuzzy modus ponens deduction (FMPD) techniques to assess the impacts of duration factors on activity duration. These factors, which in the past were interpreted in linguistic values, are quantified into numerical values using angular fuzzy set theory (Hadipriono and Sun 1990). These numerical values are used to modify the activity durations affected by the cumulative impact of different site, climatic, resource, and management factors.

FACTORS AFFECTING PRODUCTIVITY

Major site, climatic, resource, and management factors that should be considered in a construction project include site conditions, labor performance, equipment condition, material supply, weather conditions, and management performance. More detailed description of these factors is presented in Hadipriono and Chang (1988). These factors may either increase or decrease the duration of an activity. They were chosen for ADDSS to demonstrate its feasibility. Other factors may be added or deleted as necessary.

In a scheduling process, experienced schedulers may increase or decrease extra time to account for the combined impact of various factors. They frequently establish the schedule based on their past experience in a similar situation and from information obtained based on productivity calculations. However, their experience is often limited to certain types of projects. In addition, inexperienced schedulers sometimes overlook factors or may simply be limited in their ability to accurately assess activity duration. As a result, mistakes can be made during scheduling processes.

ADDSS was developed in order to avoid making such mistakes, it does so by incorporating potential factors that affect activity durations. ADDSS prompts the scheduler to assess each factor using linguistic values, such as "very good" for site condition or "poor" for equipment performance. A scheduler needs only to provide information regarding each affecting factor to ADDSS. In return, ADDSS will furnish the scheduler with an assessment of the optimistic and pessimistic durations of the activity. Further details of using ADDSS are presented later in this paper.

Although using ADDSS can be simple, in reality ADDSS is equipped with a new, quite complicated technique called FMPD. FMPD is used concurrently with angular fuzzy logic models. Since fuzzy angular models have been introduced only recently, their derivation is briefly described so that interested readers may be able to examine the models. In each operation, simple examples are inserted to illustrate the practicality and applicability of the models.

ANGULAR FUZZY SET MODELS

The concept of fuzzy sets was first introduced by Zadeh (1965) as a new method to evaluate and interpret nonnumerical values (e.g., linguistic values). In recent years, fuzzy set models have been applied in several areas. In civil engineering, these models were developed for structure damage evaluation (Yao 1980), construction project scheduling (Ayyub and Haldar 1984), and falsework safety evaluation (Hadipriono 1987). Further details about the basic concepts of fuzzy sets can be found in these references.

The use of fuzzy set models is particularly beneficial for quantifying linguistic values frequently used to determine factors affecting activity duration. In this paper, we used angular fuzzy set models to represent such values. Details of these models are presented in Hadipriono and Sun (1990) and are briefly discussed here.

Angular fuzzy sets use a semicircle on the right-hand side of the vertical axis to represent the truth values in a universe of discourse. The angle between a straight line from the center of the circle and the horizontal line represents a particular truth value. It shows the truth values from "absolutely

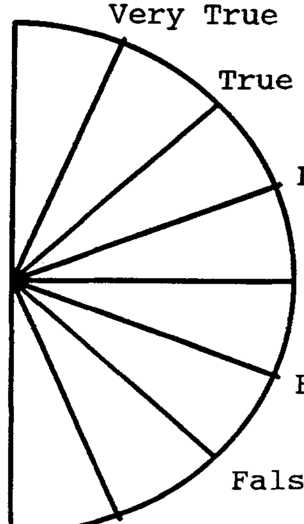

FIG. 1. Angular Fuzzy Set Models for Truth Values

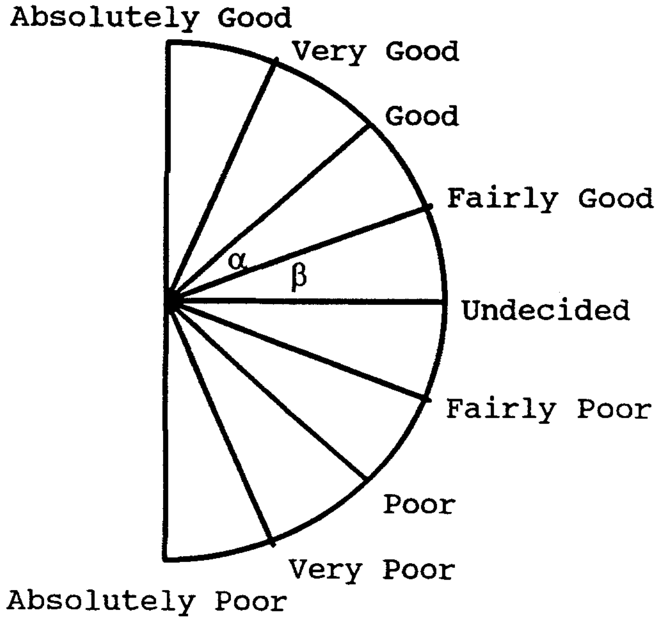

FIG. 2. Angular Fuzzy Set Models for Performance Values

true" ($\pi/2$) to "absolutely false" ($-\pi/2$). Typical linguistic values in a truth space represented by these models are shown in Fig. 1.

A particular linguistic value is represented by a line that forms an angle with the abscissa. Hence, angular fuzzy set models give a clear definition to these values since they are determined by angles. This angular model feature provides an advantage over other fuzzy set models. Furthermore, the use of angular models simplifies fuzzy logic operations that often involve graphic drawings. In addition, a series of complex fuzzy logic operations can be combined into one simple equation. Such simplicity also eliminates the problem of interpreting the results obtained by the use of earlier fuzzy set models.

FMPD includes two basic fuzzy logic operations, truth functional modification (TFM) and inverse truth functional modification (ITFM). TFM modifies the membership function of a linguistic value in a certain proposition with a known truth value. Hence, given a proposition, Θ, which is allocated a truth value restriction, then

$$\Theta: (a \text{ is } A) \text{ is } \tau_A; \qquad A \subset U \qquad \tau_A \subset T \quad \text{(1)}$$

where a = duration factor (e.g., site condition); A = value of the duration factor (e.g., "good"); and τ_A = truth value of the proposition (e.g., "fairly true"). The foregoing proposition can be read as (the site condition is "good") is "fairly true." To find out the modified value of site condition, (1) can be simplified as

$$\Theta: (a \text{ is } A'); \qquad A' \subset U \quad \text{(2)}$$

where A' = modified value of a. The membership function of A' can be solved as follows:

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$$\Phi_{A'}(z) = \Phi_{\tau_A}[\Phi_A(z)]; \qquad \forall z \in U \quad (3)$$

where $\Phi_{A'}(z)$ and $\Phi_A(z)$ = membership functions of the propositions A' and A, respectively; and $\Phi_{\tau_A}(t)$ = membership function of the truth restriction τ_A.

Suppose that α represents the membership function of fuzzy set A (e.g., "good") and β represents the membership function of truth restriction τ_A (e.g., "fairly true") on the angular fuzzy set model as shown in Fig. 2. The membership functions $\Phi_A(z)$ and $\Phi_{\tau_A}(t)$ then can be written as

$$\Phi_{\tau_A}(t) = z \tan(\alpha) \quad (4a)$$

and

$$\Phi_A(z) = z \tan(\beta) \quad (4b)$$

substituting (4) into (3)

$$\Phi_{A'}(z) = \Phi_{\tau_A}[z \tan(\alpha)] \quad (5)$$

Since

$$\Phi_{A'}(z) = z \tan(\gamma) \quad (6)$$

therefore

$$\tan(\gamma) = \tan(\alpha)\tan(\beta) \quad (7)$$

Substituting the values for the proposition (site condition is "good") is "fairly true" with $\alpha = \pi/4$ and $\beta = \pi/8$ into (7) yields $\tan(\gamma) = \tan(\pi/4)\tan(\pi/8) = \tan(\pi/8) = 0.414$. Therefore, the modified value of site conditions is "fairly good."

On the other hand, ITFM can be used to obtain the truth values of a conditional proposition. Given a proposition "a is A" (e.g., site condition is "very good"), the evidence shows that "a is A" (e.g., site condition is "good"). The truth proposition Θ' can then be obtained as follows:

$$\Theta': (a \text{ is } A | a \text{ is } A') = \tau_A; \qquad A, A' \subset U; \qquad \tau_A \subset T \quad (8)$$

where τ_A = truth restriction of the truth value for A'. The new membership function is equal to

$$\Phi_{\tau_{A'}}(t) = \bigvee_z [\Phi_{A'}(z)] = \Phi_{\tau_A}[\Phi_{A'}(z)]; \qquad \forall t \in T; \forall z \in U \quad (9)$$

in which $\bigvee_z$ denotes the value where z is the maximum. Now the proposition Θ': $(a$ is $A)|(a$ is $A')$ is τ_A can be rewritten as

$$\Theta'': (a \text{ is A}) \text{ is } \tau_A; \qquad \tau_A \subset T; \qquad A, A' \subset U \quad (10)$$

If α, α', and β are used to represent the value of A, A', and τ_A, respectively, on the angular fuzzy set model, the membership function will be

$$\Phi_A(z) = z \tan(\alpha) \quad (11a)$$

and

$$\Phi_{A'}(z) = z \tan(\alpha') \quad (11b)$$

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Substituting (11) into (9), the following is obtained:

$$\Phi_{\tau_A}(t) = \Phi_{\tau_A}[\Phi_A(z)] = \Phi_{\tau_A}[z \tan(\alpha)] = z \tan(\alpha)\tan(\alpha') \quad (12)$$

Since

$$\Phi_{\tau_A}(t) = \bigvee_z [\Phi_A(z)] = \bigvee_z [z \tan(\alpha')] \quad (13)$$

therefore

$$z \tan(\alpha') = z \tan(\alpha)\tan(\beta) \quad (14)$$

and

$$\tan(\beta) = \frac{\tan(\alpha')}{\tan(\alpha)} \quad (15)$$

By substituting into (15) $\alpha = 3\pi/8$ and $\alpha' = \pi/4$, the truth value of the proposition (site condition is "very good") given that (site condition is "good") yields $\tan(\beta) = 0.414$. Therefore, the truth value of (site condition is "very good") is "fairly true."

FMPD applies TFM and ITFM techniques to find the membership function of the linguistic value in an implication proposition under the conditional proposition. Suppose there is an implication proposition stating, "It is 'true' that if the site condition is 'good' then construction performance is 'good.'" Suppose also that the evidence (the conditional proposition) states, "It is 'true' that the site condition is 'fairly good.'" The foregoing two propositions can be written as

$$[(a \text{ is } A) \supset (b \text{ is } B)] \text{ is } \tau_1 \quad (16a)$$

$$[(a \text{ is } A')] \text{ is } \tau_2 \quad (16b)$$

The consequences yields

$$(b \text{ is } B) \text{ is } \tau_B \text{ and } (b \text{ is } B') \quad (17)$$

In this paper, these antecedents are written in a shorthand form as

$$[A \supset B] \text{ is } \tau_1 \quad (18a)$$

$$[A'] \text{ is } \tau_2 \quad (18b)$$

which yields

$$(B \text{ is } \tau_B) \text{ and } B' \quad (19)$$

FMPD can be used to find the value of construction performance, B'. For simplicity, let us write the following in a shorthand form:

$$A = \Phi_A(z) = z \tan(A) \quad (20)$$

$$B = \Phi_B(z) = z \tan(B) \quad (21)$$

$$A' = \Phi_{A'}(z) = z \tan(A') \quad (22)$$

$$\tau_A = \Phi_{\tau_A}(t) = t \tan(\tau_A) \quad (23)$$

Also, the truth value of A, given A', can be expressed as

$$\text{ITFM}[A \mid \text{TFM}(A', \tau_2)] \quad \text{(24)}$$

Using (7) and (15)

$$\Phi_{\tau_A} = t\tan(\tau_2) = \frac{t\tan(A')\tan(\tau_2)}{\tan(A)} \quad \text{(25)}$$

Similarly

$$\Phi_{\tau_A} = \Phi_B(z) = z\tan(B) \quad \text{(26)}$$

Through the use of the implication rule (Giles 1976), the membership function of τ_B is determined as

$$\Phi_{\tau_B} = \bigvee_x [\Phi_{\tau_A}(x) \wedge \text{TFM}\{\Phi_I(x, y), t_1\}]; \qquad \forall x \subset T; \qquad \forall y \subset T' \quad \text{(27)}$$

where

$$\Phi_{\tau_A}(x) = x\tan(\tau_A) \quad \text{(28a)}$$

$$\Phi_{\tau_A}(y) = y\tan(\tau_B) \quad \text{(28b)}$$

$$\Phi_I(x, y) = (y - x); \qquad x, y \geq 0; \qquad \forall y, x \in T \quad \text{(28c)}$$

where $\Phi_I(x, y)$ is the implication function of the propositions A and B, $\bigvee_x$ denotes maximum or disjunction, and $\wedge$ denotes minimum or conjunction. Hence, the membership function of τ_A yields

$$\Phi_{\tau_A}(x) = x\tan(\tau_A) = \text{TFM}[(y - x), \tau_1] = (y - x)\tan(\tau_1) \quad \text{(29)}$$

Substituting (29) into (27) yields

$$x = \frac{y\tan(\tau_1)}{[\tan(\tau_A) + \tan(\tau_1)]} \quad \text{(30)}$$

By combining (28) and (30)

$$\tan(\tau_B) = \frac{\tan(\tau_1)\tan(\tau_A)}{[\tan(\tau_1) + \tan(\tau_\mathrm{A})]} \quad \text{(31)}$$

Using TFM operation, the membership function of the new value, B', is given as

$$\Phi_{B'}(z) = \frac{z\tan(B)\tan(\tau_1)\tan(\tau_A)}{[\tan(\tau_1) + \tan(\tau_A)]} \quad \text{(32)}$$

Substituting (20)–(23) into (31) yields

$$\Phi_{B'}(z) = \frac{z\tan(B)\tan(\tau_1)\tan(A')\tan(\tau_2)}{[\tan(\tau_1)\tan(A) + \tan(\tau_2)\tan(A')]} \quad \text{(33)}$$

Therefore

$$\tan(B') = \frac{\tan(B)\tan(\tau_1)\tan(A')\tan(\tau_2)}{[\tan(\tau_1)\tan(A) + \tan(\tau_2)\tan(A')]} \quad \text{(34)}$$

For the proposition exemplified before, suppose that "good" $\equiv$ "true" $= \pi/4$, and "fairly good" $= \pi/8$. Substituting these values into (34)

$$\tan(B') = \frac{\tan\left(\frac{\pi}{4}\right)\tan\left(\frac{\pi}{8}\right)\tan\left(\frac{\pi}{4}\right)\tan\left(\frac{\pi}{4}\right)}{\left[\tan\left(\frac{\pi}{4}\right)\tan\left(\frac{\pi}{4}\right)+\tan\left(\frac{\pi}{8}\right)\tan\left(\frac{\pi}{4}\right)\right]} = 0.146447$$

Therefore $B' \cong 0.718 = \pi/8$. Referring to angular model, the value of construction performance, B', is "close to fairly good."

In a more specific problem, where it is assumed that all truth values are "true" (or tan 45 = 1), (34) can be simplified further as

$$\tan(B') = \frac{\tan(B)\tan(A')}{\tan(A) + \tan(A')} \quad \text{(35)}$$

The transformation of the result of the FMPD's angular values to actual duration was done by the use of sine functions. Adjustment factors of $(1 - 0.5 \sin A')$ and $(1 + 0.5 \sin B')$ were used to determine the optimistic and pessimistic durations, respectively, from the most likely duration; A' and B' are the angles obtained using the FMPD technique to represent the optimistic and pessimistic durations. These adjustment factors were determined subjectively based on an earlier study, which assumed that the optimistic and pessimistic durations are limited to ± 0.5 times the most likely duration (Wu 1991). As an example, if the most likely duration = 18 days, $A' = 60°$, and $B' = 45°$, then the optimistic duration is $(1 - 0.5 \sin 60) \times 18$ days = 10 days, and the pessimistic duration is $(1 + 0.5 \sin 45) \times 18 = 24$ days.

We have briefly reviewed the use of FMPD and angular fuzzy set models to obtain an implication rule when appropriate evidence is available. We also presented simple examples using linguistic values commonly used in assessing construction performance. Despite the seemingly complex FMPD operations, we have shown that by using angular models, a particular problem can be solved by a relatively simple equation [i.e., (34) or (35)]. In the next section, we elaborate the step-by-step procedure in using this technique in ADDSS.

USING FMPD IN ADDSS

ADDSS uses the FMPD technique to incorporate the duration factors described earlier. At this stage, ADDSS is connected to CA-SuperProject (1990), a widely used scheduling program available on the market. A description of this program and the interface process can be found in Wu (1991). Interfacing ADDSS with other programs can be performed with minor modifications.

ADDSS performs the following tasks: First, it inputs a data file transferred from CA-SuperProject. Second, it allows the schedulers to set up their own implication rules (IF-THEN rules) required for performing the FMPD. Third, it performs FMPD operations based on either the default implication rules or those constructed by the schedulers; here, the impacts generated by duration factors are used to calculate the values for optimistic and pessimistic duration. Fourth, it saves the modified values to a data file that can be

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Activity Duration Decision Support System

```
This program employs the Fuzzy Modus Ponens Deduction
Technique to determine the duration of construction
activity.  It is assumed that the duration of each
activity may be affected by the following factors:

          - site condition
          - equipment performance
          - labor performance
          - weather conditions
          - material supply
          - management performance
```

FIG. 3. Description Screen of Affecting Factors Used in ADDSS

Activity Duration Decision Support System

```
Assessment of the above factors is performed qualitatively
 through the use of the following linguistic values:
          - absolutely good
          - very good
          - good
          - fairly good
          - undecided
          - fairly poor
          - poor
          - very poor
          - absolutely poor
```

FIG. 4. Description of Linguistic Values

transferred back into CA-SuperProject by using the software's import command.

To perform the listed tasks, ADDSS was developed as a computer program that can be executed on an IBM PC or compatible with 640K memory or more. The following steps explain ADDSS's operations:

1. An ASCII data file transferred from CA-SuperProject should be loaded when starting ADDSS.
2. A scheduler can modify one specific construction activity or all activities at a time. The scheduler can also choose to add or delete duration factors for a particular activity based on six default factors.
3. The implication rules are constructed according to the scheduler's preference for each factor or all factors. This implication rule is represented by the first antecedent in (16). An example of a rule is, "IF site condition is 'good,' THEN we are 'optimistic' that an activity can be completed within the scheduled duration."

```
Activity Duration Decision Support System

We classify these durations into three catagories:

        - most likely duration
        - optimistic duration
        - pessimistic duration

The most likely duration is obtained from CA-SuperProject
scheduling package.  This duration and the factors mentioned
earlier will be used to determine the optimistic and the
pessimistic duration.
```

FIG. 5. Durations Description Screen

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Activity Duration Decision Support System

                    MAIN MENU

1. Load activity duration data from an existing project

2. Write current activity duration data to an ASCII file

3. Modify activity durations using FMPD

4. Review activity data

5. Quit

Please choose a number and then press Enter >1
```

FIG. 6. ADDSS Main Menu

4. The values of each factor (evidence) that may have an impact on the optimistic and pessimistic duration are chosen by the scheduler based on the scheduler's assessment. They are represented by the second antecedent in (16). An example of such evidence is still a construction site that consists of relatively flat terrain where clearing and grubbing is still needed. Hence, the terrain's, effect on the optimistic duration of a foundation construction may be assessed as "fairly good."

5. The angular FMPD operations will use (35) to calculate the angular value of the optimistic duration of an activity [value of membership function B' in (17)]. Here, the result is "close to fairly optimistic."

6. The value obtained in the previous step will be used as a weighted factor to calculate the numerical values of the optimistic and pessimistic duration, which will be explained later.

Activity Duration Decision Support System

No.	Activity Name	ID	Duration	Opt.Dur.	Like Dur.	Pess.Dur.	Unit
1.	Move In	001	3	3	3	3	day
2.	Foundation	002	14	14	14	14	day
3.	Concreting Columns	003	7	7	7	7	day
4.	Lay Brick Walls	004	5	5	5	5	day
5.	Concreting Beams	005	14	14	14	14	day
6.	Roof	006	7	7	7	7	day
7.	Exterior Painting	007	5	5	5	5	day
8.	Carpentery	008	14	14	14	14	day
9.	Electrical & Plumbing	009	5	5	5	5	day
10.	Ceiling	010	5	5	5	5	day
11.	Interior Finishing	011	7	7	7	7	day
12.	Clear Up	012	3	3	3	3	day

Please input Activity Number you want to update(0 for more) > 2

FIG. 7. Activity List and Modification Selection Screen

Activity Duration Decision Support System

FACTORS UPDATE MENU

The following factors will be considered in the duration determination process of the activity Foundation
You may select any combination of the following:

1. SITE CONDITION
2. EQUIPMENT PERFORMANCE
3. LABOR PERFORMANCE
4. WEATHER CONDITION
5. MATERIAL SUPPLY
6. MANAGEMENT PERFORMANCE

Press 1 to ADD, 2 to DELETE, or 3 to ACCEPT > and press <Enter>

FIG. 8. Factors Update Menu

*** Implication Rule For All Factors ***

By default, the following implication rule applies to all factors:

If the performance of factor(s) under consideration is *Very Good*, THEN we are *Very Optimistic* that the Foundation will be completed on scheduled duration (14 days).

FIG. 9. Default Implication Rule Display Screen

7. The modified data set will be transferred to a new data file that can be imported into CA-SuperProject.

For clarity, in the following sections, we present two case studies. The first case shows the use of ADDSS in a duration estimation process using a hypothetical project. The second case demonstrates the implementation of ADDSS in a real project.

CASE STUDY I: TUTORIAL FOR USING ADDSS

A simple project with 12 activities was used to illustrate the application of ADDSS in a duration estimation process. When the scheduler executes ADDSS, the first three screens show brief descriptions of ADDSS (Figs. 3–5).

They are followed by the main menu screen (Fig. 6), which displays the options of basic operations. Fig. 7 shows the activity list in ADDSS when options 1 and 3 are sequentially selected (after the data have been transferred from CA-SuperProject's task detail). Fig. 7 also shows that the optimistic, most likely, and pessimistic duration values are the same.

From the list in Fig. 7 the activity "Foundation" is chosen for illustration purposes. This was followed by the factors update menu screen (Fig. 8), which allows the scheduler to choose factors pertinent to the activity "Foundation." The scheduler can also add or delete any factors that could have

```
Activity Duration Decision Support System

We understand that you do not agree with the default rule
Hence, you are now required to construct your own implication
rule to relate the activity duration and the factors below:

        SITE CONDITION
        EQUIPMENT PERFORMANCE
        LABOR PERFORMANCE
        WEATHER CONDITION
        MATERIAL SUPPLY
        MANAGEMENT PERFORMANCE

Would you like to consider the same implication
rule for all the above factors (y or n)>y
```

FIG. 10. Implication Rule Factors Selection Screen

```
Here, you are asked to participate in constructing your own
rule relating those factors mentioned before to the duration
activity - Foundation

              *** Implication Rule ***

     If it is assumed that those factors are very good
     please determine the possibility that the activity
     Foundation will be completed on scheduled duration
     (14 days)?
              1. Very Optimistic
              2. Optimistic
              3. Fairly Optimistic
```

FIG. 11. Implication Construction Screen

an impact on the duration. After factors are determined, a default implication rule (IF-THEN rule) for all factors is displayed as shown in Fig. 9. The scheduler could either accept or reject the default implication rule. If the default implicaton rule is rejected, ADDSS will require the scheduler to construct a new rule(s) as shown in Figs. 10 and 11. ADDSS allows the scheduler to construct a rule for all duration factors or different rules for different factors. Fig. 12 shows the linguistic values the scheduler can select as evidence for establishing optimistic and pessimistic duration.

If the scheduler accepts the default implication rule, then information in Fig. 12 is essentially the only input (evidence) ADDSS needs to perform the FMPD operations. This input is obtained by the scheduler based on the

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Activity Duration Decision Support System

Let us return to your project and to activity-
Foundation            in particular.  In the
following, please determine your assessment on
SITE CONDITION to perform Foundation
that could produce an OPTIMISTIC DURATION.

     1. Very Good
     2. Good
     3. Fairly Good
     4. Undecided
     5. Fairly Poor
     6. Poor
     7. Very Poor

Please choose a number and then press Enter > 1
```

FIG. 12. Optimistic Value Selection Screen

```
Activity Duration Decision Support System

Fuzzy Modus Ponens Deduction Technique used in conjunction
with the Angular Fuzzy Set Models yields the following results

          For Activity - Foundation
          Most likely Duration is 14 days
          Optimistic Duration is 9 days
          Pessimistic Duration is 20 days

Do you like to modify other activity duration (y or n)>
```

FIG. 13. Activity Duration Modification Result Display

assessment of selected factors in a particular construction project. The result of FMPD operations is shown in Fig. 13. For schedulers interested in fuzzy set models, the optimistic and pessimistic duration values are also shown in Fig. 14.

Based on the information in Fig. 14, ADDSS transfers the modified data file back to CA-SuperProject through the use of option 2 in Fig. 6.

CASE STUDY II: IMPLEMENTING ADDSS

ADDSS is used here on an experimental basis for establishing the optimistic and pessimistic durations of the foundation construction of the nine-story Dreese Laboratory, at The Ohio State University. The foundation

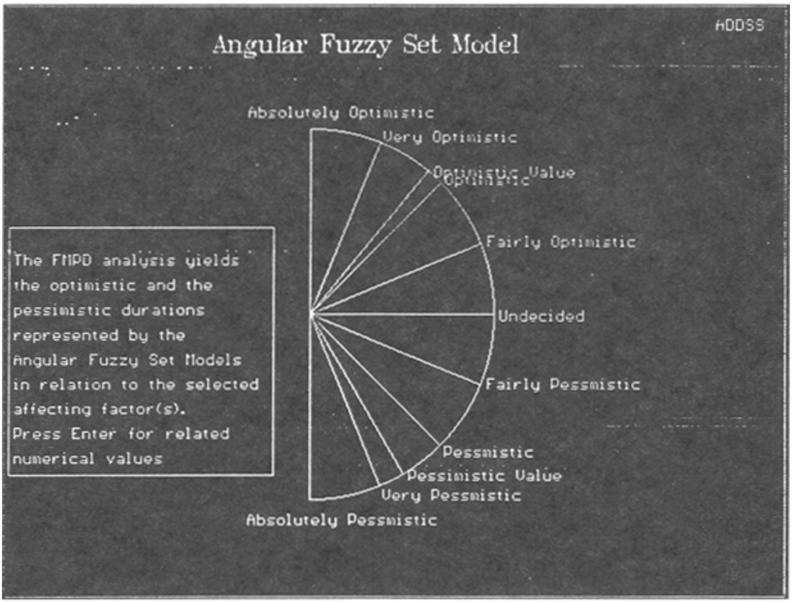

FIG. 14. Modified Activity Duration Value Interpreted in Angular Fuzzy Model

consists of cast-in-place drilled shaft foundations (caissons). The major activities in the foundation construction are site preparation, earthwork, selective demolition, drilled shaft foundation, and concrete foundation.

Factors of interest are site condition, weather condition, management performance, material supply, equipment performance, and labor performance. These factors are assumed to affect activity durations in optimistic and pessimistic ways. Knowledge about these factors was acquired from the project manager and the construction engineer. Their assessments were summarized in Table 1. For example, the project manager assessed that a "good" site condition will contribute to an optimistic duration of the activity, site preparation. In addition, the project manager and construction engineer were asked to establish the most likely duration of each activity.

Then, their assessments in Table 1 were used as the input for ADDSS. Using the procedure described in the previous sections, the optimistic and pessimistic durations of each activity were established in terms of angular models. The models were used to adjust the most likely durations in order to establish the optimistic and pessimistic durations. Their transformation into unit time is presented in Table 2. The results shown in Table 2 are in agreement with the assessment of the project manager and the construction engineer. Hence, it can be concluded that the use of ADDSS for practical purposes is feasible.

Like any other technique, ADDSS also has its limitations. Since the input is subjective, schedulers and engineers may furnish different values when assessing a construction project. Although fuzzy logic technique can be used to compromise these different values, at the current stage, ADDSS is not equipped with such a mechanism. In addition, at this stage, ADDSS's interface is limited to only CA-SuperProject package. Nevertheless, as re-

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TABLE 1. Project Manager's/Engineer's Assessment of Dreese Laboratory Project

Activities (1)	Site condition (opt/pes)[a] (2)	Weather condition (opt/pes) (3)	Management performance (opt/pes) (4)	Material supply (opt/pes) (5)	Equipment performance (opt/pes) (6)	Labor performance (opt/pes) (7)
Site preparation	Good/fairly good	Very good/good	Very good/fairly good	Very good/good	Very good/good	Very good/good
Earthwork-building	Good/fairly good	Very good/good	Very good/fairly good	—	Very good/good	Very good/good
Selective demolition	Good/fairly good	Very good/good	Very good/fairly good	—	Very good/good	Good/fairly good
Drilled shaft foundation	Good/fairly good	Very good/good	Very good/fairly good	Very good/good	Very good/good	Very good/good
Concrete foundation	Good/fairly good	Very good/good	Very good/fairly good	Very good/good	Very good/good	Very good/good

[a]opt = optimistic; pes = pessimistic.

TABLE 2. Activity Duration in Dreese Laboratory Project

Activities (1)	Identification (2)	Most likely (days) (3)	Optimistic duration (days) (4)	Pessimistic duration (days) (5)
Site preparation	001	12	8	15
Earthwork-building	002	33	21	41
Selective demolition	003	25	16	31
Drilled shaft foundation	004	31	20	39
Concrete foundation	005	54	34	68

search progresses, modificaton of ADDSS to accommodate these limitations can be made with little or no difficulty.

SUMMARY AND CONCLUSION

Factors affecting activity duration should be considered in a duration estimation process. The precise impact of these factors on an activity duration is hard to assess, because these impacts are usually expressed qualitatively. However, the values of optimistic and pessimistic duration are determined numerically (though often inaccurately).

Such a problem can be solved by using fuzzy logic operations. The FMPD technique described in this paper converts qualitative expressions used to assess these factors into numerical values. In addition, the FMPD allows a partial matching process between an evidence and a rule. For example, if the condition (IF statement) in a rule has a value of "good," the FMPD technique can still solve for the goal (THEN statement) even if the evidence has a value of "fairly good." The use of angular fuzzy set models in conjunction with FMPD simplifies the fuzzy logic operations considerably. In essence, only a relatively simple formula is needed.

Despite the seemingly complex derivations and operations of FMPD, a scheduler of this model may hardly notice the use of fuzzy logic concepts. In fact, if the default rule is used, a scheduler needs only to input the assessment of the factors that may have an effect on the scheduled duration of an activity in a particular project.

In conclusion, ADDSS shows that the use of fuzzy logic to determine activity durations is feasible. The model also provides flexibility, so that the scheduler can modify factors and rules. Interface with conventional scheduling packages can be performed as needed.

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APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A, A', B, B' = fuzzy sets representing linguistic values;
$A \supset B$ = A implies B; if A then B;
$A \subset U$ = A is subset of U;
T = truth space;
U = universe of discourse;
x = fuzzy element of fuzzy set A;
α, β, γ = angles in radians representing truth values in angular fuzzy set models;
Θ = proposition;
$\tau_A, \tau_B, \tau_1, \tau_2$ = truth restriction of proposition;
Φ = membership function;
$\forall x \in A$ = for all x contained in A;
$\bigvee_i$ = membership value where i is maximum; and
$\bigwedge_i$ = membership value where i is minimum.

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