[x] ORIGINAL [ ] REVISION NO. ______

Project No. E-20-667 GTRIXXXX DATE 5 / 18 /84

Project Director: Dr. R. Kangari SchooXXXX CE

Sponsor: National Science Foundation

Type Agreement: Grant No. CEE-8404430

Award Period: From 6/1/84 To 11/30/86 * (Performance) 2/28/87 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$ 48,000
Funded:	$	$ 48,000

Cost Sharing Amount: $ 14,272 Cost Sharing No: E-20-347

Title: "~~Research Initiation:~~ Construction Risk Analysis"

ADMINISTRATIVE DATA OCA Contact Lynn Boyd x4820

1) Sponsor Technical Contact:

Gifford H. Albright
National Science Foundation
1800 G Street, N.W.
Washington, DC 20550
(202) 357-7710

2) Sponsor Admin/Contractual Matters:

Sharon Graham, Grants Official
National Science Foundation
1800 G Street, N.W.
Washington, DC 20550
(202) 357-9626

Defense Priority Rating: n/a Military Security Classification: n/a
(or) Company/Industrial Proprietary: n/a

RESTRICTIONS

See Attached NSF Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT.

COMMENTS:

* includes 6 month unfunded flexibility period.

Sponsor I.D. #02.107.000.84.059

COPIES TO:

Project Director
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Reports Coordinator (OCA)
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GTRI
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FORM OCA 4 383

EORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 3-20-87

oject No. E-20-667 School/~~Lab~~ CE

cludes Subproject No.(s) N/A

oject Director(s) Dr. R. Kangari GTRC /~~GIT~~

onsor National Science Foundation

tle "~~Research Initiation:~~ Construction Risk Analysis"

fective Completion Date: 11/30/86 (Performance) 2/28/87 (Reports)

ant/Contract Closeout Actions Remaining:

- [ ] None
- [ ] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [x] Final Report of Inventions - Questionnaire sent to P.I.
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ______

ntinues Project No. ______ Continued by Project No. ______

PIES TO:

iject Director
search Administrative Network
search Property Management
counting
curement/GTRI Supply Services
search Security Services
ports Coordinator (OCA)
gal Services

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GTRC
Research Communications (2)
Project File
Other Duane H.
Angela DuBose
Russ Embry

RM OCA 69.285

Georgia Institute of Technology

A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA

ATLANTA, GEORGIA 30332

SCHOOL OF
CIVIL ENGINEERING

TELEX: 542507 GTRC OCA ATL

TELEPHONE
(404) 894-2296

September 3, 1985

Research Initiation Program
National Science Foundation
1800 G Street, N.W.
Washington, DC 20550

Dear Sir:

Enclosed please find two copies of the Annual Progress Report of Research Initiation "Construction Risk Analysis" NSF Grant No. CEE-8404430.

Sincerely yours,

Roozbeh Kangari,
Assistant Professor of
Civil Engineering,
Construction Management
Program

Enclosures

TO: National Science Foundation

FROM: Prof. Roozbeh Kangari

Civil Engineering Department

Georgia Institute of Technology

SUBJECT: Annual Progress Report of Research Initiation

"Construction Risk Analysis" Grant No. CEE-8404430

SUMMARY OF THE ANNUAL PROGRESS REPORT

During the first year of the research, the following progresses were made:

1) A detail literature research of risk in construction, and fuzzy set theory were conducted.
2) High potential risk factors based on the industry survey were selected for in-depth analysis.
3) A construction risk analysis model was developed based on the fuzzy set theory.
4) A microcomputer program for the above model has been developed. The program allows the contractor to analyze their risk by linguistic variables. The program also has been implemented by the graduate students at Georgia Tech in the "Construction Risk Analysis" course. A brief description of the program is presented in Appendix I.
5) The developed microcomputer program was presented at the Construction Research Workshop at University of Illinois (May 1985). The program has been made available to the researchers on this topic.
6) The results of this research was presented (July 1985) to the graduate students and faculties in Civil Engineering Department (Construction Management Program) at Unviersity of California at Berkeley. As a

result of that, similar line of research has been developed by Mr. T. C. Chang, a Ph.D. student at UC Berkeley in Construction Management Program.

7) Preliminary draft of a paper on the topic is prepared to be presented to the ASCE Journal of Construction Engineering and Management.
8) One graduate student in the Construction Management Program at Georgia Tech has completed his M.S. special research on this topic. This thesis "Application of Fuzzy Set Theory in the Construction Industry" has explored the theoretical and practical aspects of the fuzzy set theory in construction industry.

PROBLEMS AND DIFFICULTIES RELATED TO THE RESEARCH

In the original proposal budget no fund was allocated for the purchase of personal computer, however, during the research a set of complex mathematical equations and matrices was developed which required APL computer language to solve these problems. It was felt that a personal computer will be a suitable tool to resolve the problem. Therefore, with the permission of Institute, a part of fund from personal services was transfered to the capital outlay fund for the purchase of a microcomputer. The micro has served as a useful tool for the graduate students for the in-depth study of the developed model.

The second problem was that the overhead rate at Georgia Tech has increased from originally 49.4% to 63.5%. Therefore, due to the budget limitations only one part time graduate student was hired to assist the research.

SECOND YEAR'S RESEARCH FOCUS

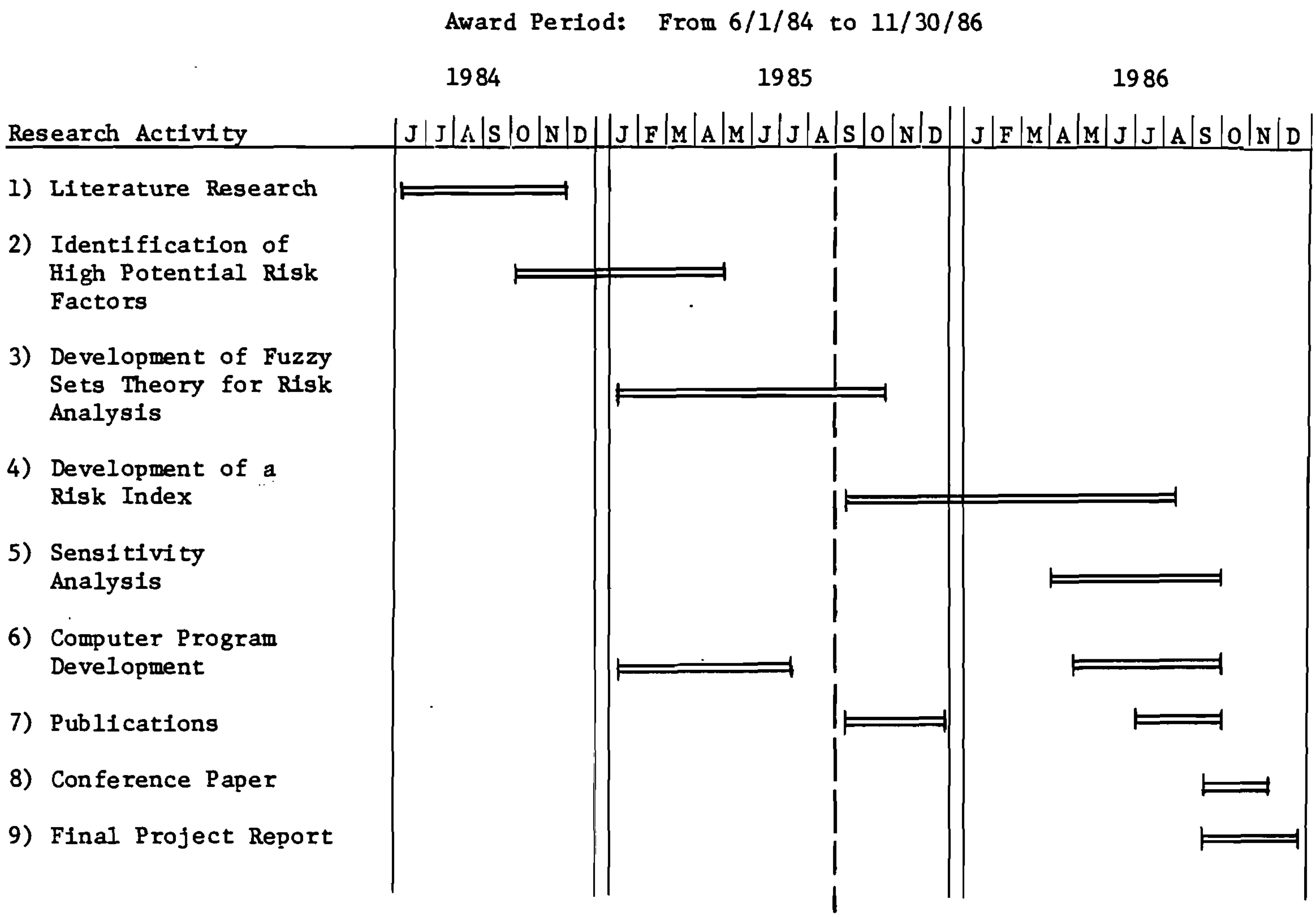
During the second year, this research will focus on the following areas:

1) The developed system in part one is based on three mathematical models. The objective is to test these models and integrate them into one system. The system will attempt to evaluate a risk index by linguistic variables. At this stage the qualitative variables will be translated into mathematical terms in order to evaluate a failure index for the construction industry. The evaluaton of the index will provide a framework with which the high rate of failure can be analyzed.
2) The sensitivity of the developed model to the major risk variables will be examined. The results of the sensitivity analysis will be compared with present risk analysis techniques (classical probability and utility theories).
3) The microcomputer program developed in the first year will be further expanded to analyze risk by fuzzy sets. The program will be made available to other investigators who are doing research in this area.
4) The results of the research will be presented to the ASCE Journal of Construction Engineering and Management for possible publication. Two reprints of the paper will be provided to NSF for approval.
5) The investigator will present a paper about the results of this research at the ASCE Spring Convention in 1986 at Seattle, Washington.
6) Final NSF Project Reports will be prepared.

RESEARCH SCHEDULE

The following time-seal bar chart as presented in Figure 1, shows the research schedule for this research. The schedule includes six months unfunded flexibility period.

Figure 1. Research Schedule



Appendix I

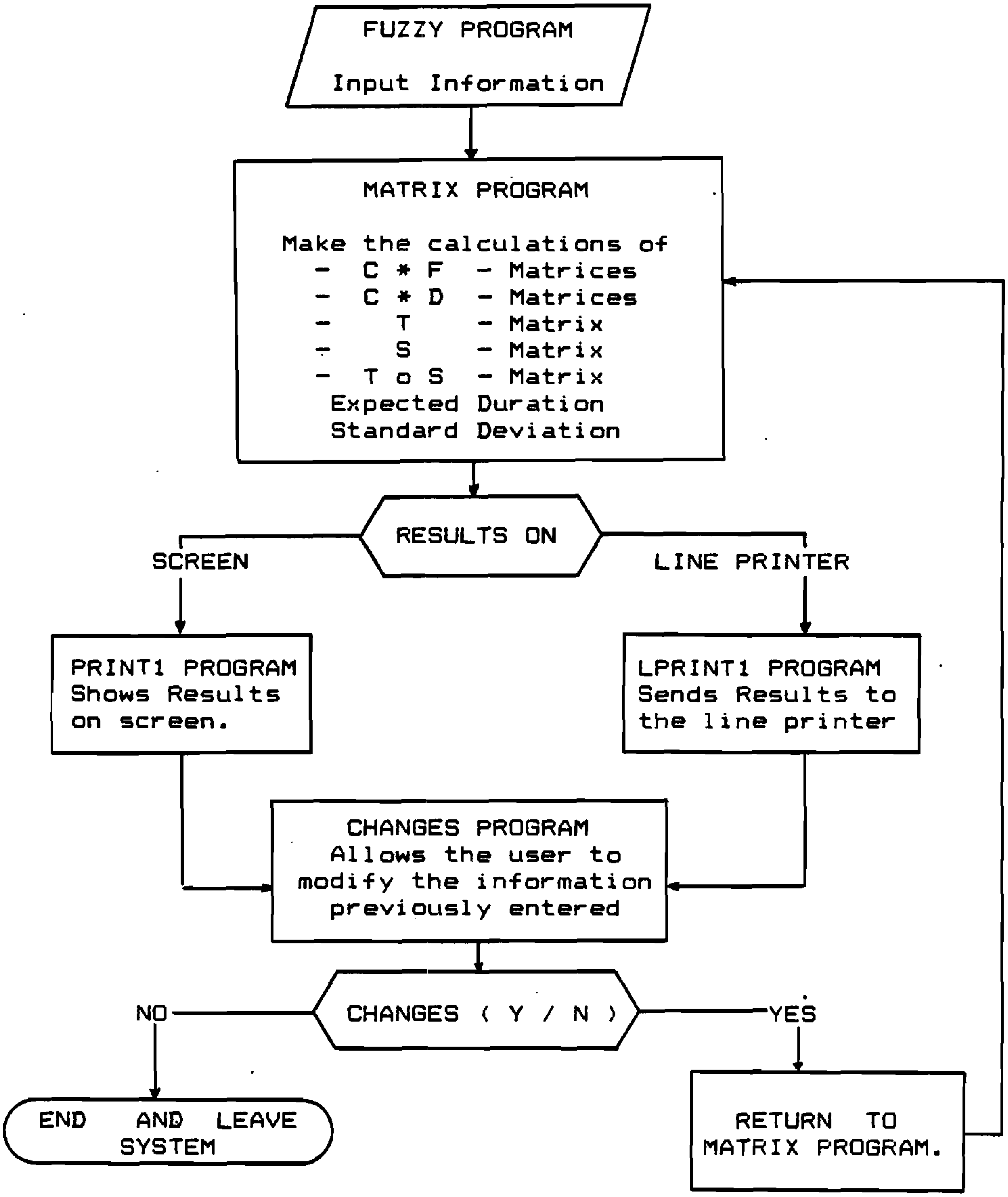
Fuzzy Set Analysis of Construction Risk

Dr. Roozbeh Kangari

School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

Fuzzy Set Program #117

Computer Program Flow Chart



TUTORIAL EXAMPLE

```
A>BASICA B:FUZZY

          ________________________________________
           F U Z Z Y   S E T S   P R O G R A M
          ________________________________________

Enter the DECISION ELEMENT      =? DURATION
Enter the OBJECTIVE FUNCTION    =? COST
How many LINGUISTIC VARIABLES do you have =? 2

Enter a LINGUISTIC VARIABLE    =? WEATHER
Enter the LINGUISTIC VALUES associated with this L.V. =? BAD
Enter the LINGUISTIC VALUES associated with this L.V. =? NORMAL
Enter the LINGUISTIC VALUES associated with this L.V. =? GOOD

Enter a LINGUISTIC VARIABLE    =? EXPERIENCE
Enter the LINGUISTIC VALUES associated with this L.V. =? LOW
Enter the LINGUISTIC VALUES associated with this L.V. =? MEDIUM
Enter the LINGUISTIC VALUES associated with this L.V. =? HIGH




 ___________________________________________________________

                      S U M M A R Y
 ___________________________________________________________
 DECISION ELEMENT   = DURATION
 OBJECTIVE FUNCTION = COST
-------------------------------------------------------------
 LINGUISTIC VARIABLE | ASSOCIATED LING. VALUES | POSITION
-------------------------------------------------------------
  1 )-WEATHER
                        BAD                        1 , 1
                        NORMAL                     1 , 2
                        GOOD                       1 , 3

  2 )-EXPERIENCE
                        LOW                        2 , 4
                        MEDIUM                     2 , 5
                        HIGH                       2 , 6
 ___________________________________________________________

Do you want to make corrections. ( Y / N )?
```

Enter GENERAL LINGUISTIC VALUES and their respective LIMITS

```
Enter a GENERAL LINGUISTIC VALUE        =? SMALL
Enter the LOWER LIMIT of this L. V.     =? 0
Enter the UPPER LIMIT of this L. V.     =? 3

Enter a GENERAL LINGUISTIC VALUE        =? MEDIUM
Enter the LOWER LIMIT of this L. V.     =? 4
Enter the UPPER LIMIT of this L. V.     =? 7

Enter a GENERAL LINGUISTIC VALUE        =? LARGE
Enter the LOWER LIMIT of this L. V.     =? 8
Enter the UPPER LIMIT of this L. V.     =? 10
```

Enter associated MEMBERSHIP VALUES

```
General Linguistic Value         =SMALL
Associated Uncertainty Grade     = 0
Enter MEMBERSHIP VALUE           =? 1

General Linguistic Value         =SMALL
Associated Uncertainty Grade     = 1
Enter MEMBERSHIP VALUE           =? .7

General Linguistic Value         =SMALL
Associated Uncertainty Grade     = 2
Enter MEMBERSHIP VALUE           =? .5

General Linguistic Value         =SMALL
Associated Uncertainty Grade     = 3
Enter MEMBERSHIP VALUE           =? .2
```

Enter associated MEMBERSHIP VALUES

```
General Linguistic Value         =MEDIUM
Associated Uncertainty Grade     = 4
Enter MEMBERSHIP VALUE           =? .3

General Linguistic Value         =MEDIUM
Associated Uncertainty Grade     = 5
Enter MEMBERSHIP VALUE           =? .8

General Linguistic Value         =MEDIUM
Associated Uncertainty Grade     = 6
Enter MEMBERSHIP VALUE           =? 1

General Linguistic Value         =MEDIUM
Associated Uncertainty Grade     = 7
Enter MEMBERSHIP VALUE           =? .6
```

Enter associated MEMBERSHIP VALUES

General Linguistic Value =LARGE
Associated Uncertainty Grade = 8
Enter MEMBERSHIP VALUE =? .7

General Linguistic Value =LARGE
Associated Uncertainty Grade = 9
Enter MEMBERSHIP VALUE =? .9

General Linguistic Value =LARGE
Associated Uncertainty Grade = 10
Enter MEMBERSHIP VALUE =? 1

LINGUISTIC VALUE	UNCERTAINTY GRADE	MEMBERSHIP VALUE	POSITION
1 -SMALL	0	1	1 , 0
1 -SMALL	1	.7	1 , 1
1 -SMALL	2	.5	1 , 2
1 -SMALL	3	.2	1 , 3
2 -MEDIUM	4	.3	2 , 4
2 -MEDIUM	5	.8	2 , 5
2 -MEDIUM	6	1	2 , 6
2 -MEDIUM	7	.6	2 , 7
3 -LARGE	8	.7	3 , 8
3 -LARGE	9	.9	3 , 9
3 -LARGE	10	1	3 , 10

Do you want to make corrections (Y / N)? NO

F U Z Z Y S E T T A B L E (Relations)

You have to enter the FREQUENCY OF OCCURRENCE of the Linguistic variables, the CONSEQUENCE on the OBJECTIVE FUNCTION, and the EFFECT on the DECISION ELEMENT.

Linguistic Variable = WEATHER
Linguistic Value = BAD

Enter FREQUENCY OF OCCURRENCE = ? SMALL
Enter CONSEQUENCE ON OBJECTIVE F. =? LARGE
Enter EFFECT ON DECISION ELEMENT =? LARGE

```
---------------------------------------
Linguistic Variable = WEATHER
Linguistic Value    = NORMAL
---------------------------------------
Enter FREQUENCY OF OCCURRENCE = ? MEDIUM
Enter CONSEQUENCE ON OBJECTIVE F. =? MEDIUM
Enter EFFECT ON DECISION ELEMENT  =? MEDIUM

---------------------------------------
Linguistic Variable = WEATHER
Linguistic Value    = GOOD
---------------------------------------
Enter FREQUENCY OF OCCURRENCE = ? MEDIUM
Enter CONSEQUENCE ON OBJECTIVE F. =? SMALL
Enter EFFECT ON DECISION ELEMENT  =? SMALL
```

F U Z Z Y S E T T A B L E (Relations)

```
You have to enter the FREQUENCY OF OCCURRENCE
of the Linguistic variables, the CONSEQUENCE
on the OBJECTIVE FUNCTION, and the EFFECT on
the DECISION ELEMENT.

---------------------------------------
Linguistic Variable = EXPERIENCE
Linguistic Value    = LOW
---------------------------------------
Enter FREQUENCY OF OCCURRENCE = ? LARGE
Enter CONSEQUENCE ON OBJECTIVE F. =? MEDIUM
Enter EFFECT ON DECISION ELEMENT  =? LARGE

---------------------------------------
Linguistic Variable = EXPERIENCE
Linguistic Value    = MEDIUM
---------------------------------------
Enter FREQUENCY OF OCCURRENCE = ? MEDIUM
Enter CONSEQUENCE ON OBJECTIVE F. =? SMALL
Enter EFFECT ON DECISION ELEMENT  =? SMALL

---------------------------------------
Linguistic Variable = EXPERIENCE
Linguistic Value    = HIGH
---------------------------------------
Enter FREQUENCY OF OCCURRENCE = ? SMALL
Enter CONSEQUENCE ON OBJECTIVE F. =? SMALL
Enter EFFECT ON DECISION ELEMENT  =? SMALL
```

F U Z Z Y   S E T   T A B L E   S U M M A R Y

Pos.	LINGUISTIC VARIABLES	GENERAL LINGUISTIC VALUES: FREQUENCY	CONSEQUENCE	DECISION
1 , 1 -	WEATHER BAD	SMALL	LARGE	LARGE
1 , 2 -	WEATHER NORMAL	MEDIUM	MEDIUM	MEDIUM
1 , 3 -	WEATHER GOOD	MEDIUM	SMALL	SMALL
2 , 4 -	EXPERIENCE LOW	LARGE	MEDIUM	LARGE
2 , 5 -	EXPERIENCE MEDIUM	MEDIUM	SMALL	SMALL
2 , 6 -	EXPERIENCE HIGH	SMALL	SMALL	SMALL

Do you want to make corrections (Y / N)? NO

Enter DURATION associated with uncertainty grades.

Position No.	UNCERTAINTY GRADE	
0)-	0	Enter associated DURATION = ? 30
1)-	1	Enter associated DURATION = ? 32
2)-	2	Enter associated DURATION = ? 35
3)-	3	Enter associated DURATION = ? 37
4)-	4	Enter associated DURATION = ? 40
5)-	5	Enter associated DURATION = ? 43
6)-	6	Enter associated DURATION = ? 45
7)-	7	Enter associated DURATION = ? 47
8)-	8	Enter associated DURATION = ? 49
9)-	9	Enter associated DURATION = ? 51
10)-	10	Enter associated DURATION = ? 53

ASSOCIATED DURATIONS SUMMARY

Post. No.	Uncertainty G.	DURATION
0)-	0	30
1)-	1	32
2)-	2	35
3)-	3	37
4)-	4	40
5)-	5	43
6)-	6	45
7)-	7	47
8)-	8	49
9)-	9	51
10)-	10	53

Do you want to make corrections (Y / N)? NO

```
Do you want PARTIAL RESULTS ( Y / N )? YES
Do you want a PRINT OUT ( Y / N )? YES



 Please  TURN  THE PRINTER ON
 Press RETURN when ready ?
```

FUZZY SET TABLE SUMMARY

LINGUISTIC VARIABLES	GENERAL LINGUISTIC VALUES		
	FREQUENCY	CONSEQUENCE COST	DECISION DURATION
WEATHER BAD	SMALL	LARGE	LARGE
WEATHER NORMAL	MEDIUM	MEDIUM	MEDIUM
WEATHER GOOD	MEDIUM	SMALL	SMALL
EXPERIENCE LOW	LARGE	MEDIUM	LARGE
EXPERIENCE MEDIUM	MEDIUM	SMALL	SMALL
EXPERIENCE HIGH	SMALL	SMALL	SMALL

MEMBERSHIP VALUES TABLE

LINGUISTIC VALUE	UNCERTAINTY GRADES	MEMBERSHIP VALUES
SMALL	0	1
SMALL	1	.7
SMALL	2	.5
SMALL	3	.2
MEDIUM	4	.3
MEDIUM	5	.8
MEDIUM	6	1
MEDIUM	7	.6
LARGE	8	.7
LARGE	9	.9
LARGE	10	1

ASSOCIATED DURATIONS

0	1	2	3	4	5	6	7	8	9	10
30	32	35	37	40	43	45	47	49	51	53

MATRIX - C * F - Number = 1

	0	1	2	3	4	5	6	7	8	9	10
[0 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.9	1.0
[1 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.7
[2 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5
[3 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2
[4 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[5 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[6 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[7 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[8 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[9 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[10 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

MATRIX - C * F - Number = 2

	0	1	2	3	4	5	6	7	8	9	10
[0 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[1 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[2 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[3 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[4 :	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.3	0.0	0.0	0.0
[5 :	0.0	0.0	0.0	0.0	0.3	0.8	0.8	0.6	0.0	0.0	0.0
[6 :	0.0	0.0	0.0	0.0	0.3	0.8	1.0	0.6	0.0	0.0	0.0
[7 :	0.0	0.0	0.0	0.0	0.3	0.6	0.6	0.6	0.0	0.0	0.0
[8 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[9 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[10 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

MATRIX - C * F - Number = 3

	0	1	2	3	4	5	6	7	8	9	10
[0 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[1 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[2 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[3 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[4 :	0.3	0.3	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[5 :	0.8	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[6 :	1.0	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[7 :	0.6	0.6	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[8 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[9 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[10 :	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

MATRIX - C * F - Number = 4

	0	1	2	3	4	5	6	7	8	9	10
[0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[8	0.0	0.0	0.0	0.0	0.3	0.7	0.7	0.6	0.0	0.0	0.0]
[9	0.0	0.0	0.0	0.0	0.3	0.8	0.9	0.6	0.0	0.0	0.0]
[10	0.0	0.0	0.0	0.0	0.3	0.8	1.0	0.6	0.0	0.0	0.0]

MATRIX - C * F - Number = 5

	0	1	2	3	4	5	6	7	8	9	10
[0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[4	0.3	0.3	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[5	0.8	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[6	1.0	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[7	0.6	0.6	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]

MATRIX - C * F - Number = 6

	0	1	2	3	4	5	6	7	8	9	10
[0	1.0	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[1	0.7	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[2	0.5	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[3	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]

MATRIX - C * D - Number = 1

	0	1	2	3	4	5	6	7	8	9	10
[0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.7]
[9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.9	0.9]
[10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.9	1.0]

MATRIX - C * D - Number = 2

	0	1	2	3	4	5	6	7	8	9	10
[0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[4	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.3	0.0	0.0	0.0]
[5	0.0	0.0	0.0	0.0	0.3	0.8	0.8	0.6	0.0	0.0	0.0]
[6	0.0	0.0	0.0	0.0	0.3	0.8	1.0	0.6	0.0	0.0	0.0]
[7	0.0	0.0	0.0	0.0	0.3	0.6	0.6	0.6	0.0	0.0	0.0]
[8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]

MATRIX - C * D - Number = 3

	0	1	2	3	4	5	6	7	8	9	10
[0	1.0	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[1	0.7	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[2	0.5	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[3	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]

MATRIX - C * D - Number = 1

	0	1	2	3	4	5	6	7	8	9	10
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.7
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.9	0.9
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.9	1.0

MATRIX - C * D - Number = 2

	0	1	2	3	4	5	6	7	8	9	10
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.3	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.3	0.8	0.8	0.6	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.3	0.8	1.0	0.6	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.3	0.6	0.6	0.6	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

MATRIX - C * D - Number = 3

	0	1	2	3	4	5	6	7	8	9	10
0	1.0	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.7	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.5	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

MATRIX - C * D - Number = 4

	0	1	2	3	4	5	6	7	8	9	10
[0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.3]
[5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.8	0.8]
[6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.9	1.0]
[7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.6	0.6]
[8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]

MATRIX - C * D - Number = 5

	0	1	2	3	4	5	6	7	8	9	10
[0	1.0	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[1	0.7	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[2	0.5	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[3	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]

MATRIX - C * D - Number = 6

	0	1	2	3	4	5	6	7	8	9	10
[0	1.0	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[1	0.7	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[2	0.5	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[3	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]
[10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0]

- T - MATRIX 1

	0	1	2	3	4	5	6	7	8	9	10
0	1.0	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.7	0.9	1.0
1	0.7	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.7	0.7	0.7
2	0.5	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.5	0.5	0.5
3	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.2	0.2	0.2
4	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.0	0.0	0.0
5	0.8	0.7	0.5	0.2	0.3	0.8	0.8	0.6	0.0	0.0	0.0
6	1.0	0.7	0.5	0.2	0.3	0.8	1.0	0.6	0.0	0.0	0.0
7	0.6	0.6	0.5	0.2	0.3	0.6	0.6	0.6	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.3	0.7	0.7	0.6	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.3	0.8	0.9	0.6	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.3	0.8	1.0	0.6	0.0	0.0	0.0

- S - MATRIX 1

	0	1	2	3	4	5	6	7	8	9	10
0	1.0	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.7	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.5	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.3	0.3	0.3	0.3
5	0.0	0.0	0.0	0.0	0.3	0.8	0.8	0.6	0.7	0.8	0.8
6	0.0	0.0	0.0	0.0	0.3	0.8	1.0	0.6	0.7	0.9	1.0
7	0.0	0.0	0.0	0.0	0.3	0.6	0.6	0.6	0.6	0.6	0.6
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.7
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.9	0.9
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.9	1.0

Combined - ToS - MATRIX (Frequency / Duration) 1

	0	1	2	3	4	5	6	7	8	9	10		
0	1.0	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.7	0.9	1.0	5.0	0.0
1	0.7	0.7	0.5	0.2	0.0	0.0	0.0	0.0	0.7	0.7	0.7	4.2	4.2
2	0.5	0.5	0.5	0.2	0.0	0.0	0.0	0.0	0.5	0.5	0.5	3.2	6.4
3	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.2	0.2	0.2	1.4	4.2
4	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.2	12.8
5	0.8	0.7	0.5	0.2	0.3	0.8	0.8	0.6	0.7	0.8	0.8	7.0	35.0
6	1.0	0.7	0.5	0.2	0.3	0.8	1.0	0.6	0.7	0.9	1.0	7.7	46.2
7	0.6	0.6	0.5	0.2	0.3	0.6	0.6	0.6	0.6	0.6	0.6	5.8	40.6
8	0.0	0.0	0.0	0.0	0.3	0.7	0.7	0.6	0.7	0.7	0.7	4.4	35.2
9	0.0	0.0	0.0	0.0	0.3	0.8	0.9	0.6	0.7	0.9	0.9	5.1	45.9
10	0.0	0.0	0.0	0.0	0.3	0.8	1.0	0.6	0.7	0.9	1.0	5.3	53.0

FINAL RESULTS TABLE

Duration		Probability	
30	----->	0.000	0.00 %
32	----->	0.000	0.00 %
35	----->	0.000	0.00 %
37	----->	0.000	0.00 %
40	----->	0.057	5.66 %
43	----->	0.151	15.09 %
45	----->	0.189	18.87 %
47	----->	0.113	11.32 %
49	----->	0.132	13.21 %
51	----->	0.170	16.98 %
53	----->	0.189	18.87 %

Expected Value (days) = 47.70 --> 48 (days)
Standard Deviation (days) = 3.94 --> 4 (days)

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Please WAIT a few seconds
============================================================
=                     CHANGES  MENU                         =
=-----------------------------------------------------------=
= 1)- CHANGE GENERAL LINGUISTIC VALUES , their respective   =
=     LIMITS , and MEMBERSHIP VALUES.                       =
= 2)- CHANGE FUZZY SET RELATIONS (Frequency , Consequence , =
=     and Decision Element).                                =
= 3)- CHANGE ASSOCIATED DURATIONS.                          =
=-----------------------------------------------------------=
= 4)- TO SOLVE                                              =
= 5)- TO END and LEAVE THE SYSTEM                           =
============================================================
Enter ONE of above ( 1 , 2 , 3 , 4 , 5 )? 5


A>
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NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I—PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
School of Civil Engineering Georgia Institute of Technology Atlanta, GA 30332	Structures & Build. System	CEE-8404430
	4. Award Period (Report) From 6/1/84 To 2/28/87	5. Cumulative Award Amount $48,000.

6. Project Title

"Construction Risk Analysis"

PART II—SUMMARY OF COMPLETED PROJECT (FOR PUBLIC USE)

The main objective of this research was to develop a methodology for evaluating risk of a construction project based on fuzzy set theory in order to translate qualitative uncertainty variables into a mathematical model. In most construction projects it is difficult or even impossible to collect sufficient information to develop a statistical pattern for probabilistic analysis. Many of the uncertainty factors are expressed in qualitative or linguistic terms instead of quantitative terms. Two risk analysis models were developed during this research. The first model evaluates the overall risk of a construction risk, and the second model estimates the impact of uncertainty factors on duration of a project. It was concluded that fuzzy set theory is an appropriate tool for construction risk analysis. The implementation of the fuzzy set theory presents two major problems, first: how to associate a label to an unlabeled fuzzy set on the basis of semantic similarity (linguistic approximation), and second: how to perform arithmetic operations with fuzzy numbers. It was also concluded that there is a lack of adequate tools available for evaluating the membership values of a fuzzy set. The developed models have solved some of the problems of present mathematical models, and have developed a stronger theoretical base for other research areas such as productivity analysis.

PART III—TECHNICAL INFORMATION (FOR PROGRAM MANAGEMENT USES)

1. ITEM (Check appropriate blocks)	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM Check (✓)	Approx. Date
a. Abstracts of Theses					
b. Publication Citations					
c. Data on Scientific Collaborators					
d. Information on Inventions					
e. Technical Description of Project and Results					
f. Other (specify)					

2. Principal Investigator/Project Director Name (Typed)	3. Principal Investigator/Project Director Signature	4. Date
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FINAL RESEARCH INITIATION REPORT

NSF GRANT NO. CEE-8404430

CONSTRUCTION RISK ANALYSIS

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February 24, 1987

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VII. Final Comprehensive Research Project Report

1. INTRODUCTION:

A comprehensive report of the research project based on the major items in the original proposal schedule is given in the following sections. In effect, all items scheduled for work during the two years have been commenced and satisfactory progress has been achieved.

2. OBJECTIVES AND SCOPE OF THE RESEARCH PROJECT:

The main objective of this research was to develop a methodology for evaluating risk and uncertainty of a construction project based on fuzzy set theory in order to translate qualitative uncertainty variables into mathematical model.

Two fuzzy set models for construction risk analysis was developed which evaluate an index for the level of uncertainty by available linguistic information. These models have solved some of the problems of present mathematical models, and have developed a strong theoretical base for other research areas such as productivity analysis.

3. DEVELOPMENT OF RISK ANALYSIS MODELS:

Two risk analysis models were developed during this research. The first model evaluates the overall risk of a construction risk, and the second model estimates the impact of uncertainty factors on duration or production of a project. Both methods implement fuzzy set theory which allows linguistic analysis of risk of construction projects. The following sections (3.1, and 3.2) describe in more detail the application of these methods.

3.1 Construction Risk Analysis by Fuzzy Sets (First Model):

The evaluation and analysis of risk associated with a construction project is a topic of great practical and theoretical interest. It is of practical interest because risks associated with construction projects are potentially serious and have high financial and social impact on major parties involved in the project. It is of theoretical interest because it is a complex and difficult problem to model.

There are various techniques for the evaluation and analysis of risk. In general, they can be categorized as: 1) probabilistic models; and 2) conceptual models. The probabilistic models are based on the principles of probability theory which provides the necessary tools to evaluate a project's uncertainty. In these models, the uncertainty factors are expressed in quantitative terms (numerical data). The conceptual models are expressed in qualitative or linguistic terms (linguistic data) which is based on the past experience of decision-maker. A promising approach in dealing with nonstatistical uncertainties is based on the theory of sets. The theory allows for the input of natural language expressions as opposed to the numerical input by the classical probabilistic models.

In most construction projects it is difficult or even impossible to collect sufficient information to develop a statistical pattern for probabilistic analysis. Many of the uncertainty factors are expressed in qualitative or linguistic terms instead of quantitative terms. Many contractors have little knowledge about probablistic concepts, therefore, they can not express themselves in the required mathematical terms. However, they can use natural language in any dialogue to express their feelings and analyze the uncertainty factors. When information about risk is captured in natural language, the linguistic variables (words) are modeled based on the fuzzy set theory. Since much of the uncertainty which is intrinsic in construction risk is rooted in the fuzziness of the information (a property of natural language), therefore, fuzzy set technique seems useful for understanding and expressing the construction uncertainty factors. The main goal of this part is to develop a conceptual framework for the analysis of complex or ill-defined construction uncertainty factors expressed in linguistic terms.

One reason for this effort is to provide the most natural and easily learned input method for construction risk analysis. This allows the analyst to communicate with the people in construction field and aquire further information about the uncertainty factors based on everyday conversation. The second reason for developing this model is to provide a fundamental base for the development of a knowledge-based expert systems in construction risk analysis by natural language. This will allow the contractors to communicate with the super computer programs developed based on expert systems to reach the level of performance of a human expert in the construction risk domain.

3.1.1 Background

In 1965, Zadeh introduced the concept of a fuzzy set as a model of a vague fact [24,26,27]. Fuzzy set theory is a generalization of ordinary set theory which provides an adequate conceptual framework as well as a mathematical tool to solve real physical world problems which are usually fuzzy. Zadeh's analysis led him to two basic observations. First, humans had a capability to understand and analyze imprecise concepts which were not properly understood by existing analytical methods. Second, current methodologies showed a concern for precise representation of certain system aspects that were irrelevant to the system understanding objectives.

Since its inception, the theory of fuzzy sets has evolved in many directions, and is finding applications in a wide variety of fields [5,6,8,18,20]. However, its application to construction engineering and management has not yet fully explored. Ayyab and Haldar [1] applied the fuzzy set concepts to project scheduling. In another paper, Nguyen [21] applied the theory to a decision model for selecting bid contracts. Koehn [17] worked on the utilization of fuzzy sets to the complex problems of building or facility satisfaction and productivity on a construction site. However, no significant work in construction risk analysis by fuzzy sets has been conducted. The purpose of this part is to provide a basic framework for the utilization of the theory in construction risk analysis.

3.1.2 Risk Evaluation Techniques

There are various methods of risk evaluation of construction projects. However, in general they can be categorized as: 1) Classical models (i.e., probabilistic analysis); and 2) Conceptual models (i.e., fuzzy set analysis). As shown in Fig. 1, some of the probabilistic factors affecting a construction project are data based. That is, sufficient numerical information is available for a statistical characterization of these factors. However, some other probabilistic factors do not have enough information to develop a statistical pattern. They need to be updated as information becomes available. In this case, the statistical Bayesian updating approach can be used.

Although, these classical models are useful for risk analysis, they are limited in their applicability to real construction risk analysis where nearly all real contractor's decision problems are imprecise,

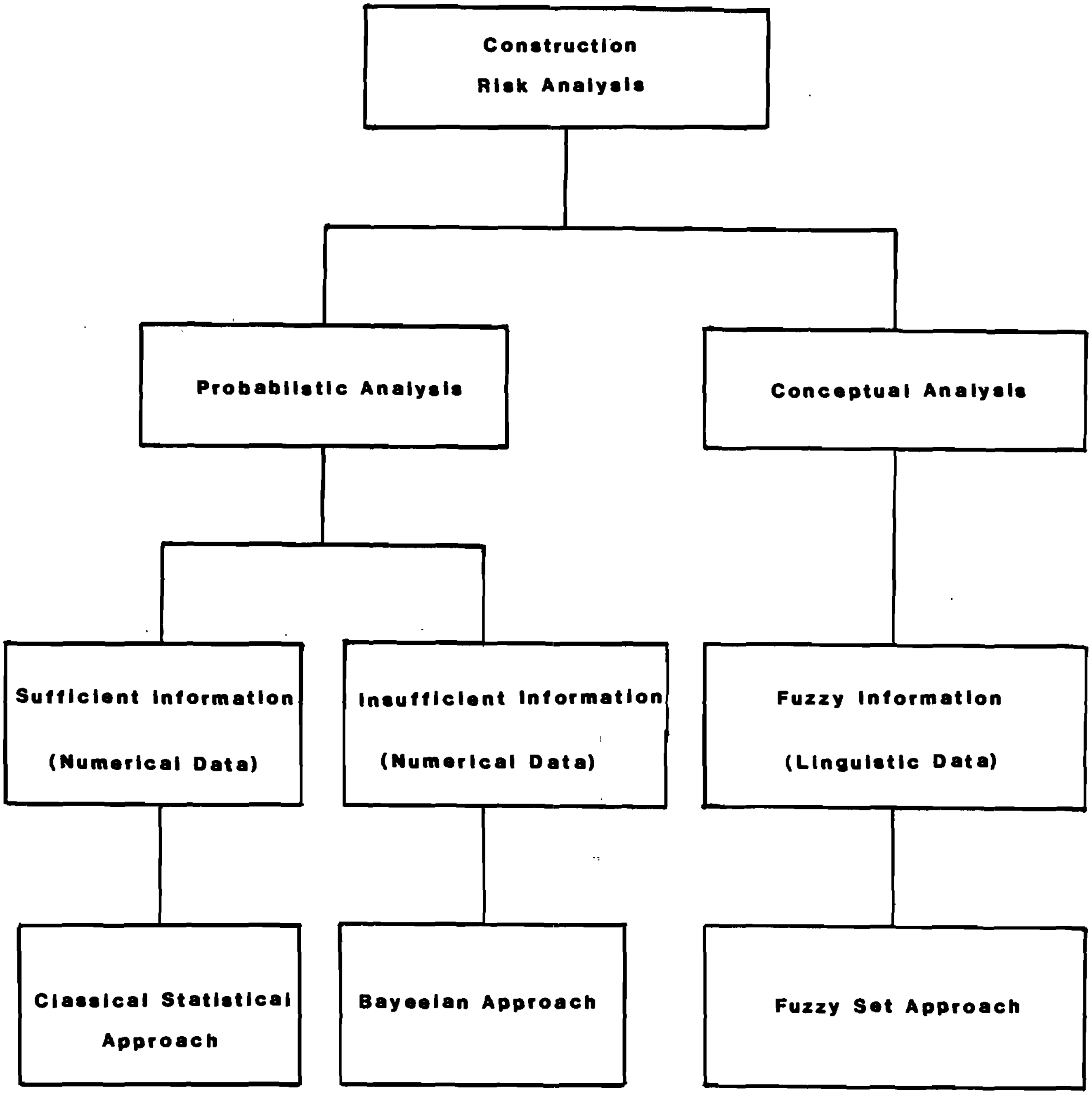


FIG. 1.- Interrelationship of Risk Analysis Techniques

ill-defined and vague in nature. The imprecision, ill-definedness and vagueness that tend to characterized various construction problems are predominantly subjective and linguistic in their nature.

In the real construction world, there are many situations where the quantitative and detailed information to evaluate uncertainty is not available. These conceptual factors can be expressed in qualitative or linguistic terms, that is, so called fuzzy information. Uncertainty factors such as "bad weather", "poor design", or "weak management" fall into this category [3,16]. Direct analysis of these linguistic factors are often neglected in classical construction risk analysis techniques. One of the major objectives of this paper is to describe how linguistic fuzzy variables can be translated into mathematical measures using fuzzy set theory. This part of research attempts to establish the basic feasibility of using fuzzy set concepts in the construction risk analysis. Certain simplifications have been made to ease an understanding of the most important features of the theory.

3.1.3 Concepts of Fuzzy Set Theory

A fuzzy set is class of objects with a continuum of grades of membership. Such a set is characterized by a membership function which assigns to each object a grade of membership ranging between zero and one. A fuzzy set A in universe X is characterized by a membership value $\mu_A(x)$ which associates with each point in X a real number in the interval [0,1] as follows:

$$A = \lfloor x \mid \mu_A(x) \rfloor \qquad (1)$$

in which A = a fuzzy set; $\mu_A(x)$ = a membership value between zero and one; and x = a generic element of universe X.

The union of fuzzy sets A and B of a universe X, is experessed by the operation, A 'or' B as follow:

$$\mu_{AUB}(x) = \max[\mu_A(x), \mu_B(x)] \qquad (2)$$

in which U = union of sets.

The intersection of fuzzy sets A and B is expressed by the operation, A 'and' B as follow:

$$\mu_{A \cap B}(x) = \min[\mu_A(x), \mu_B(x)] \qquad (3)$$

in which $\cap$ = intersection of sets. These are basic notions relating to fuzzy sets which will be utilized by the proposed model using the Zodeh's extension principle. More detail of these equations can be found in [24,26,27]. The results of the extension principle are the following definitions of fuzzy addition, multiplication, and division. If A, and B are two fuzzy sets as follows:

$$A = [x \mid \mu_A(x)] \qquad (4)$$

$$B = [y \mid \mu_B(y)] \qquad (5)$$

in which x and y = elements of universe X, and universe Y respectively. Then:

$$A + B = [(x + y) \mid \min(\mu_A(x), \mu_B(y))] \quad (6)$$

$$A \times B = [(x \times y) \mid \min(\mu_A(x), \mu_B(y))] \quad (7)$$

$$A \div B = [(x \div y) \mid \min(\mu_A(x), \mu_B(u))] \quad (8)$$

In most cases, $A \div B$ must be approximated. One approach is to reduce this set over the integers by deleting any element not over an integer base [7,8,11,27].

It is not feasible to perform the calculations by hand if the universe over which fuzzy sets are defined are large. Many fuzzy set applications are done in APL (A Programming Language), a computer language that allows very flexible vector manipulations and in particular allows vectors to grow in length [6,9].

3.1.4 Linguistic Approach to Risk Analysis

Fuzzy set analysis of risk presents a linguistic approach to the uncertainty analysis of construction projects that allows neutral language expressions be analyzed. The model consists of three parts: 1) Natural Language Computation by Fuzzy Set Theory; 2) Fuzzy Set Evaluation of Risk; and 3) Linguistic Approximation.

Natural Language Computation

A linguistic variable is a variable whose values are not numbers but words or sentences in a natural or synthetic language. Fuzzy set theory provides a framework for dealing with such variables. Linguistic variables and fuzzy sets have the relationship of goal and tool. Manipulating natural language expressions is the goal, and fuzzy set theory is a tool to achieve that goal.

Thus, each word x in a natural language can be viewed as a summarized description of a fuzzy set A(x) of a universe of discourse U, which A(x) represents the meaning of x. For example, if the meaning of the noun 'management' is a fuzzy set A(management), and the meaning of the adjective 'bad' is a fuzzy set A(bad), then the meaning of phrase 'bad management' can be given by the intersection of A(bad) and A(management). Consider a set of natural language expressions that 'management' can take as: 'poor', 'average', and 'excellent'. Then the fuzzy sets of these variable based on integers between zero and ten can be evaluated as follow:

Poor Management =

$$[0\ |0.8,1\ |1.0,2\ |0.7,3\ |0.4,4\ |0.1,5\ |0.,6\ |0.,7\ |0.,8\ |0.,9\ |0.,10\ |0.] \qquad (9)$$

Average Management =

$$[0\ |0.,1\ |0.,2\ |0.2,3\ |0.5,4\ |0.8,5\ |1.0,6\ |0.8,7\ |0.5,8\ |0.2,9\ |0.,10\ |0.] \qquad (10)$$

Excellent Management =

$$[0\ |0.,1\ |0.,2\ |0.,3\ |0.,4\ |0.,5\ |0.,6\ |0.2,7\ |0.3,8\ |0.7,9\ |0.8,10\ |1.0] \qquad (11)$$

The positions of the elements in the arrays represent corresponding points in the universe of discourse. The number represents degree of membership of these points. In this way, the meaning of linguistic values as fuzzy sets of an appropriate psychological continuum can be modeled.

It should be noted that these definitions are provided by the user or the system designer based on his understanding of the linguistic variables.

If it is defined by the system designer, the assumption is that these definitions correspond in some way with the user's intuitive meaning for the terms, or a high correlation exists between the designer's fuzzy definitions and the user's intuitions.

Fuzzy Set Evaluation of Risk

The second part of model, evaluates the risk of an entire system based on the fuzzy estimate of the risk components. The model allows the user to provide a fuzzy estimate of the probability occurance and severity of loss of the lower components of risk. Then the uncertainty values of the lower levels are composed to generate the risk value of a higher level using the concepts of fuzzy set theory. These risk values are then combined with the fuzzy weighted factors of each componenet until all risk components are considered and the total risk is evaluated. The fuzzy weighted mean can be calculated as follows:

$$[R] = \frac{\Sigma[W_i]\ [R_i]}{\Sigma[W_i]} \qquad i = 1 \text{ to } n \qquad (12)$$

In which [R] = a fuzzy set which represents the fuzzy risk value of a higher level; n= total number of risk components; $[W_i]$ = fuzzy weight factor of lower level of component i; and $[R_i]$ = fuzzy risk value of lower level of component i. This equation uses the Zadeh's extension principle [7,24,26,27], a general method for extending functions over the integers to functions over fuzzy subsets based over the integers. The method of evalution was described in Eqs. 6,7, and 8.

To further illustrate this part of the model, assume the following simplified example in which the total risk of a construction project as shown in Fig. 2 is divided into two main components:
1) contractual risk; and 2) construction risk. Let us further assume that each of these components are divided into the small elements. For example, the uncertainties that generate the contractual risk are due to the: lack of contract clarity; and absence of communication. And the uncertainty

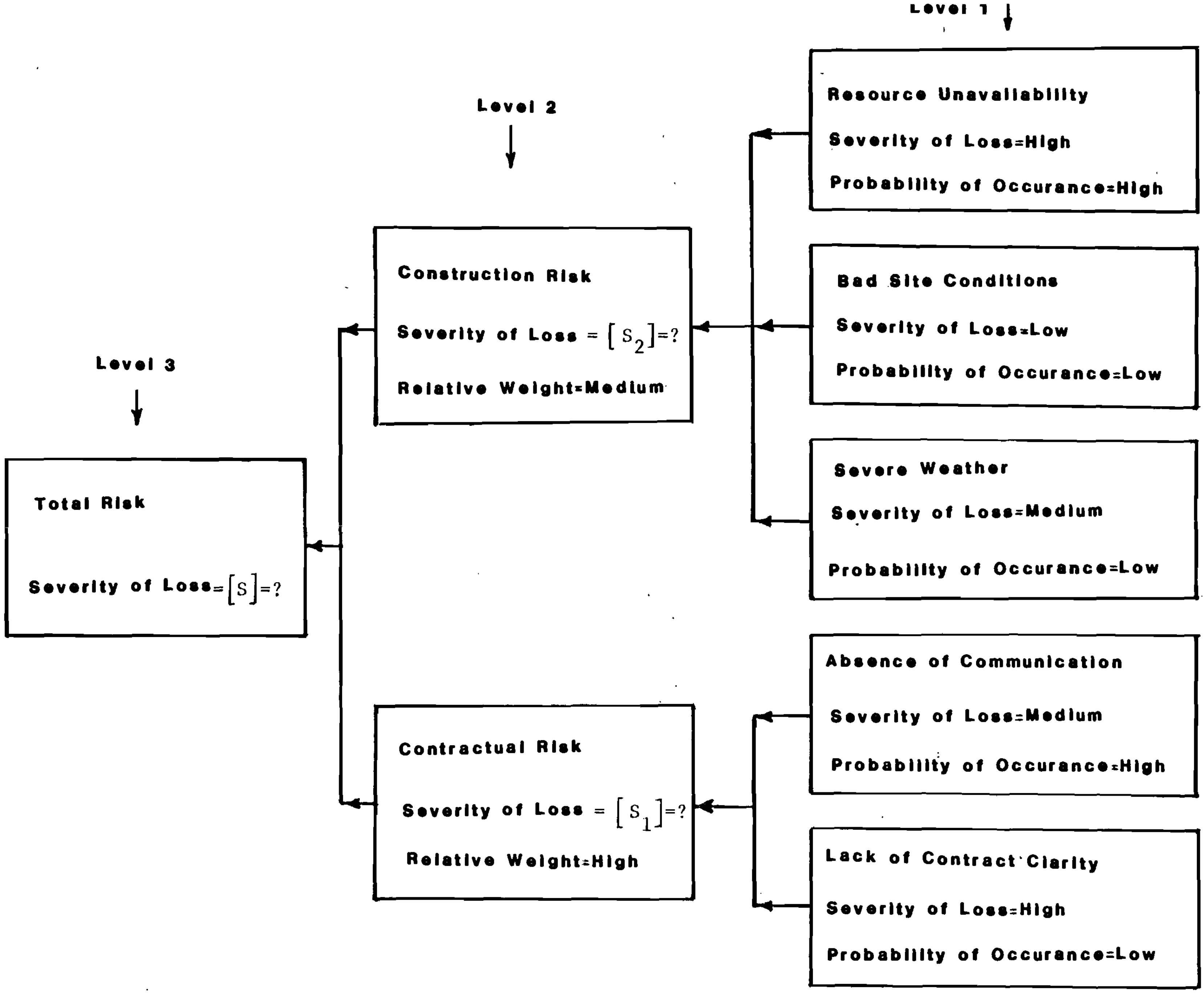


FIG. 2.- Structure of the Fuzzy Risk Analysis

components of the construction risk are: bad site conditions; resource unavailability; and severe weather conditions.

The next step is to describe linguisticaly (e.g., high, medium, low) the severity of loss of profit, and probability of occurence of each uncertainty factor at the lowest level. The probability of occurence is only described at the lowest level, the higher levels are defined by relative weights which show their importance compared to the other components. The severity of loss of higher levels are identified by a question mark, and are estimated based on Eq. 12 as follows:

$$[S_1] = \frac{[H][L] + [M][H]}{[L] + [H]} \qquad (13)$$

$$[S_2] = \frac{[M][L] + [L][L] + [H][H]}{[L] + [L] + [H]} \qquad (14)$$

in which $[S_1]$ and $[S_2]$ = fuzzy sets representing the severity of loss of the contractual and construction risks respectively; and [L], [M], [H] = fuzzy sets desciiing linguistic variable of Low, Medium, and High respectively. The estimated $[S_1]$ and $[S_2]$ fuzzy sets are then combined to calculate the total risk as follows:

$$[S] = \frac{[S_1]\ [H] + [S_2]\ [M]}{[H] + [M]} \qquad (15)$$

in which [S] = a fuzzy set representing the total severity of loss or total risk of the project. The objective of the next part of the model is to translate the estimated fuzzy set, [S], into a natural language expression.

Linguistic Approximation

The objective of this part is to find an appropriate natural language expression for the estimated fuzzy set, [S]. There are basically three techniques: 1) euclidean distance; 2) successive approximation; and 3) piecewise decomposition.

The first method is usually applied when the set of natural language expressions is small. It calculates the euclidean distance from the given fuzzy set to each of the fuzzy sets representing the natural language expressions. The distance between fuzzy set X (unknown), and fuzzy set A (known) can be calculated as follow:

$$d(X,A) = \left[\sum (X(i) - A(i))^2\right]^{1/2} \qquad i = 1 \text{ to } n \qquad (16)$$

in which d = euclidean distance between two fuzzy sets; i = an integer between 1 and n; n = an integer that defines the highest value of the fuzzy set universe [4,7,16].

The second method is applied when the set is large. This method assumes two close primary terms, then various expressions are applied to these two points in order to approximate the closest natural language expression [7,20]. The third method, divides the linguistic variables into intervals then each interval is combined with one of the standard logical connectives (e.g., and) to approximate the natural expression [18].

The last two methods are difficult to implement, and it is recommended that the first method (euclidean distance) be utilized. The proposed model is developed based on the first technique which identifies the closest natural expression by minimizing the euclidean distance.

3.1.5 Illustrative Example

To further clarify the proposed model, a simple numerical example will be used to explain the mechanics of the theory. It is assumed that the overall risk of a construction project is presented as Fig. 2. The severity of loss, and probability of occurence are described by linguistic variables. The objective is to evaluate the total risk, [S], of this project.

To calculate the risk in the universe over which fuzzy sets are defined between zero and ten as shown in Eqs. 9, 10, and 11 requires a computer program, and it is not feasible to perform the calculation by hand. Therefore, the universe is limited to [0,1,2,3] for the illustration purpose. The following definitions of fuzzy set variables are assumed (by the system engineer or user for the three natural language expressions in Fig. 2.

$$\text{Low} = \lfloor L \rfloor = \lfloor 0 \,|1.0, 1\, |0.6, 2\, |0.2, 3\, |0. \rfloor \qquad (17)$$

$$\text{Medium} = \lfloor M \rfloor = \lfloor 0 \,|0.3, 1\, |1.0, 2\, |1.0, 3\, |0.3 \rfloor \qquad (18)$$

$$\text{High} = \lfloor H \rfloor = \lfloor 0 \,|0.0, 1\, |0.2, 2\, |0.6, 3\, |1.0 \rfloor \qquad (19)$$

Then the components of Eqs. 13, and 14 can be evaluated based on Eqs. 6,7,8, and using the concepts of normalization and convexity [24,26,28] as follows:

$$[L] + [H] = [1 \,|0.2, 2 \,|0.6, 3 \,|1.0, 4 \,|0.6, 5 \,|0.2] \tag{20}$$

$$[L] + [L] + [H] = [2 \,|0.2, 3 \,|0.2, 4 \,|0.6, 6 \,|1.0, 7 \,|0.6, 8 \,|0.2] \tag{21}$$

$$[H] + [M] = [1 \,|0.2, 2 \,|0.3, 3 \,|0.6, 4 \,|1.0, 5 \,|1.0, 6 \,|0.3] \tag{22}$$

$$[H]\,[L] = [0 \,|1.0, 1 \,|0.8, 2 \,|0.6, 3 \,|0.6, 4 \,|0.2, 5 \,|0.2, 6 \,|0.2] \tag{23}$$

$$[M]\,[H] = [0 \,|0.3, 1 \,|0.45, 2 \,|0.6, 3 \,|1.0, 4 \,|1.0, 5 \,|1.0, 6 \,|1.0, 7 \,|0.77, 8 \,|0.54, 9 \,|0.3] \tag{24}$$

$$[M]\,[L] = [0 \,|1.0, 1 \,|0.6, 2 \,|0.6, 3 \,|0.3, 4 \,|0.2, 5 \,|0.2, 6 \,|0.2] \tag{25}$$

$$[L]\,[L] = [0 \,|1.0, 1 \,|0.6, 2 \,|0.2, 3 \,|0.2, 4 \,|0.2] \tag{26}$$

$$[H]\,[H] = [1 \,|0.2, 2 \,|0.2, 3 \,|0.2, 4 \,|0.6, 5 \,|0.6, 6 \,|0.6, 7 \,|0.74, 8 \,|0.87, 9 \,|1.0] \tag{27}$$

Then the fuzzy values of $[S_1]$ and $[S_2]$ can be calculated from Eqs. 13, and 14 as:

$$[S_1] = [0 \,|0.3, 1 \,|1.0, 2 \,|1.0, 3 \,|0.6] \tag{28}$$

$$[S_2] = [0 \,|0.0, 1 \,|1.0, 3 \,|0.34] \tag{29}$$

Then the total risk can be estimated from Eq. 15 as:

$$[S] = \frac{[S_1][H] + [S_2][M]}{[H] + [M]} \tag{30}$$

$$[S] = \frac{[1 \,|0.3, 1 \,|0.45, 2 \,|0.6, 3 \,|1.0, 4 \,|1.0, 5 \,|1.0, 6 \,|1.0, 7 \,|0.87, 8 \,|0.73, 9 \,|0.6]}{[1 \,|0.2, 2 \,|0.3, 3 \,|0.6, 4 \,|1.0, 5 \,|1.0, 6 \,|0.3]} \tag{31}$$

$= [0| 0.3, 1| 1.0, 2| 0.73, 3| 0.6]$

Using the euclidean method, the above fuzzy set result, [S], can be translated into natural language expression as described in Eq. 16.

$$d(S, Low) = [(0.3-1.0)^2 + (1.0-0.6)^2 + (0.73-0.2)^2 + (0.6-0.)^2]^{1/2} = 1.136 \quad (32)$$

$$d(S, Medium) = [(0.3-0.3)^2 + (1.0-1.0)^2 + (0.73-1.0)^2 + (0.6-0.3)^2]^{1/2} = 0.404 \quad (33)$$

$$d(S, High) = [(0.3-0.)^2 + (1.0-0.2)^2 + (0.73-0.6)^2 + (0.6-1.0)^2]^{1/2} = 0.952 \quad (34)$$

Among the three natural language expressions to choose from, Medium has the lowest distance (closest) to the fuzzy set, [S], resulted from overall risk. Therefore, it can be concluded that the total risk of this project is Medium. To comeup with more accurate linguistic description of the overall risk, two actions should be taken: 1) Increase the number of linguistic variables (i.e., Very Low, Low, Medium, Fairly High, and High); and 2) The universe of fuzzy terms should increase, for example, from zero to ten.

3.2 Construction Risk Analysis by Fuzzy Sets (Second Model):

In the past few years construction projects have acquired a superior degree of complexity due to the increasing needs of the modern world. This fact has forced construction managers to look toward more sophisticated estimating techniques.

In the construction industry exists several factors that introduce different degrees of uncertainty to the project's estimates. Generally, these factors are expressed in linguistic rather than mathematical terms. For this reason, the effects that these factors cause to the overall accuracy of the project's estimates are difficult to evaluate with the techniques currently used. Fortunately, these factors or linguistic factors, as they are denominated, can now be evaluated by using a new technique based on fuzzy set and system theory.

This recent technique allows construction managers to translate these linguistic factors into mathematical measures in order to incorporate them to the estimating process of a project.

3.2.1 OBJECTIVES

The main objective of this part is to develop a mathematical model for the analysis of linguistic variables in construction projects under conditions of uncertainty and risk. This model enables construction managers to evaluate the possible repercussions of linguistic factors, such as weather conditions and level of experience of a labor, in construction project estimates. This technique which is based on fuzzy set theory is principally used to translate the different linguistic factors encountered in the construction industry into mathematical expressions in order to facilitate their incorporation in the estimating process of a project.

A secondary objective of this paper is to introduce different approaches for data collection which is required by this technique.

The information obtained from this research will be finally used to develop a computer program which will permit construction managers an easy access to this technique in future applications.

3.2.2 HISTORICAL REMARKS

Fuzzy set theory was originated in the work of Lotfi A. Zadeh in 1965. Since then, it has blossomed into a many-faceted field of science inquiry, drawing on and contributing to a wide spectrum of areas ranging from pure mathematics and physics to medicine, linguistics, and philosophy.

Since 1965, fuzzy set theory has been considerably developed by Zadeh himself and some 300 researchers, such as Ronald Yager and Richard Bellman [2, and 22].

In the last few years, several other researchers have been interested in the applications of this theory in many different fields. In the construction industry for instance, E. Koehn [17] has studied the applications of fuzzy sets to complex problems of buildings or facility satisfaction on a construction site.

Van Uu Nguyen [21], developed a systematic procedure based on fuzzy set theory and multicriteria-decision modelling, for the selection of bid contracts.

Finally, B.M. Ayyub and A. Haldar [1], proposed a technique based on fuzzy set theory to incorporate and translate linguistic variables in construction project estimations.

3.2.3 BASIC PRINCIPLES OF FUZZY SET THEORY:

The industrialized world has been demanding more sophisticated and complicated buildings, factories, and other civil works, construction projects have been converted, in most of the cases, in huge and very complex enterprises. As a result of these increasing demands, construction projects have to be planned in great detail. Consequently, construction projects should be divided into several different activities which are ordered in a specific sequence according to the construction progress estimates and priorities of the project itself. These projects generally comprise a relatively large amount of resources which are required by activities at different stages of the project.

Several techniques have been developed to help construction managers to allocate the available resources in such a way that the cost and duration of a project could be minimized. These techniques, such as the program evaluation and review technique (PERT), and the critical path method (CPM) [11, and 12], require the estimation of the duration of each one of the activities involved in a project. Generally, the duration of an activity is estimated based on available statistical data from projects already built or on past experience of the people involved in the project. These estimates usually incorporate a certain degree of uncertainty to the project since several factors may differ from one project to another.

The current available techniques do not take into account such factors due to the fact that they are expressed in linguistic rather than mathematical terms. For this reason, the estimates obtained, when using these techniques, are sometimes far away from the actual values encountered during construction of a project.

These uncertainty factors play an important role in the accuracy of the project's estimates. However, a more complex situation is presented since the effect of these uncertainty factors on the activity's duration, production, or profitability is also expressed in linguistic terms. The effects of weather conditions in a particular activity for instance, could be expressed as good, normal, and bad introducing a new set of linguistic values to the evaluation problem. Fortunately, these linguistic values can be translated into mathematical measures by using fuzzy sets and systems theory [1,2, and 25]. Then, the results obtained can be incorporated to the current available techniques in order to obtain more accurate estimates of construction operations.

The concept of fuzzy sets theory that will be introduced in this section utilizes basic mathematical operations. For this reason, its application in different construction fields, especially in construction project scheduling is not a difficult task.

3.2.4 FUZZY SETS AND FUZZY STATEMENTS:

In the past few years, many researchers have been studying the problems of a decision-making process on a fuzzy or imprecise environment. The first mathematical approach to deal with this problem was introduced by Zadeh [25, and 27]. The basic principles of this mathematical approach or fuzzy set theory, as it was denominated, and its possible application to the different problems encountered in the construction industry will be explained in the following pages.

As mentioned before, several uncertainty factors are encountered in most of the construction projects. These factors can be expressed by words, phrases, and sentences. In other words, they are expressed in linguistic terms. For example, productivity levels of a particular operation can be defined as a linguistic variable since the different values that this linguistic variable can take are not expressed in a mathematical manner. Low, medium, and high are some of the possible values of this linguistic variable. These values are not defined mathematically but they represent a clear and conceptual linguistic classification.

Suppose that U represents an infinite number of elements, i.e., let U be a universe conformed by an infinite number of elements, x's, and let A be a subset of elements belonging to the universe U. A different membership value is then associated with each element of the subset A, Ua(x). Also suppose that the membership value is binary, either one or zero. In such a case, the subset A is said to be non-fuzzy or a crisp set since there are only two possibilities for an element x, Ua(x)=0 which represents non-membership of x in the subset A, and Ua(x)=1 which represents full-membership of x in the subset A. Contrarily, if the membership value is not binary, i.e., it is allowed to take any value in the interval (0,1). Then, the subset A is said to be a fuzzy set. Consequently, the membership x to A is fuzzy.

As an illustration, the level of experience of a construction labor is the linguistic variable x which is associated with the following linguistic values:

A = Short Experience.

B = Medium Experience.

C = Long Experience.

In order to translate the linguistic variable x into mathematical values, the following steps are required:

First, it is necessary to define an adequate grading scale for the different linguistic values, such as a scale from zero (0) to ten (10) in which a zero (0) grade represents no experience at all, and a ten (10) grade represents an excellent experience. Secondly, different membership values have to be assigned to each one of the diverse levels of experience.

After having defined the appropriate grading scale, the limits of each one of the linguistic values (Short, Medium, Long) associated with the linguistic variable (Level of Experience) can be defined. As a result, the limits of A, B, and C are defined as follows:

A = Short E.   Lower limit - Upper limit 3

B = Medium E.   Lower limit 4 - Upper limit 7

C = Long E.   Lower limit 8 - Upper limit 10

Graphical representation of the limits of the linguistic values are shown in Fig. 3.

Following this step, the different membership values can be assigned. These values are for illustrative purposes.

A = Short experience. =

{X0 = 0 Ua(X0) = 1.0 , X1 = 1 Ua(X1) = 0.8 ,
X2 = 2 Ua(X2) = 0.4 , X3 = 3 Ua(x3) = 0.1 ,
X4 = 4 Ua(X4) = 0.0 , X5 = 5 Ua(X5) = 0.0 ,
X6 = 6 Ua(X6) = 0.0 , X9 = 9 Ua(X9) = 0.0 ,
X10 = 10 Ua(X10) = 0.0}.

The membership values for X4, X5, X6, X7, X8, X9, and X10 are zero (0.0) since the upper limit of this linguistic value (Short) has been defined to be equal to three (3).

In a similar way, the membership values of the linguistic values B and C can be defined as follows:

B = Medium experience. =

{X4 = 4 Ub(X4) = 0.4 , X5 = 5 Ub(X5) = 0.8 ,
X6 = 6 Ub(X6) = 1.0 , X7 = 7 Ub(X7) = 0.6.}

C = Long experience. =

{X8 = 8 Uc(X8) = 0.3 , X9 = 9 Uc(X9) = 0.6,
X10 = 10 Uc(X10) = 1.0}.

Table 1 summarizes the membership values associated with the different linguistic values A, B, and C.

Generally, the membership values are assigned based on subjective judgement of experts in the subject and on available statistical data. It is important to give special emphasis to

```
0    1    2    3    4    5    6    7    8    9    10
|====|====|====|====|====|====|====|====|====|====|
|              |                   |              |
|---- SHORT ---|                   |              |
               |------ MEDIUM -----|              |
                                   |---- LONG ----|

|--------------> EXPERIENCE LEVEL -------------->|
```

FIG. 3

LINGUISTIC VARIABLE : LEVEL OF EXPERIENCE OF A LABOR											
Linguistic Values	Grading scale or x's values										
	0	1	2	3	4	5	6	7	8	9	10
	Membership values										
Short A	1.0	0.8	0.4	0.1	0	0	0	0	0	0	0
Medium B	0	0	0	0	0.4	0.8	1.0	0.6	0	0	0
Long C	0	0	0	0	0	0	0	0	0.3	0.6	1.0

TABLE 1

the way in which the membership values are assigned since they play an important role in fuzzy set theory. This topic will be studied in some detail in next chapters.

A general expression to represent any subset, A, conformed by, n, discrete values of, x, together with the membership values Ua(x), can be defined as follows:

$$\text{Subset } A = \{X0 \mid Ua(X) \ , X1 \mid Ua(X1) \ , \ldots, Xn \mid Ua(Xn)\}$$

where the equal sign (=) signifies "is identified with" and (|) is a delimiter.

Some operational rules have to be defined in order to apply fuzzy set theory in practical problems.

Operational Rules:

The membership function for the intersection, n, of two fuzzy subsets A and B belonging to a universe, U, is expressed by the operation, A "and" B, and it is defined as

$$U\, a \cap B\ (X) = \text{Max.}\ \{Ua(X),\ Ub(X)\}. \qquad (35)$$

Similarly, the membership function for the union, U, of two fuzzy subsets A and B belonging to a universe U, is expressed by the operation, A "or" B, and it is defined as

$$U\, A \cup B\ (X) = \text{Min.}\ \{Ua(X),\ Ub(X)\}. \qquad (36)$$

For example, the intersection of the fuzzy subset A, given in Table 1 and the subset D,

$$
R = (A \times B) \quad A \left\{ \begin{array}{c|cccc}
 & y1 & y2 & \cdots & ym \\
\hline
x1 & UR(x1,y1) & UR(x1,y2) & \cdots & UR(x1,ym) \\
x2 & UR(x2,y1) & UR(x2,y2) & \cdots & UR(x2,ym) \\
\vdots & \vdots & \vdots & & \vdots \\
xn & UR(xn,y1) & UR(xn,y2) & \cdots & UR(xn,ym)
\end{array} \right.
$$

Where UR(xi,yj) is the membership value for the ordered pair (xi,yj), and it represents the association grade between (xi,yj). UR(xi,yj) is calculated by choosing the minimum value between the membership value Ua(xi) and Ub(yj), as was formulated in Eq. 38. As an illustration, consider the fuzzy subset D = (Medium Productivity Level) and the fuzzy subset A = (Short Experience). In order to evaluate the effect that these two fuzzy subsets would introduce in the overall production of a particular project, they should be related. As defined earlier,

A = {0 | 1.0, 1 | 0.8, 2 | 0.4, 3 | 0.1}.

D = {0 | .1, 1 | .4, 2 | .6, 3 | .8, 4 | .9, 5 | 1.0}

the relation R = (A x B) can be calculated as follows:

by applying Eq. 38.

UR(0, 0) = Min. (1.0, 0.1) = 0.1
UR(0, 1) = Min. (1.0, 0.4) = 0.4
UR(0, 2) = Min. (1.0, 0.6) = 0.6
UR(0, 3) = Min. (1.0, 0.8) = 0.8
UR(0, 4) = Min. (1.0, 0.9) = 0.9
UR(0, 5) = Min. (1.0, 1.0) = 1.0

Following the same procedure, all UR(xi,yj) values are calculated. Then, the relation R = (A x d) can be expressed in matrix form as:

D = {0 | 1.0, 1 | 0.8, 2 | 0.6, 3 | 0.8, 4 | 0.9, 5 | 1.0}

is expressed as follows:

A n D = {0 | 1.0, 1 | 0.8, 2 | 0.6, 3 | 0.8, 4 | 0.9, 5 | 1.0}.

Consequently, the union of the fuzzy subsets A and D is expressed as follows:

A U D = {0 | 0.1, 1 | 0.4, 2 | 0.4, 3 | 0.1, 4 | 0.0, 5 | 0.0}.

Continuing with the operational rules, the complement of any fuzzy subset A, called not A, is denoted by A, and is given by the following equation:

$$U \bar{A} (X) = 1 - Ua(x). \qquad (37)$$

For example, the complement of the fuzzy subset A, $\bar{A}$ is expressed by:

$\bar{A}$ = {0 | 0.0, 1 | 0.2, 2 | 0.6, 3 | 0.9, 4 | 1.0,
5 | 1.0, 6 | 1.0, 7 | 1.0, 8 | 1.0, 9 | 1.0,
10 | 1.0}.

<u>Fuzzy Relations</u>

A fuzzy relation, R, or cartesian-product, A x B, between two different fuzzy subsets A and B, where A and B belong to a different universes X and Y, is expressed by the following equation:

$$U_R(Xi,Yj) = UAxB\ (Xi,Yj) = Min.\ Ua(Xi),\ Ub(Yj) \qquad (38)$$

This relation, R, can be expressed in a matrix form as follows:

A = R = (Short Experience), D = (Medium Productivity)

A \ D	0	1	2	3	4	5
0	0.1	0.4	0.6	0.8	0.9	1.0
1	0.1	0.4	0.6	0.8	0.8	0.8
2	0.1	0.4	0.4	0.4	0.4	0.4
3	0.1	0.1	0.1	0.1	0.1	0.1

Fuzzy compositions:

The different operational rules explained before can be applied to fuzzy relations. Consequently, the union U, of two fuzzy relations, R and S, has the following membership function:

$$U_{R \cup S}(x_i,y_j) = \text{Max.} \{U_R(x_i,y_j), U_S(x_i,y_j)\}. \qquad (39)$$

Similarly, the intersection, of two fuzzy relations, R and S, has the following membership function:

$$U_{R \cap S}(x_i,y_j) = \text{Min.} \{U_R(x_i,y_j), U_S(x_i,y_j)\} \qquad (40)$$

Suppose that R is a fuzzy relation between X and Y, and that S is also a fuzzy relation between Y and Z. Then, the composition of R and S, ($R \circ S$), is a fuzzy relation that can be calculated by utilizing the following membership function:

$$U_{R \circ S}(x_i,z_k) = \underset{y_j}{\text{Max.}} [\text{Min.} \{U_R(x_i,y_j) , U_S(y_j,z_k)\}] \qquad (41)$$

Finally, an interesting case of fuzzy composition is the composition of a fuzzy subset A with a fuzzy relation R. This composition can be calculated by using the following membership function:

$$U A \circ R(yt) = \underset{xi}{Max}. [Min. \{UA(xi), UR(xi,yt)\}] \qquad (42)$$

The operational rules, fuzzy relations, and fuzzy compositions explained before are based on studies conducted by Zadeh, Yager, and Bellman [1,2,22,23,25, and 27].

3.2.5 DEFINITION OF VARIABLES

This section intends to define different terminologies that will be used in next sections. It is important that the following definitions be clearly understood for a better understanding of the application of fuzzy set theory in the construction industry.

Linguistic Variables: As explained earlier, a linguistic variable is a variable which values can be expressed by words, phrases, or sentences in a given language. For example, weather conditions is a linguistic variable, the values of which can be expressed by the following words: Good, Medium, and Bad.

It is important to make clear that linguistic variables are also referred as fuzzy factors since they introduce uncertainty to decision-processes.

Linguistic Values: These values are defined as the different linguistic terms that are assigned to a linguistic variable. Low, Average, and High are some of the linguistic factors that can be assigned to any linguistic variable.

Decision Element: A decision element is considered as an element which evaluation of its statistical variation is the principal objective of the fuzzy set analysis. Duration or Productivity are considered as decision elements which variation from a preestablished value is the principal objective of a fuzzy study.

Objective Function: Objective function is defined as a factor that will be maximized or minimized according to the needs of the people involved in an operation. The following factors may be considered as objective functions in a fuzzy set analysis: maximize profit, minimize cost, or maximize utility, etc.

Table 2, shows typical linguistic values for the use of fuzzy set analysis in the construction industry.

Table 3, presents an example of general linguistic values associated with a linguistic variables. It also describes the different relations among frequency of occurrence of the linguistic variables, consequence on objective function, and effect on assumed decision element.

3.2.6 DIFFERENT APPROACHES FOR DATA COLLECTION

In order to apply fuzzy set theory in construction project evaluation, a great amount of information regarding different decision factors of a project, have to be obtained based on conceptual analysis of the people involved in several fields. Obviously, it is intended that the information obtained by this process be as accurate as possible due to the fact that this information will have a direct repercussion in the accuracy of the expected final results.

It is important to make clear that this process of

TYPICAL VALUES OF THE LINGUISTIC VARIABLES					
LEVELS	First Set	Second Set	Third Set	Fourth Set	Fifth Set
Level 1 (HIGH)	Excellent Fine Superior Favorable Very Good	Hard Difficult Puzzling Tough Severe Massive Huge	Large Big Great Sizable Broad	Long Extensive Lengthy	High Tall Expensive Costly
Level 2 (MEDIUM)	Good Standard Usual	Medium Normal Common Typical	Medium Average Normal	Medium Normal Average	Average Normal Medium
Level 3 (LOW)	Bad Poor Inferior	Easy Soft Simple	Small Minor Little	Short Brief Limited	Low Short

TABLE 2

Linguistic Variables or Fuzzy Factors	GENERAL VALUES OF THE LINGUISTIC VARIABLES		
	Frequency Occurrence of the Linguistic Variables	Consequence on a defined Objective Function (PROFIT)	Effect on an assumed Decision Element (DURATION)
	Frequency (F)	Consequence (C)	Decision (D)
Weather			
Bad	F1 = Small	C1 = Small	D1 = Large
Normal	F2 = Medium	C2 = Medium	D2 = Small
Good	F3 = Small	C3 = Large	D3 = Small
Manpower Skill			
Low	F4 = Medium	C4 = Small	D4 = Large
Normal	F5 = Medium	C5 = Medium	D5 = Large
High	F6 = Small	C6 = Large	D6 = Small
Subcontractor's Performance			
Low	F7 = Small	C7 = Small	D7 = Large
Average	F8 = Medium	C8 = Medium	D8 = Medium
Excellent	F9 = Small	C9 = Large	D9 = Medium

TABLE 3. Fuzzy Set Table

conceptual analysis sometimes leads to obtain inappropriate information from people, such as construction managers, contractors, laborers, weather forecasters, etc., due to the lack of knowledge of the basic principles and primary goals of the fuzzy set theory.

The use of this theory implies the assumption and evaluation of a grading scale for the linguistic variable's levels, the upper and lower limits of the different linguistic values, and the membership values associated with the linguistic variables.

In this section, different approaches to collect this information is presented. These approaches are intended to serve as a guide for the data collection required by this technique.

Grading Scale:

It is important to choose an appropriate grading scale for the diverse values that can be assigned to a linguistic variable. For this reason, it is recommended that a scale ranging from zero (0) to ten (10) be chosen since this particular grading scale is commonly known.

Table 4, shows different values of the linguistic variable (weather conditions) assigned to a (0) to (10) grading scale.

In Table 4, it is clear that the lower values are assigned to poor or bad weather conditions, the middle values are assigned to normal or average weather conditions, and the upper values are assigned to good weather conditions. Consequently, the three general linguistic values can be represented as Fig. 4. Where zero (0) and three (3) are the lower and upper limits of the linguistic value (bad), three (3) and seven (7) are the lower and

LINGUISTIC VARIABLE : Weather Conditions	
Grading Scale (0 to 10)	Linguistic Values assigned
0	Terrible
1	
2	Bad
3	
4	Normal
5	
6	Pleasant
7	
8	Good
9	
10	Excellent

TABLE 4

```
0    1    2    3    4    5    6    7    8    9    10
|----|----|----|----|----|----|----|----|----|----|
|<--- Bad ---->|<---- Normal ----->|<--- Good --->|
```

FIG. 4. Weather Conditions

upper limits of the linguistic value (Normal), and seven (7) and ten (10) are the lower and upper limits of the linguistic value (Good).

Membership Values:

Two of the different approaches that can be used for the evaluation of the membership values are the numeric and the graphical. The use of either one of these approaches depends upon the background of the people from which the information will be collected. Both numerical and graphical approaches are designed to be simple and clear to understand in order to avoid misleading information.

Table 5 illustrates the numerical approach for the evaluation of the membership values. The use of this table is simple and straightforward. As an example, the linguistic variable (weather conditions), defined before in Fig. 4, is being analyzed.

By entering in Table 5, the membership value that better satisfies the different grades of the linguistic value (Bad) is defined.

	Scale (x's)	-	M. value	Ua(x).
	0	⟶	1.0	bad - bad
BAD	1	⟶	0.8	avg.- bad
	2	⟶	0.6	avg.- bad
	3	⟶	0.4	not too bad

The membership values Ua(x's) is an indicative of how well, xi (grade), satisfies a linguistic variable. In this case, the membership value Ua(0) = 1.0 associated with the x = 0,

LINGUISTIC VARIABLE : (weather conditions.)											
linguistic Values	(Bad)				(Normal)				(Good)		
Scale (x's)	0	1	2	3	4	5	6	7	8	9	10
	0	0	0	0	0	0	0	0	0	0	0
	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
Membership	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5
Values	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6
	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7
Ua(xi)	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8
	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9
	1	1	1	1	1	1	1	1	1	1	1

TABLE 5

indicates that this is the worst weather condition possible. Generally, the lowest and highest grades, x = 0 and x = 10, are associated with a membership value Ua(x) = 1.0.

A similar procedure must be utilized to define the membership values associated with the linguistic values normal and good.

Normal = {4 | .4, 5 | .8, 6 | 1.0, 7 | .5}.

Good = {8 | .3, 9 | .7, 10 | 1.0}.

In general, the assignation of the membership values for different linguistic terms can be shown as Fig. 5.

Graphical Approach:

The graphical approach has the same fundamental basis and it follows the same basic steps as the numerical approach. As shown in Fig. 6 the main difference is that this approach utilizes geometric figures instead of numerical values to determine the membership values. The geometrical figures can be circles which variation in color and intensity and diameter length represents a predetermined numerical grade.

3.2.7 DESCRIPTION OF THE PROBLEM

This example intends to illustrate the application of fuzzy set theory in construction project scheduling. Specifically, this example presents different mathematical operations and steps to be followed in order to determine the probabilistic mass

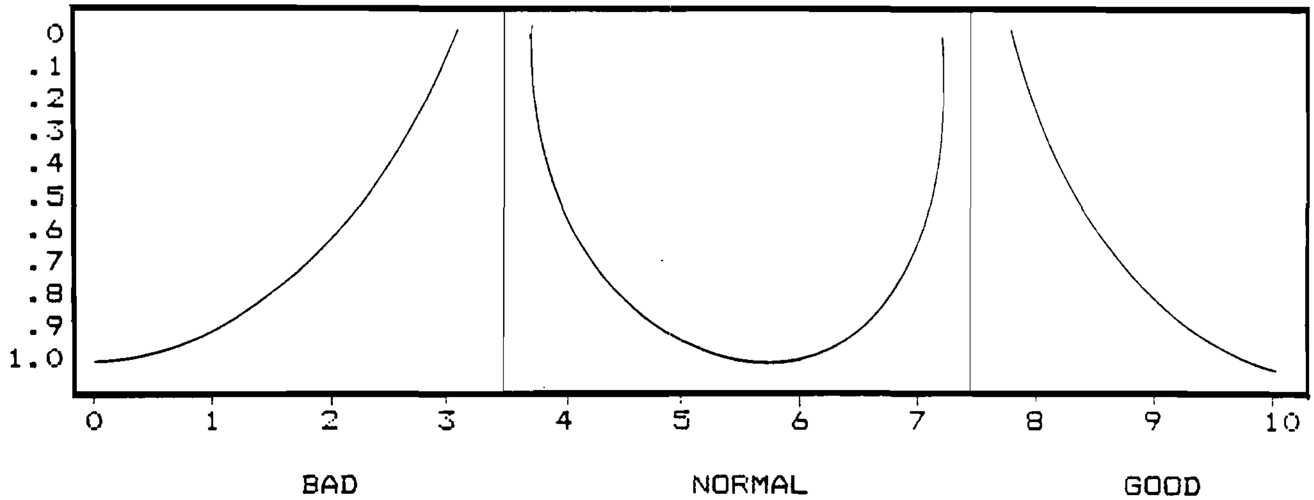


FIG. 5

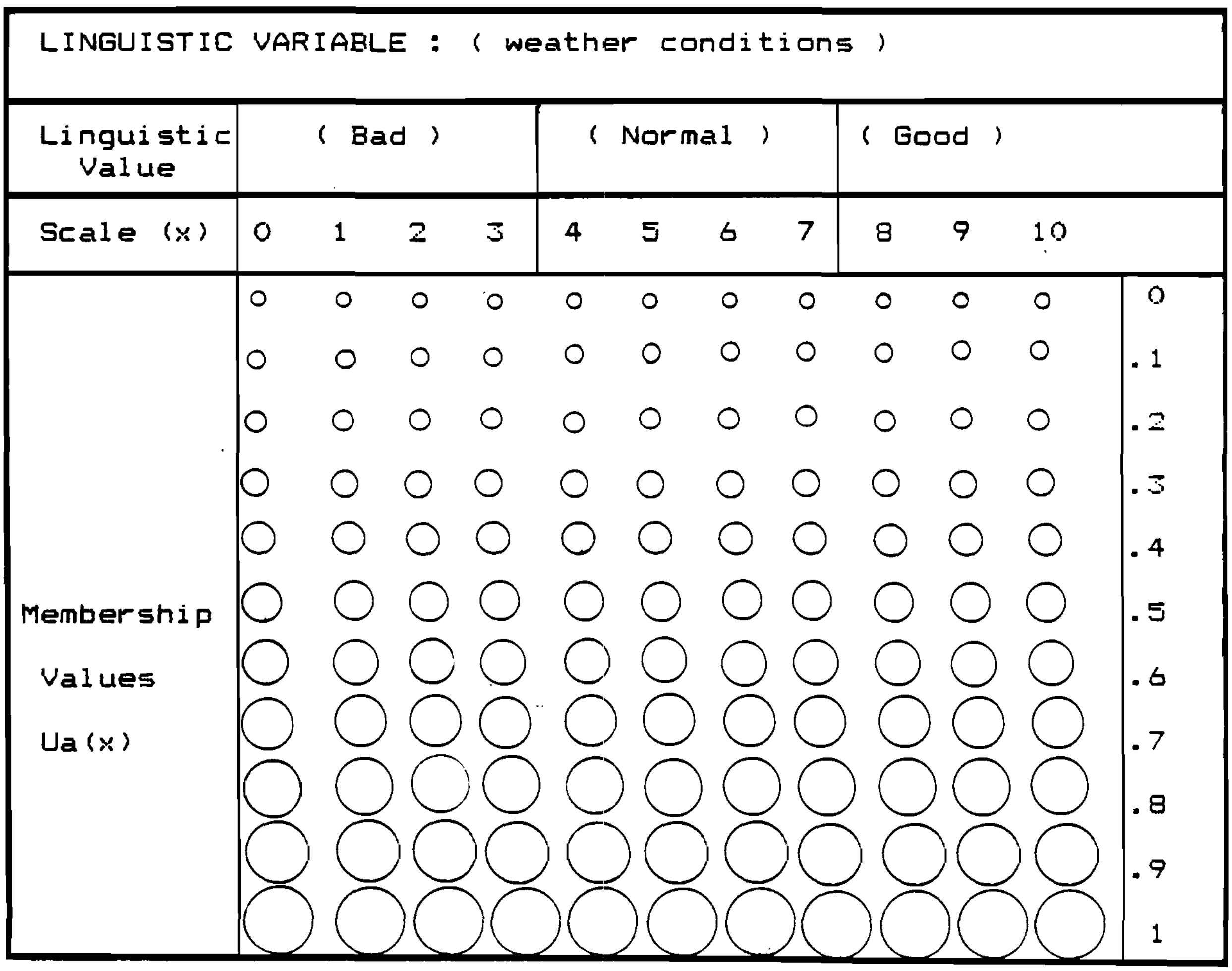


TABLE 6. Graphical Approach

function of any activity's duration.

For illustrative purposes, suppose that a contractor is considering the effect of two major uncertainty factors or linguistic variables, (weather conditions, and level of labor experience), on the duration of a concrete pouring operation. Also suppose that after having conducted an extensive analysis, the contractor has collected the following information about different factors involved in the operation:

- Defined objective function of the operation = COST.

- Decision element of the operation = DURATION.

- Frequency of occurrence, consequences on the defined objective function (COST), and effect on the decision element (Duration) are presented in Table 7.

- General linguistic values and their respective lower and upper limits are:

Small → Lower limit = 0 Upper limit = 3

Medium → Lower limit = 4 Upper limit = 7

Large → Lower limit = 8 Upper limit = 10

- Associated membership values

0	1	2	3	4	5	6	7	8	9	10	(xi)
1	0.7	0.5	0.2	0.3	0.8	1	0.6	0.7	0.9	1	Ua(x)
Small				Medium				Large			

- The expected operation's duration varies between 30 days to 53 days. The different durations associated with the scalar grades are shown in Table 7.

After having collected this information, the contractor can

0	1	2	3	4	5	6	7	8	9	10 (xi)
30	32	35	37	40	43	45	47	49	51	53 D(xi)

Linguistic Variables	Frequency of Occurrence F		Consequence on COST (C)		Effect on Act. DURATION (D)	
	General Linguistic Values					
WEATHER						
BAD	SMALL	F1	LARGE	C1	LARGE	D1
NORMAL	MEDIUM	F2	MEDIUM	C2	MEDIUM	D2
GOOD	MEDIUM	F3	SMALL	C3	SMALL	D3
EXPERIENCE						
LOW	LARGE	F4	MEDIUM	C4	LARGE	D4
MEDIUM	MEDIUM	F5	SMALL	C5	SMALL	C5
HIGH	SMALL	F6	SMALL	C6	SMALL	C6

TABLE 7

now commence the analysis of the operation by applying different concepts to the fuzzy set theory.

3.2.8 PROCEDURES AND SOLUTION:

By utilizing Eq. 38, the fuzzy relation between frequency of occurrence (Fi), and consequence on cost (C1) can be calculated as follows:

F1 = Small = {0 1.0, 1 0.7, 2 0.5, 3 0.2}.

C1 = Large = {8 0.7, 9 0.9, 10 1.0}.

taking UF1(0) = 1.0

$$\text{If } 1.0 \leftarrow UC1(yi)\ i = 0 \text{ to } 10 \quad \begin{cases} \text{Yes} \rightarrow Ua(xi,yi) = UF1(xi) \\ \text{No} \rightarrow UA(xi,yi) = UC1(yi) \end{cases}$$

as a result,

UA1 (0,8) = 0.7
UA1 (0,9) = 0.9
UA1(0,10) = 1.0

By taking UF1(1), UF1(2), and UF1(3) and following the same procedure, the relation F1 x C1 = A1 is expressed as:

F1 x C1 = A1 =

Frequency (Small) \ Consequence (large)	8	9	10
0	0.7	0.9	1.0
1	0.7	0.7	0.7
2	0.5	0.5	0.5
3	0.2	0.2	0.2

Following the same procedure, the fuzzy relations A2 = F2 x C2, A3 = F3 x C3, A4 = F4 x C4, A5 = F5 x C5, and A6 = F6 x C6 can be calculated.

F2 x C2 = A2 =

Consequence (Medium)

Frequency (Medium)	4	5	6	7
4	0.3	0.3	0.3	0.3
5	0.3	0.8	0.8	0.6
6	0.3	0.8	1.0	0.6
7	0.3	0.6	0.6	0.6

F3 x C3 = A3 =

Consequence (Small)

Frequency (Medium)	0	1	2	3
4	0.3	0.3	0.3	0.2
5	0.8	0.7	0.5	0.2
6	1.0	0.7	0.5	0.2
7	0.6	0.6	0.5	0.2

F4 x C4 = A4 =

Consequence (Medium)

Frequency (Large)	4	5	6	7
8	0.3	0.7	0.7	0.6
9	0.3	0.8	0.9	0.3
10	0.3	0.8	1.0	0.6

F5 x C5 = A5 =

Consequence (Small)

Frequency (Medium)	0	1	2	3
4	0.3	0.3	0.3	0.2
5	0.8	0.7	0.5	0.2
6	1.0	0.7	0.5	0.2
7	0.6	0.6	0.5	0.2

F6 x C6 = A6 =

Consequence (Small)

Frequency (Small)	0	1	2	3
0	1.0	0.7	0.5	0.2
1	0.7	0.7	0.5	0.2
2	0.5	0.5	0.5	0.2
3	0.2	0.2	0.2	0.2

The fuzzy relations between consequence on cost and effect on activity's duration are also calculated by applying Eq. 38.

C1 × D1 = B1 =

Frequency (Large) \ Duration (Long)	8	9	10
8	0.7	0.7	0.7
9	0.7	0.9	0.9
10	0.7	0.9	1.0

C2 × D2 = B2 =

Frequency (Medium) \ Duration (Medium)	4	5	6	7
4	0.3	0.3	0.3	0.3
5	0.3	0.8	0.8	0.6
6	0.3	0.8	1.0	0.6
7	0.3	0.6	0.6	0.6

C3 × D3 = B3 =

Frequency (Small) \ Duration (Small)	0	1	2	3
0	1.0	0.7	0.5	0.2
1	0.7	0.7	0.5	0.2
2	0.5	0.5	0.5	0.2
3	0.2	0.2	0.2	0.2

C4 × D4 = B4 =

Frequency (Medium) \ Duration (Large)	8	9	10
4	0.3	0.3	0.3
5	0.7	0.8	0.8
6	0.7	0.9	1.0
7	0.6	0.6	0.6

C5 x D5 = B5 =

Frequency (Small) \ Duration (Small)	0	1	2	3
0	1.0	0.7	0.5	0.2
1	0.7	0.7	0.5	0.2
2	0.5	0.5	0.5	0.2
3	0.2	0.2	0.2	0.2

C6 x D6 = B6 =

Frequency (Small) \ Duration (Small)	0	1	2	3
0	1.0	0.7	0.5	0.2
1	0.7	0.7	0.5	0.2
2	0.5	0.5	0.5	0.5
3	0.2	0.2	0.2	0.2

At this point, the total effect of these linguistic factors can be obtained by taking the union of these relations (Fi xCi).

As a result:

T = Total effect matrix

T = {(F1 x C1) U (F2 x C2) U ..... (F5 x D5) U (F6 x D6)}

T = {A1 U A2 U A3 U A4 U A5 U A6}.

By applying Eq. 39, the T matrix can be obtained as follows:

T MATRIX

Frequence Xi \ Consequence Yj	0	1	2	3	4	5	6	7	8	9	10
0	1.0	0.7	0.5	0.2	0	0	0	0	0.7	0.9	1.0
1	0.7	0.7	0.5	0.2	0	0	0	0	0.7	0.7	0.7
2	0.5	0.5	0.5	0.2	0	0	0	0	0.5	0.5	0.5
3	0.2	0.2	0.2	0.2	0	0	0	0	0.2	0.2	0.2
4	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0	0	0
5	0.8	0.7	0.5	0.2	0.3	0.8	0.8	0.6	0	0	0
6	1.0	0.7	0.5	0.2	0.3	0.8	1.0	0.6	0	0	0
7	0.6	0.6	0.5	0.2	0.3	0.6	0.6	0.6	0	0	0
8	0	0	0	0	0.3	0.7	0.7	0.6	0	0	0
9	0	0	0	0	0.3	0.8	0.9	0.6	0	0	0
10	0	0	0	0	0.3	0.8	1.0	0.6	0	0	0

In a similar way, S matrix represents the union of the relations (C1 X Di).

S = Total effect matrix

S = {(C1 x D1) U (C2 x D2) U ..... (C5 x D5) U (C6 x D6)}.

S = {B1 U B2 U B3 U B4 U B5 U B6}.

By applying Eq. 39, the total effect S matrix can be calculated.

- S - MATRIX

Consequence Yj \ Duration Zk	0	1	2	3	4	5	6	7	8	9	10
0	1.0	0.7	0.5	0.2	0	0	0	0	0	0	0
1	0.7	0.7	0.5	0.2	0	0	0	0	0	0	0
2	0.5	0.5	0.5	0.2	0	0	0	0	0	0	0
3	0.2	0.2	0.2	0.2	0	0	0	0	0	0	0
4	0	0	0	0	0.3	0.3	0.3	0.3	0.3	0.3	0.3
5	0	0	0	0	0.3	0.8	0.8	0.6	0.7	0.8	0.8
6	0	0	0	0	0.3	0.8	1.0	0.6	0.7	0.9	1.0
7	0	0	0	0	0.3	0.6	0.6	0.6	0.6	0.6	0.6
8	0	0	0	0	0	0	0	0	0.7	0.7	0.7
9	0	0	0	0	0	0	0	0	0.7	0.9	0.9
10	0	0	0	0	0	0	0	0	0.7	0.9	1.0

After having calculated the effect matrices T and S, a subjective estimation of the duration can be obtained by combining these two matrices. Consequently, the combined matrix (ToS) is calculated by applying Eq. 41.

Taking the first column of elements of the S matrix, US(Yj,Zk) j = 0 to 10 and k = 0, and the first row of elements of the T matrix, UT(Xi,Yj) i = 0 and j = 0 to 10, by comparing element by element and taking the minimum value of each comparison, a set of minimum values is conformed. By taking the maximum value of this set of minimum values, an element, UToS(Xi,Zk), of the combined matrix ToS is obtained:

Column

Yj	US(Yj,ZO)
0	1.0
1	0.7
2	0.5
3	0.2
4	0
5	0
6	0
7	0
8	0
9	0
10	0.

Row

Yj =>	0	1	2	3	4	5	6	7	8	9	10
UT(XO,Yj)	1	.7	.5	.2	0	0	0	0	.7	.9	1

COMPARISON

Yj	0	1	2	3	4	5	6	7	8	9	10
US(Yj,ZO)	1	.7	.5	.2	0	0	0	0	0	0	0
UT(XO,Yj)	1	.7	.5	.2	0	0	0	0	.7	.9	1
Minimum Values	1	.7	.5	.2	0	0	0	0	0	0	0

Maximum Value -> UToS(XO , ZO) 1.0

This process is repeated, this time taking the second row of the T matrix.

COMPARISON

Yj	0	1	2	3	4	5	6	7	8	9	10
US(Yj,ZO)	1	.7	.5	.2	0	0	0	0	0	0	0
UT(X1,Yj)	.7	.7	.5	.2	0	0	0	0	.7	.7	.7
Minimum Values	.7	.7	.5	.2	0	0	0	0	0	0	0

Maximum Value -> UToS(X1 , ZO) = 0.7

This process continues until all the elements of the combined - ToS - matrix have been calculated.

- ToS - MATRIX

Duration

Frequency	0	1	2	3	4	5	6	7	8	9	10	Row	RxF.
0	1	.7	.5	.2	0	0	0	0	.7	.9	1	5.0	0.0
1	.7	.7	.5	.2	0	0	0	0	.7	.7	.7	4.2	4.2
2	.5	.5	.5	.2	0	0	0	0	.5	.5	.5	3.2	6.4
3	.2	.2	.2	.2	0	0	0	0	.2	.2	.2	1.4	4.2
4	.3	.3	.3	.2	.3	.3	.3	.3	.3	.3	.3	3.2	12.8
5	.8	.7	.5	.2	.3	.8	.8	.6	.7	.8	.8	7.0	35.0
6	1	.7	.5	.2	.3	.8	1	.6	.7	.9	1	7.7	46.2
7	.6	.6	.5	.2	.3	.6	.6	.6	.6	.6	.6	5.8	40.6
8	0	0	0	0	.3	.7	.7	.6	.7	.7	.7	4.4	35.2
9	0	0	0	0	.3	.8	.9	.6	.7	.9	.9	5.1	45.9
10	0	0	0	0	.3	.8	1	.6	.7	.9	1	5.3	53.0

According to Ayyub and Haldar [1], a row or subset which maximizes the product of the row summation and the correspondent frequency is chosen from the combined ToS matrix.

$$\text{Row summation} = Rsi. = \sum_{k=0}^{10} U_{ToS}(Xi,Zk) \text{ for } i = 0 \text{ to } 10$$

Rsi x its correspondent Frequency = Rsi x i for i = 0 to 10

In this particular example, the last row of the combined ToS matrix gives the maximum value of this product. As a result, the subset which will be associated with the subset of activity's duration, D, is expressed as:

Combined Subset = {0 | 0, 1 | 0, 2 | 0, 3 | 0, 4 | .3, 5 | .8, 6 | 1, 7 | .6, 8 | .7, 9 | .9, 10 | 1}.

The subset D (Activity's Duration) was defined earlier as:

D = {0 | 30, 1 | 32, 2 | 35, 3 | 37, 4 | 40, 5 | 43, 6 | 45, 7 | 47, 8 | 49, 9 | 51, 10 | 53}.

At this point, the fuzzy subset of activity's duration can be obtained as:

Da = (Fuzzy subset of activity's duration).

Da = {30 | 0, 32 | 0, 35 | 0, 37 | 0, 40 | .3, 43 | .8, 45 | 1, 47 | .6, 49 | .7, 51 | .9, 53 | 1}.

According to Zadeh [25], the probabilistic mass function can be obtained by applying the following formula:

$$P(\text{Duration}) = \frac{U(Xi,Zk)}{Rsi} \quad \begin{array}{l} i = \text{Maximum product Row.} \\ k = 0 \text{ to } 10. \end{array}$$

In this particular example, the probabilistic mass function is calculated as follows:

P(Da=30) = 0 / 5.30 = 0% P(Da=32) = 0 / 5.30 = 0%

P(Da=35) = 0 / 5.30 = 0% P(Da=37) = 0 / 5.30 = 0%

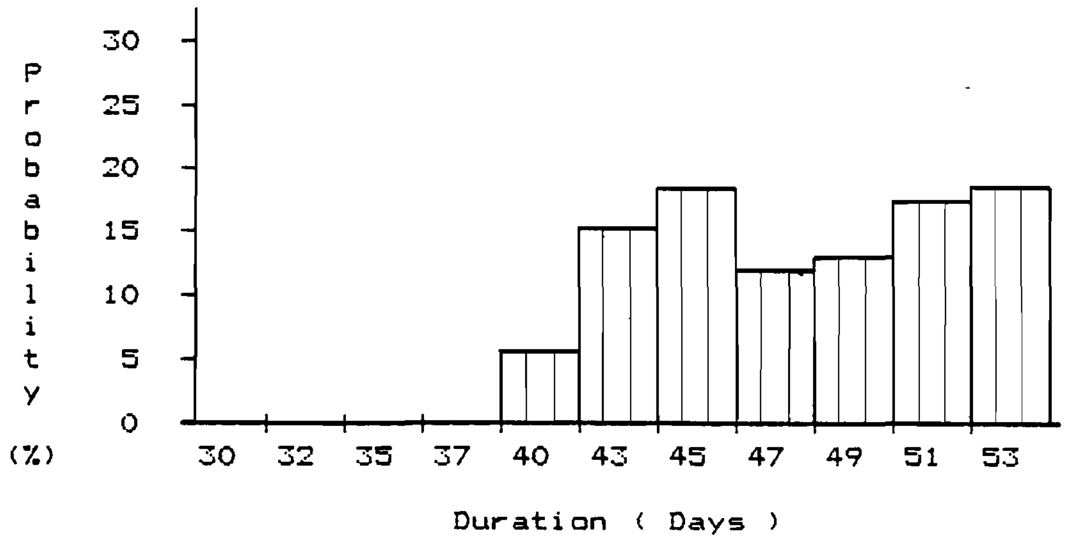
P(Da=40) =.3 / 5.30 = 5.66% P(Da=43) =.8 / 5.30 = 15.09%

P(Da=45) = 1 / 5.30 = 18.87% P(Da=47) =.6 / 5.30 = 11.32%

P(Da=49) =.7 / 5.30 = 13.21% P(Da=51) =.9 / 5.30 = 16.98%

P(Da=53) = 1 / 5.30 = 18.87%

Figure 6 shows a bar graph of the probability distribution



Probability (%)
30
25
20
15
10
5
0
30
32
35
37
40
43
45
47
49
51
53
Duration (Days)

FIG. 6

of this example.

Finally, the mean or expected duration value $\overline{Da}$, and standard deviation σDa of the activity's duration can be calculated by applying the following statistical formulas:

$$\overline{Da} = \sum_{i=0}^{n} Da \times P(Dai)$$

$$\sigma Da = \sqrt{\sum_{i=0}^{n} P(Dai)\,[Dai - Da]^2}$$

As a result, the estimated duration mean is equal to

$\overline{Da} = 47.698$ (days). → 48 (days).

and the standard deviation is

$\sigma Da = 3.936$ (days). → 4 (days).

In spite of the fact that this particular example has a bimodal probability mass function, the expected activity's duration (48 days) can be an acceptable value since there is approximately 80% probability that the expected duration falls between 45 days and 53 days.

3.2.9 SENSITIVITY ANALYSIS:

In this section a sensitivity analysis of the different variables involved in the technique explained before will be presented. The objective of this analysis is to determine how small variations on the values of a particular variable or variables will affect the final outcome of the proposed technique. Based on this analysis, it will be also determined which variables are more sensitive to these changes than the others.

For the purpose of this analysis, the example presented in section 3.2.7 will be used as a reference or comparative point. At the beginning, the membership values of the different linguistic values will be increased or decreased by small amounts. The problem will be solved again and the new results will be compared to the reference results shown in Table 10. After that, the different linguistic values that a linguistic variable can take will be changed as shown in Table 9.

3.2.10 ANALYSIS:

In order to evaluate how sensitive this technique is to small variations on the membership values, the initial sets of membership values associated with the general linguistic values (Small, Medium, and Large) will be changed as shown in Table 8.

The results obtained due to these changes are presented in Tables 11 through 19 respectively. Finally, all the membership values were changed at the same time as shown in Table 20. The result obtained due to these changes is presented in the same Table 20.

In order to determine this technique's sensitivity to changes in fuzzy relations, an example was solved with the following arrangement of relations among frequency of occurrence, consequence on cost, and effect on duration as shown in Table 9.

Table 21 shows the result obtained by changing the fuzzy relations.

Finally, another example was solved in order to analyze the effect of overlapping the limits associated with the general

Change No.	Linguistic Values	Membership Values (M.V.)				
	SMALL	0	1	3	4	X's Values.
		1.0	0.7	0.5	0.2	Initial M.V.
1	Lower Values	1.0	0.3	0.2	0.1	New M.V.
2	Middle Values	1.0	0.6	0.5	0.4	New M.V.
3	Upper Values	1.0	0.9	0.8	0.7	New M.V.
	MEDIUM	4	5	6	7	X's Values
		0.3	0.8	1.0	0.6	Initial M.V.
4	Lower Values	0.1	0.4	1.0	0.3	New M.V.
5	Middle Values	0.5	0.7	1.0	0.5	New M.V.
6	Upper Values	0.7	0.9	1.0	0.8	New M.V.
	LARGE	8	9	10		X's Values
		0.7	0.9	1.0		Initial M.V.
7	Lower Values	0.2	0.4	1.0		New M.V.
8	Middle Values	0.5	0.6	1.0		New M.V.
9	Upper Values	0.8	0.9	1.0		New M.V.

TABLE 8

linguistic values, on the final results as shown in Figs. 7.

The information obtained from the sensitivity analysis (Tables 10 through 20) is summarized in Fig. 8. This figure shows that the biggest difference in expected duration is 0.82 days which indicates that this technique is not sensitive to small variations in the membership values. This lack of sensitivity can be interpreted as an advantage of this technique since the assignation of the membership values can be difficult to determine in a precise and objective way.

On the other hand, the expected duration (Da) shown in Table 21 differs by 4.82 days from the initial expected duration shown in Table 10. This clearly indicates that this technique is sensitive to the choice of fuzzy relations.

Finally, the analysis of the different results shown in Tables 10 and 22 in which different limits were assigned to the linguistic values, has indicated that this technique is sensitive to the choice of these limits. For example, the results shown in Table 10 are based on the following limits assigned to the general linguistic values (SMALL, MEDIUM, and LARGE):

	Lower Limit.	Upper Limit.
SMALL →	0	3
MEDIUM →	4	7
LARGE →	8	10

With these limits, the problem was solved. The expected duration ($\bar{Da}$) was equal to 47.70 days and the standard deviation (σDa) was equal to 3.94 days. On the other hand, the same example was

Linguistic Variables	Frequency of Occurrence F	Consequence on COST (C)	Effect on Act. DURATION (D)
	General Linguistic Values		
WEATHER			
BAD	SMALL	LARGE	LARGE
NORMAL	MEDIUM	MEDIUM	LARGE
GOOD	SMALL	SMALL	MEDIUM
EXPERIENCE			
LOW	LARGE	LARGE	LARGE
MEDIUM	MEDIUM	MEDIUM	MEDIUM
HIGH	MEDIUM	SMALL	SMALL

TABLE 9

0	1	2	3	4	5	6	7	8	9	10	X's Values.
1	.7	.5	.2	.3	.8	1	.6	.7	.9	1	Membership V.

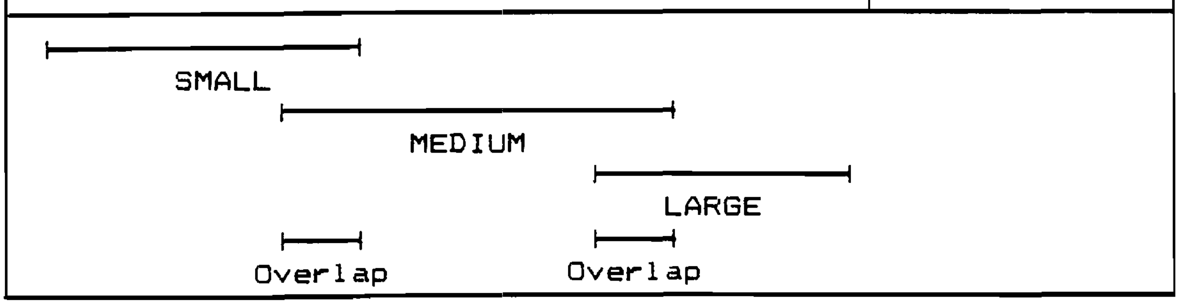


FIG. 7

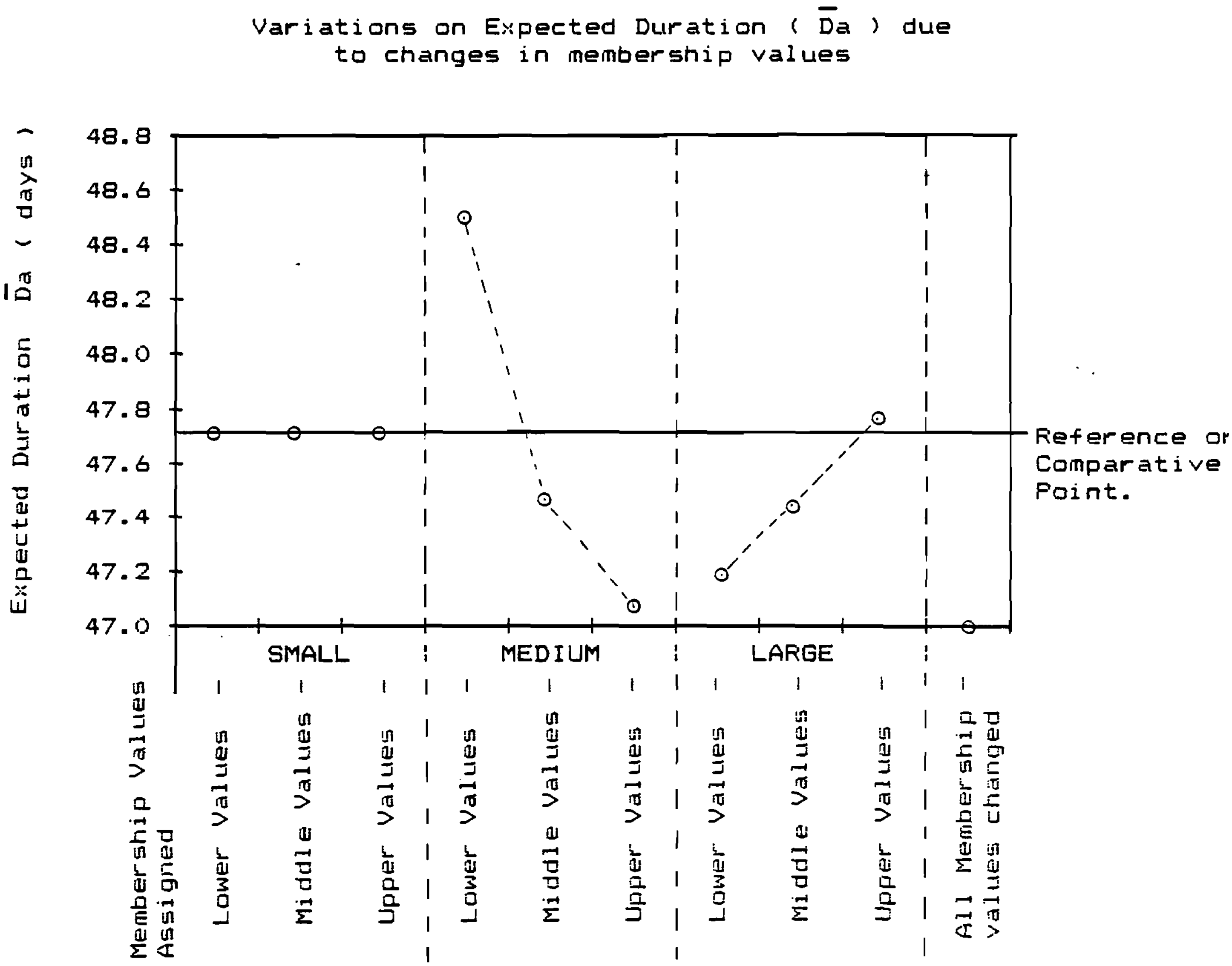

Variations on Expected Duration (Da) due to changes in membership values
Expected Duration Da (days)
48.8
48.6
48.4
48.2
48.0
47.8
47.6
47.4
47.2
47.0
Reference or Comparative Point.
SMALL
MEDIUM
LARGE
Membership Values Assigned
Lower Values
Middle Values
Upper Values
Lower Values
Middle Values
Upper Values
Lower Values
Middle Values
Upper Values
All Membership values changed

FIG. 8

Sensitivity Analysis

General Linguistic Values

SMALL				MEDIUM				LARGE			
0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.7	0.5	0.2	0.3	0.8	1.0	0.6	0.7	0.9	1.0	Membership Values

F I N A L   R E S U L T S   T A B L E

Duration		Probability	
30	----->	0.0000	0.00 %
32	----->	0.0000	0.00 %
35	----->	0.0000	0.00 %
37	----->	0.0000	0.00 %
40	----->	0.0566	5.66 %
43	----->	0.1509	15.09 %
45	----->	0.1887	18.87 %
47	----->	0.1132	11.32 %
49	----->	0.1321	13.21 %
51	----->	0.1698	16.98 %
53	----->	0.1887	18.87 %
Expected value (days)= 47.6981 ==> 48			
Standard Deviation (days)= 3.93621 ==> 4			

Probability Bar Graph

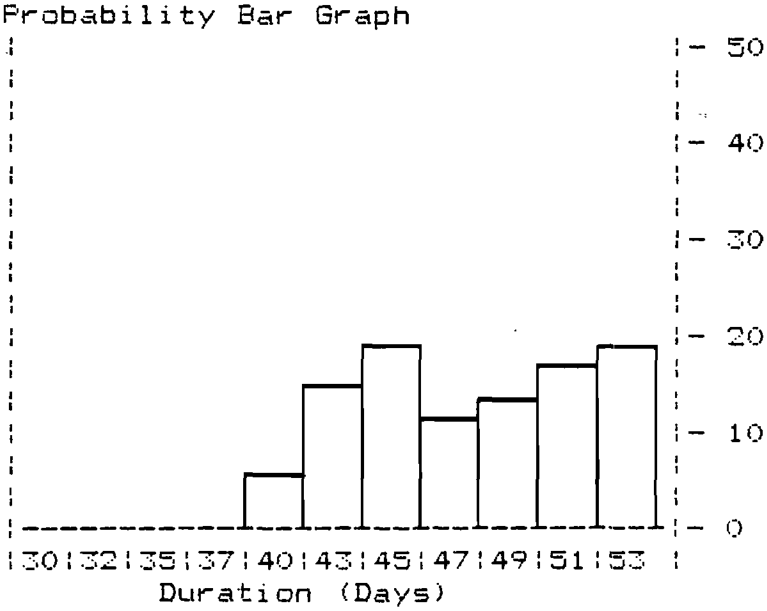


TABLE 10

Sensitivity Analysis

General Linguistic Values

SMALL				MED				LARGE			
0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.3	0.2	0.1	0.3	0.8	1.0	0.6	0.7	0.9	1.0	Membership Values

F I N A L R E S U L T S T A B L E

Duration		Probability	
30	----->	0.0000	0.00 %
32	----->	0.0000	0.00 %
35	----->	0.0000	0.00 %
37	----->	0.0000	0.00 %
40	----->	0.0566	5.66 %
43	----->	0.1509	15.09 %
45	----->	0.1887	18.87 %
47	----->	0.1132	11.32 %
49	----->	0.1321	13.21 %
51	----->	0.1698	16.98 %
53	----->	0.1887	18.87 %
Expected Value (days)= 47.6981 ==> 48			
Standard Deviation (days)= 3.93621 ==> 4			

Probability Bar Graph

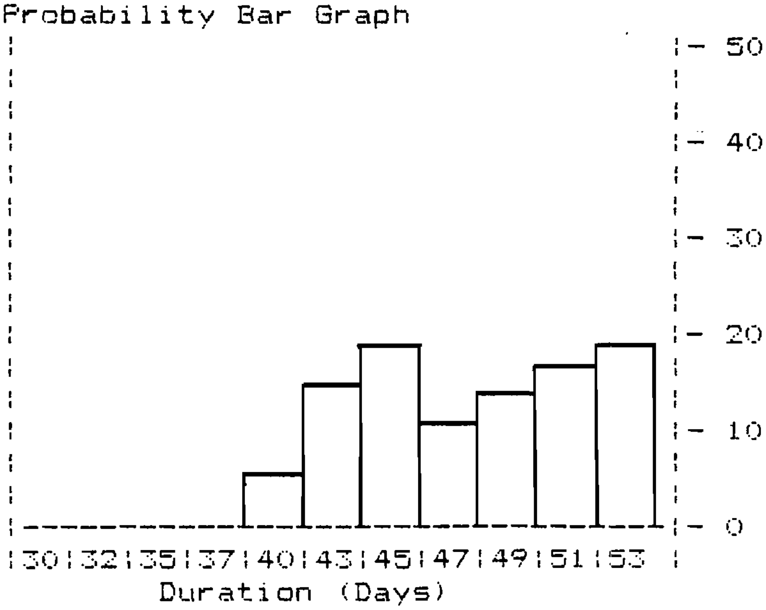


TABLE 11

Sensitivity Analysis

General Linguistic Values

SMALL				MED				LARGE			
0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.6	0.5	0.4	0.3	0.8	1.0	0.6	0.7	0.9	1.0	Membership Values

F I N A L R E S U L T S T A B L E

Duration		Probability	
30	----->	0.0000	0.00 %
32	----->	0.0000	0.00 %
35	----->	0.0000	0.00 %
37	----->	0.0000	0.00 %
40	----->	0.0566	5.66 %
43	----->	0.1509	15.09 %
45	----->	0.1887	18.87 %
47	----->	0.1132	11.32 %
49	----->	0.1321	13.21 %
51	----->	0.1698	16.98 %
53	----->	0.1887	18.87 %

Expected value (days)= 47.6981 ==> 48

Standard Deviation (days)= 3.93621 ==> 4

Probability Bar Graph

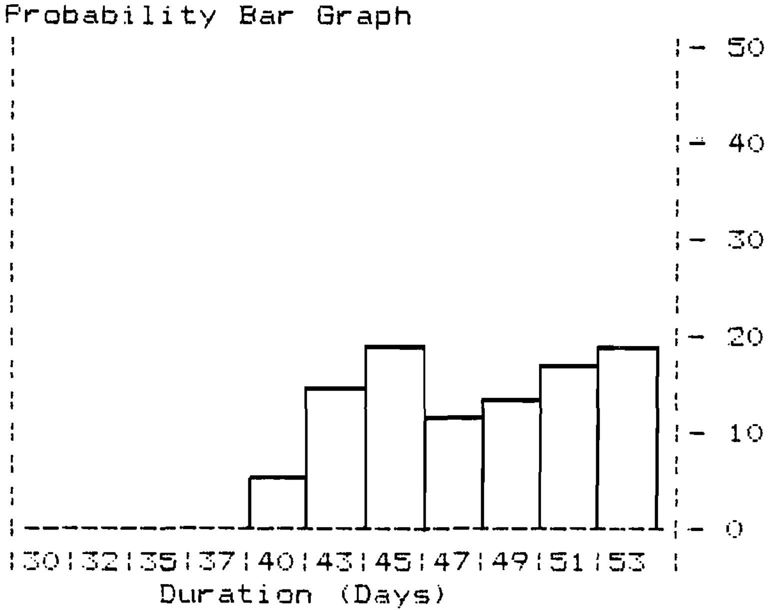


TABLE 12

Sensitivity Analysis

General Linguistic Values

SMALL				MED				LARGE			
0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.9	0.8	0.7	0.3	0.8	1.0	0.6	0.7	0.9	1.0	Membership Values

F I N A L   R E S U L T S   T A B L E

Duration		Probability	
30	----->	0.0000	0.00 %
32	----->	0.0000	0.00 %
35	----->	0.0000	0.00 %
37	----->	0.0000	0.00 %
40	----->	0.0566	5.66 %
43	----->	0.1509	15.09 %
45	----->	0.1887	18.87 %
47	----->	0.1132	11.32 %
49	----->	0.1321	13.21 %
51	----->	0.1698	16.98 %
53	----->	0.1887	18.87 %

Expected value (days)= 47.6981 ==> 48

Standard Deviation (days)= 3.93621 ==> 4

Probability Bar Graph

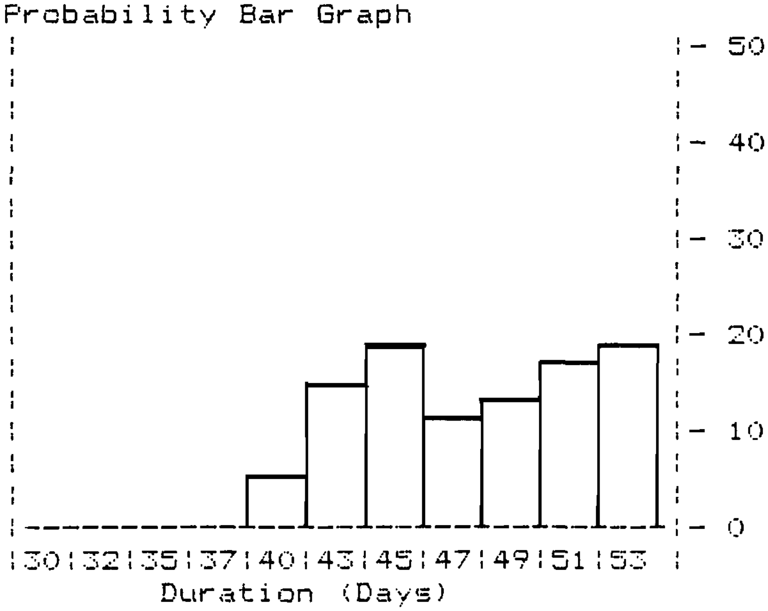


TABLE 13

Sensitivity Analysis

General Linguistic Values

SMALL				MED				LARGE			
0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.7	0.5	0.2	0.1	0.4	1.0	0.3	0.7	0.9	1.0	Membership Values

F I N A L   R E S U L T S   T A B L E

Duration		Probability	
30	----->	0.0000	0.00 %
32	----->	0.0000	0.00 %
35	----->	0.0000	0.00 %
37	----->	0.0000	0.00 %
40	----->	0.0227	2.27 %
43	----->	0.0909	9.09 %
45	----->	0.2273	22.73 %
47	----->	0.0682	6.82 %
49	----->	0.1591	15.91 %
51	----->	0.2045	20.45 %
53	----->	0.2273	22.73 %

= Expected value (days)= 48.5227 ==> 49 =

= Standard Deviation (days)= 3.63998 ==> 4 =

Probability Bar Graph

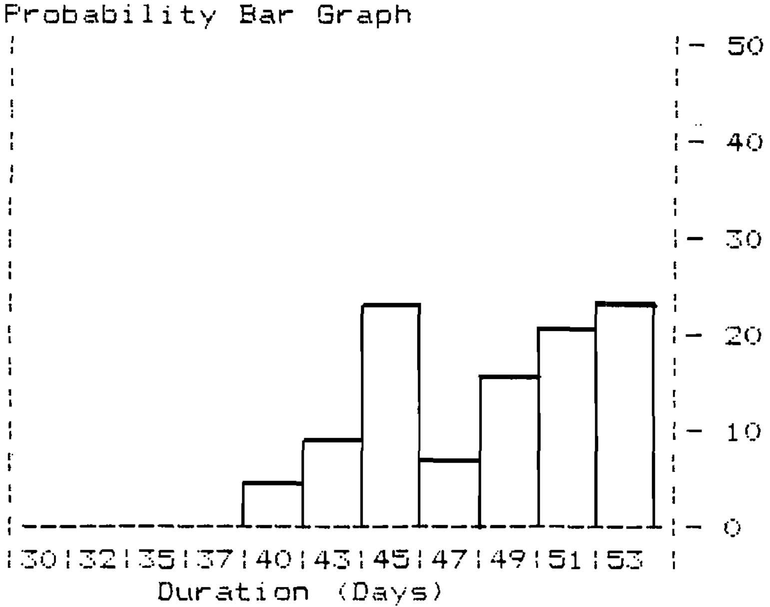


TABLE 14

Sensitivity Analysis

General Linguistic Values

SMALL				MED				LARGE			
0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.7	0.5	0.2	0.5	0.7	1.0	0.5	0.7	0.9	1.0	Membership Values

F I N A L R E S U L T S T A B L E

Duration		Probability	
30	----->	0.0000	0.00 %
32	----->	0.0000	0.00 %
35	----->	0.0000	0.00 %
37	----->	0.0000	0.00 %
40	----->	0.0943	9.43 %
43	----->	0.1321	13.21 %
45	----->	0.1887	18.87 %
47	----->	0.0943	9.43 %
49	----->	0.1321	13.21 %
51	----->	0.1698	16.98 %
53	----->	0.1887	18.87 %

Expected value (days)= 47.5094 ==> 48

Standard Deviation (days)= 4.15557 ==> 4

Probability Bar Graph

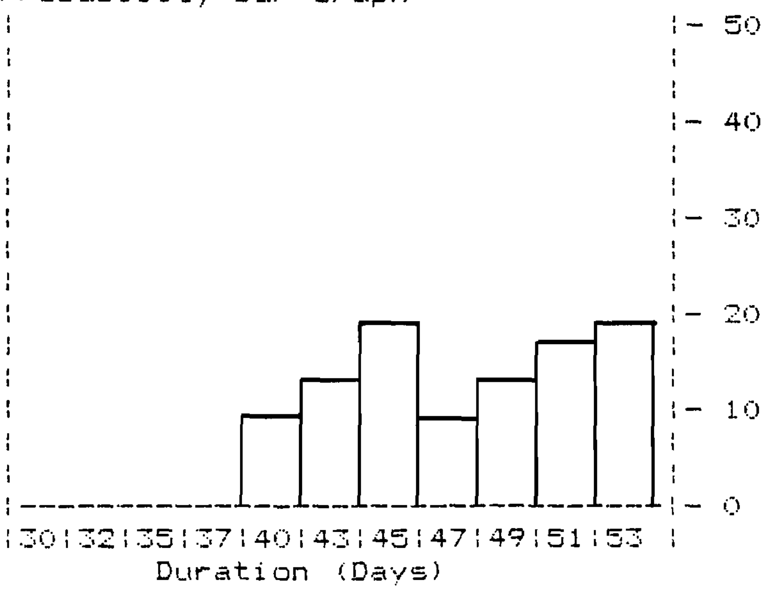


TABLE 15

Sensitivity Analysis

General Linguistic Values

SMALL				MED				LARGE			
0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.7	0.5	0.2	0.7	0.9	1.0	0.8	0.7	0.9	1.0	Membership Values

F I N A L R E S U L T S T A B L E

Duration		Probability	
30	----->	0.0000	0.00 %
32	----->	0.0000	0.00 %
35	----->	0.0000	0.00 %
37	----->	0.0000	0.00 %
40	----->	0.1167	11.67 %
43	----->	0.1500	15.00 %
45	----->	0.1667	16.67 %
47	----->	0.1333	13.33 %
49	----->	0.1167	11.67 %
51	----->	0.1500	15.00 %
53	----->	0.1667	16.67 %
Expected value (days)=	47.0833 ==>	47	
Standard Deviation (days)=	4.20036 ==>	4	

Probability Bar Graph

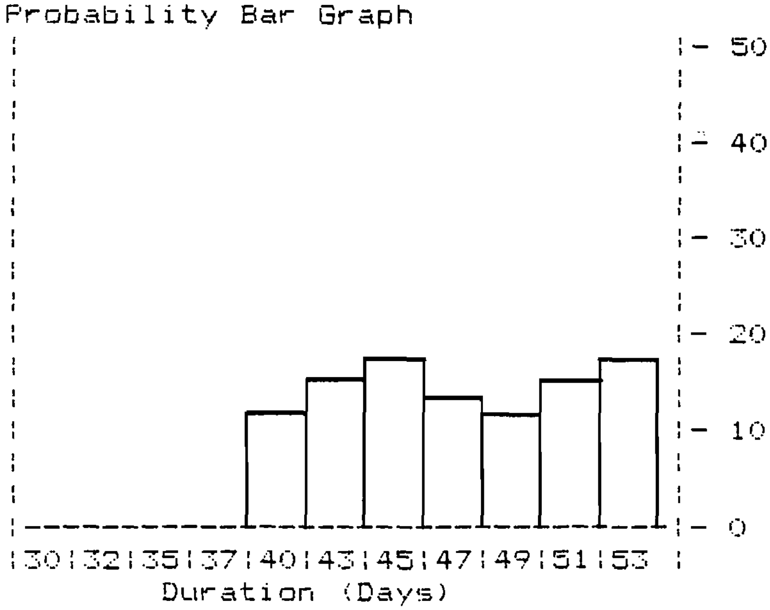


TABLE 16

Sensitivity Analysis

General Linguistic Values

SMALL				MED				LARGE			
0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.7	0.5	0.2	0.3	0.8	1.0	0.6	0.2	0.4	1.0	Membership Values

F I N A L R E S U L T S T A B L E

Duration		Probability	
30	----->	0.0000	0.00 %
32	----->	0.0000	0.00 %
35	----->	0.0000	0.00 %
37	----->	0.0000	0.00 %
40	----->	0.0698	6.98 %
43	----->	0.1860	18.60 %
45	----->	0.2326	23.26 %
47	----->	0.1395	13.95 %
49	----->	0.0465	4.65 %
51	----->	0.0930	9.30 %
53	----->	0.2326	23.26 %
Expected value (days)= 47.1628 ==> 47			
Standard Deviation (days)= 4.1648 ==> 4			

Probability Bar Graph

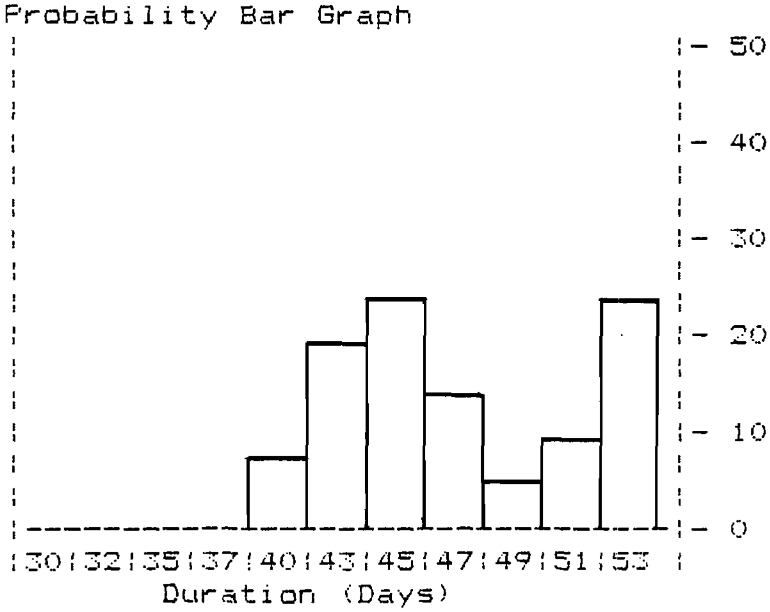


TABLE 17

Sensitivity Analysis

General Linguistic Values

SMALL				MED				LARGE			
0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.7	0.5	0.2	0.3	0.8	1.0	0.6	0.5	0.6	1.0	Membership Values

F I N A L R E S U L T S T A B L E

Duration		Probability	
30	----->	0.0000	0.00 %
32	----->	0.0000	0.00 %
35	----->	0.0000	0.00 %
37	----->	0.0000	0.00 %
40	----->	0.0625	6.25 %
43	----->	0.1667	16.67 %
45	----->	0.2083	20.83 %
47	----->	0.1250	12.50 %
49	----->	0.1042	10.42 %
51	----->	0.1250	12.50 %
53	----->	0.2083	20.83 %

Expected value (days)= 47.4375 ==> 47

Standard Deviation (days)= 4.03581 ==> 4

Probability Bar Graph

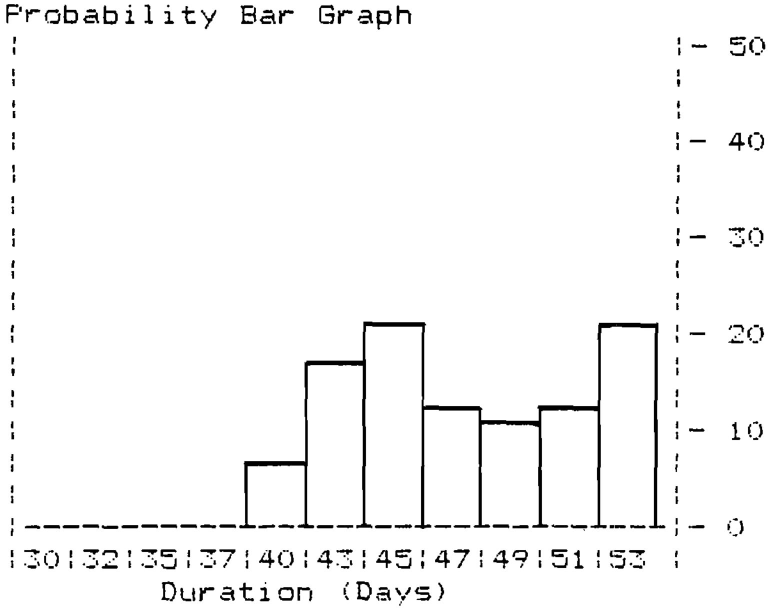


TABLE 18

Sensitivity Analysis

General Linguistic Values

SMALL				MED				LARGE			
0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.7	0.5	0.2	0.3	0.8	1.0	0.6	0.8	0.9	1.0	Membership Values

F I N A L R E S U L T S T A B L E

Duration		Probability	
30	----->	0.0000	0.00 %
32	----->	0.0000	0.00 %
35	----->	0.0000	0.00 %
37	----->	0.0000	0.00 %
40	----->	0.0556	5.56 %
43	----->	0.1481	14.81 %
45	----->	0.1852	18.52 %
47	----->	0.1111	11.11 %
49	----->	0.1481	14.81 %
51	----->	0.1667	16.67 %
53	----->	0.1852	18.52 %

Expected value (days)= 47.7222 ==> 48

Standard Deviation (days)= 3.90354 ==> 4

Probability Bar Graph

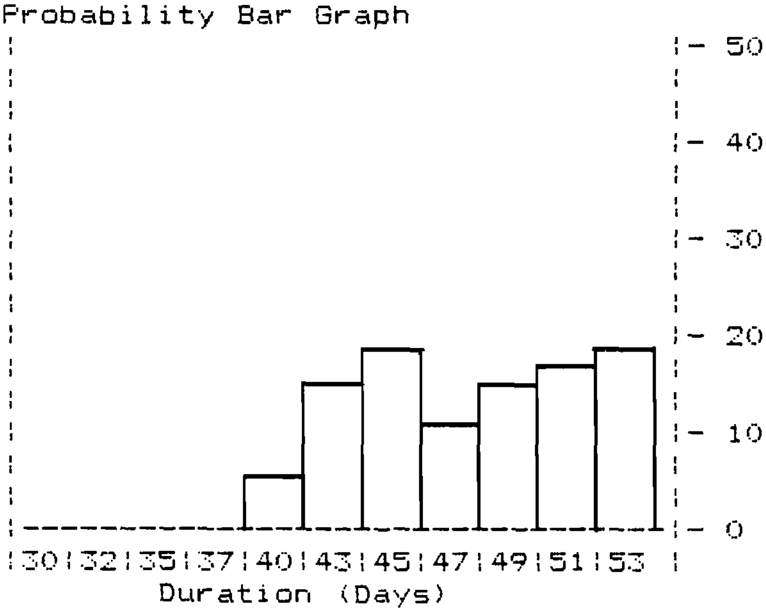


TABLE 19

Sensitivity Analysis

General Linguistic Values

SMALL				MED				LARGE			
0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.9	0.8	0.7	0.8	0.9	1.0	0.8	0.8	0.9	1.0	Membership Values

F I N A L   R E S U L T S   T A B L E

Duration		Probability	
30	------>	0.0000	0.00 %
32	------>	0.0000	0.00 %
35	------>	0.0000	0.00 %
37	------>	0.0000	0.00 %
40	------>	0.1290	12.90 %
43	------>	0.1452	14.52 %
45	------>	0.1613	16.13 %
47	------>	0.1290	12.90 %
49	------>	0.1290	12.90 %
51	------>	0.1452	14.52 %
53	------>	0.1613	16.13 %
Expected value (days)= 47 ==> 47			
Standard Deviation (days)= 4.23503 ==> 4			

Probability Bar Graph

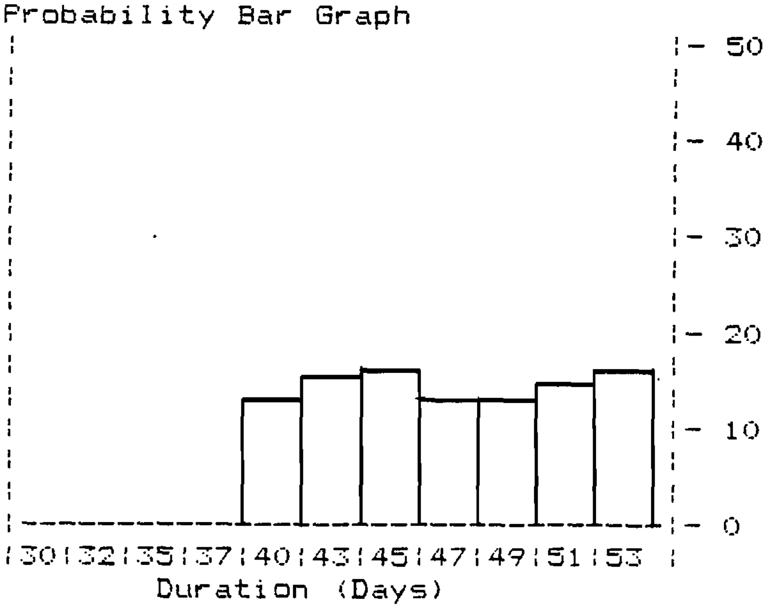


TABLE 20

Sensitivity Analysis

General Linguistic Values

SMALL				MED				LARGE			
0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.7	0.5	0.2	0.3	0.8	1.0	0.6	0.7	0.9	1.0	Membership Values

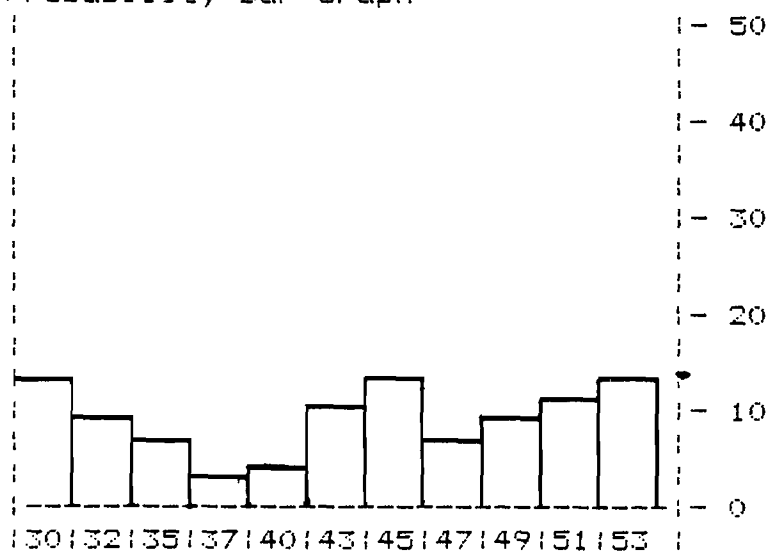
F I N A L   R E S U L T S   T A B L E

Duration		Probability	
30	----->	0.1299	12.99 %
32	----->	0.0909	9.09 %
35	----->	0.0649	6.49 %
37	----->	0.0260	2.60 %
40	----->	0.0390	3.90 %
43	----->	0.1039	10.39 %
45	----->	0.1299	12.99 %
47	----->	0.0779	7.79 %
49	----->	0.0909	9.09 %
51	----->	0.1169	11.69 %
53	----->	0.1299	12.99 %

= Expected value (days)= 42.8701 ==> 43 =

= Standard Deviation (days)= 7.99245 ==> 8 =

Probability Bar Graph



Duration (Days)

TABLE 21

Sensitivity Analysis - OVERLAP EXAMPLE

General Linguistic Values

0	1	2	3	4	5	6	7	8	9	10	X's Values
1.0	0.7	0.5	0.2	0.3	0.8	1.0	0.6	0.7	0.9	1.0	Menbership Values

```
|------ SMALL ----------|
                   |-------- MEDIUM ------------|
                                      |------ LARGE ------|
```

F I N A L   R E S U L T S   T A B L E

Duration		Probability	
30	------>	0.0469	4.69 %
32	------>	0.0469	4.69 %
35	------>	0.0469	4.69 %
37	------>	0.0313	3.13 %
40	------>	0.0469	4.69 %
43	------>	0.1250	12.50 %
45	------>	0.1563	15.63 %
47	------>	0.0938	9.38 %
49	------>	0.1094	10.94 %
51	------>	0.1406	14.06 %
53	------>	0.1563	15.63 %

= Expected value (days)= 45.2031 ==> 45

= Standard Deviation (days)= 6.63132 ==> 7

Probability Bar Graph

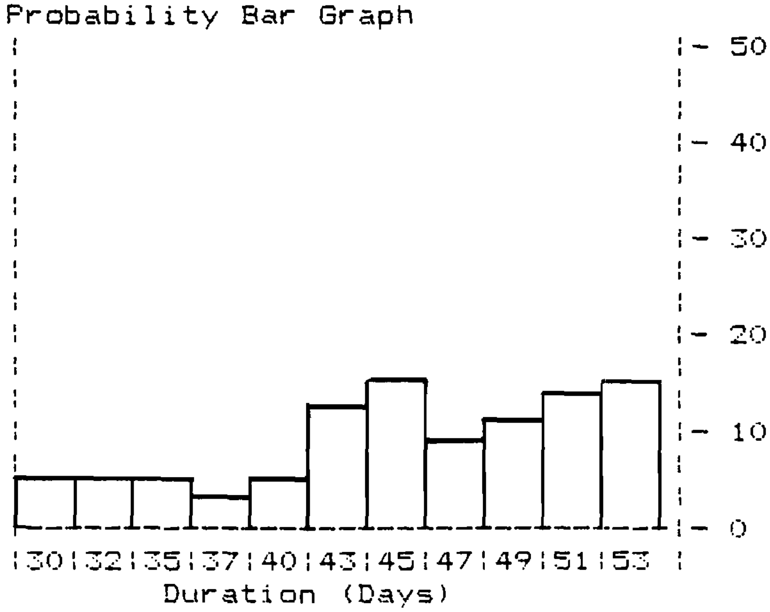


TABLE 22

solved again but this time with the following limits assigned to the linguistic values:

	Lower Limit.	Upper Limit.
SMALL ⟶	0	4
MEDIUM ⟶	3	8
LARGE ⟶	7	10

As shown in Table 22, the expected duration (Da) was equal to 45.20 days and the standard deviation (σDa) was equal to 6.63 days. By analyzing these results, it can be clearly noted that they are quite different from the results shown in Table 10. For this reason, it was deduced that this technique is sensitive to the choice of the limits assigned to the different linguistic values. This is not a desired property of this technique since there is not a defined criterion to assign these limits to the different linguistic variables.

VIII. Problems, Findings, and Implementations:

The implementation of the fuzzy set theory presents two major problems, first: how to associate a label to an unlabeled fuzzy set on the basis of semantic similarity (linguistic approximation), and second: how to perform arithmetic operations with fuzzy numbers.

There is also a lack of adequate tools available for evaluating the membership value of a fuzzy set. Since this evaluation marks the starting point for using this theory, many researchers are tempted to choose a membership function heuristically.

In some cases, a simple ranking method of the natural expressions are used to model complex linguistic variables, however, this kind of analysis is simply a trick, and should not be implemented. For example, ranking language expressions as Low = 1, High = 9, and then averaging the two ranks in order to calculate Medium as:

$$\text{Medium} = \frac{\text{Low} + \text{High}}{2} = \frac{1 + 9}{2} = 5$$

This kind of analysis should not be applied. Natural expressions should be combined meaningfully by fuzzy set theory, unlike the simple averaging scheme detailed above.

Although, extensive research has been done to develop the basic concepts of fuzzy set theory, it often happens that each individual researcher has his own intuitive notions about how concepts should be applied, and it is not always possible to preserve all such intuitions when extending defintiions to the realm of fuzzy sets.

Two risk analysis models were developed to provide a linguistic approach based on fuzzy set theory. Most of the uncertainty factors in construction industry are ill-defined, usually they can be described by experts (e.g., project manager, and field engineer) in linguistic (qualitative) terms rather than numerical terms. It was found that the conventional quantitative risk analysis techniques do not include all the available data in their analysis, therefore, the additional (or in place of) available information (linguistic data) should be considered by utilizing fuzzy set theory as a base for captuing linguistic information.

It was concluded that fuzzy set theory is an appropriate tool for construction risk analysis. However, the mathematical calculations become very complex as number of uncertainty factors increase. APL computer language is an appropriate program for fuzzy set analysis.

For future research, the investigator believes that research should continue in two directions: 1) testing and validating the developed models by experts in construction industry and insurance companies; and 2) developing a knowledge-based expert system for construction risk analysis by fuzzy sets.

IX. Publications and Graduate Research Assistants:

Two papers about construction risk analysis based on this research has been presented: 1) "Application of Expert Systems to Construction Management Decision-Making and Risk Analysis", published in the Proceedings of the Expert Systems in Civil Engineering in the ASCE Convention in Seattle, Washington, April 8-9, 1986; and 2) "Knowledge-Based Expert Systems for Construction Risk Analysis", published in the Proceedings of the 10th Congress of the CIB.86 in the Advancing Building Technology in Washington, D.C., September 22-26, 1986. A copy of each paper is presented in the appendix.

The investigator also acknowledges the contributions of Nicholas Latoussakis, Gudni Gudnason, Zuhair El-Itr, and Choong-Hee Han, graduate research assistants at the School of Civil Engineering, Georgia Institute of Technology.

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APPENDIX

Construction Risk Analysis Papers
Presented at Two Conferences

1. ASCE Convention

2. CIB.86 Congress

EXPERT SYSTEMS

IN CIVIL ENGINEERING

Proceedings of a Symposium sponsored by the
Technical Council on Computer Practices
of the American Society of Civil Engineers
in conjunction with the ASCE Convention in
Seattle, Washington
April 8-9, 1986

Published by the
American Society of Civil Engineers
345 East 47th Street
New York, New York 10017-2398

Application of Expert Systems to Construction Management Decision-Making and Risk Analysis

By Roozbeh Kangari,[1] M. ASCE

ABSTRACT: Application of expert systems in the area of construction management decision-making and risk analysis are explored. Decision-making under uncertainty is one of the attributes of human intelligence. Contractors use rules of thumb and subjective evaluation to analyze a construction project's uncertainty elements. Traditional construction risk analysis models based on algorithmic programs have not fully incorporated the significance of empirical knowledge. As a result of this deficiency, the practical application of these models have been limited. A successful construction risk management system requires a significant amount of empirical input from construction experts and specialists. The main objective of this paper is to present the potential applications of knowledge based expert systems in risk management. A microcomputer rule-based expert system is introduced. Difficulties in developing the system are discussed.

INTRODUCTION:

The construction industry is a dynamic field with a high rate of business failure among contractors. Major causes of the failures according to Dun and Bradstreet are directly related to management problems. Construction engineering and management involves many complex decision-making problems in such areas as resource planning, cost estimating and control, contractual and legal, political and public, and other construction management related problems. The analysis of risk associated with each of these factors is a topic of great practical interest, because these risks are potentially serious and have high financial and social impact on major parties involved in the project.

Traditionally, construction risk analysis models are developed based on algorithmic analysis and optimization programs. In these models the creative component of the construction risk analysis has been largely ignored. In the real construction world, a large number of decision-making rules are not based on the mathematical law, but they are based on the contractor's assumptions, limitations, rules of thumb, and management style. Contractors use rules of thumb and subjective evaluations to analyze the uncertainty factors for solving the problems. This is basically due to the fact that construction industry has an ill-defined and ill-structured environment. At every

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level of decision-making, an engineer has to rely on his judgement and expertise.

The traditional algorithmic risk analysis and evaluation models have not fully incorporated the significance of empirical knowledge. As a result, model users are usually faced with intractable questions. This deficiency has made it impossible for contractors to practically implement these algorithmic models successfully.

A successful construction risk management system requires a significant amount of empirical inputs from construction experts and specialists. This information can be denoted as empirical knowledge, which includes heuristic rules, expert opinions and inferences, and rules of thumb. Empirical knowledge plays a major role at every stage of construction decision-making. Many risk analysis models have failed due to the lack of expert support for novice or semi-experienced model users.

Recent advances in Artificial Intelligence have created new opportunities for solving ill-defined construction management problems by Expert Systems (2, 4, 6, and 7). This allows risk analysis models to combine the classical, physically-based type knowledge, with the much larger body of empirical, rule-based knowledge. This is an important step in the direction of more advanced and practical construction risk analysis and evaluation models.

OBJECTIVES AND SCOPE:

The objectives of this paper are to explore the implementation of expert systems in construction risk analysis, and to develop a prototype expert system for decision-making under uncertainty. This paper is focused on risk analysis from contractors viewpoint.

During the next decade, the field of expert systems will have an impact on all areas of construction management where knowledge provides the power for solving construction engineering and management problems. The first and most obvious advance will be the development of construction management knowledge base which converts professional construction knowledge into an efficient and productive industrial field. The second benefit is that expert construction systems will catalyze a global effort to collect, codify, exchange, and exploit applicable forms of construction engineering and management knowledge.

In recent years, researchers in the construction field have shown a strong interest in implementing artificial intelligence techniques into the construction field. Expert systems have been implemented in the following construction related areas: pump repair; well selection; structural design; change order evaluation; advice on quality control; estimating the safety practices of contractors seeking bonding; claims analysis; planning and scheduling; construction robotics; etc. The common objective of these expert systems is to absorb technical knowledge from experts, apply it to various situations, and reach conclusions (8,9,11,14,15, and 16).

APPLICATION OF EXPERT SYSTEMS IN CONSTRUCTION RISK ANALYSIS:

Let us look first at the characteristics of construction risk management which makes expert system development possible. One of the most important characteristics is that people with an extremely high level of expertise exist in the construction management area. They have many years of professional construction experience, and can provide the knowledge necessary to build the expert systems. Many of these people are able to articulate and explain the methods that they use to analyze risk.

The second aspect which makes construction risk management appropriate for expert system is that risk management is cognitive, and does not require physical skills. The third characteristic is that risk analysis is not too difficult or too complex for a knowledge engineer to approach. Many sources of information (e.g., papers, books, and etc.) are available in this area which can establish the basic framework for knowledge acquisition.

There are many reasons which justify expert system development effort in risk analysis. First, risks associated with construction projects are potentially serious and have financial and social impact on contractors; therefore, there is a reasonable possibility of high payoff when an expert system is developed. Second, for an inexperienced engineer an expert system can act as an advisor when the professional experts are unavailable. Expert systems are justified especially when significant expertise is being lost to a construction company through personnel changes (e.g., retirement, job transfers, etc.). Finally, expert system development in construction risk management is justified because of the dynamic, ill-structured, and high risk environment of construction field which requires quick decision-making (9,10,13).

In summary, construction risk management is an appropriate area for expert systems since it requires symbolic reasoning, and it is heuristic in nature, that is, it requires the use of rules of thumb to solve problems. Risk management is not easy to model, it takes a human years of study or practice to achieve the status of an expert. Finally, it is of manageable size to be handled adequately by expert systems, and it has a practical value.

COMPONENTS OF RISK MANAGEMENT EXPERT SYSTEM:

Figure 1 shows a schematic view of the construction risk management expert system. The system helps contractors to identify the uncertainty factors, and provides a risk index for the overall project. The system is implemented in INSIGHT 2, a microcomputer knowledge engineering language for rule-based representation. The knowledge base systems created with INSIGHT 2 are complete knowledge and information processing systems capable of applying heuristic knowledge to direct the control and management of conventional programs and data bases. The system's control structure makes use of backward and forward chainings. Numeric data can be expressed as

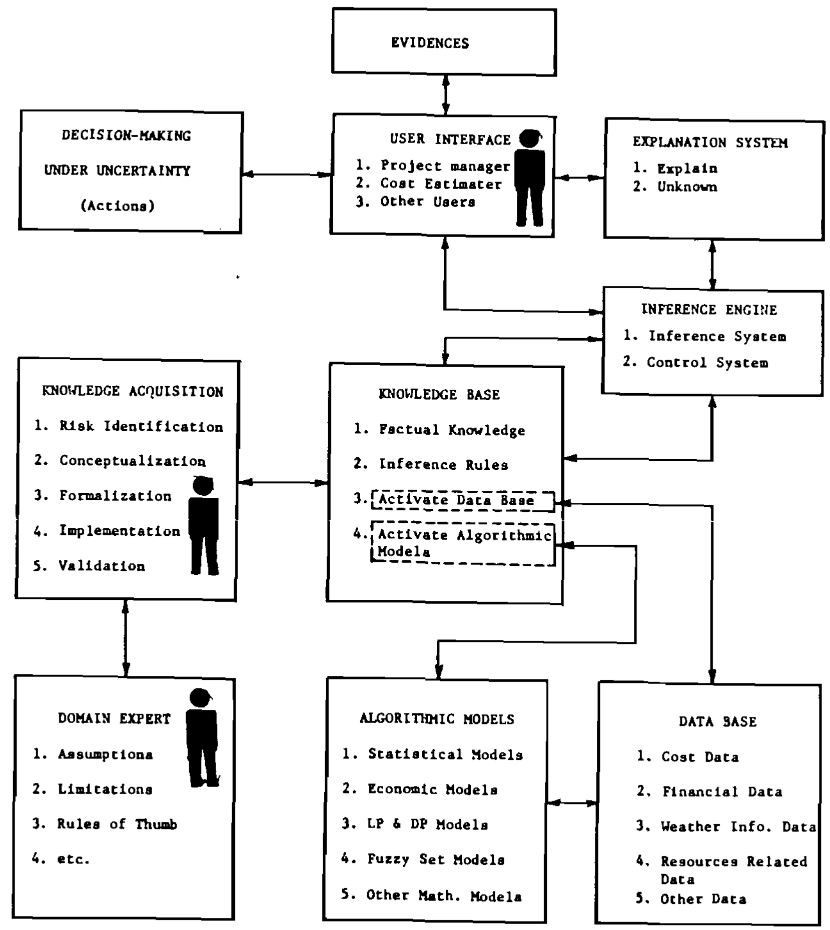

FIG. 1.- Basic Structure of Risk Management Knowledge Base Expert System

real numbers and variables and can be manipulated with the basic relational and arithmetic operations. Each supporting condition and conclusion of a rule can have its own confidence factor. Each knowledge base has a variable threshold of acceptability which is used to evaluate the viability of a path of reasoning. The system also provides the facility for the activation of other programs written in any language during the execution of a knowledge base. The system also contains an interface to a Pascal programming environment which is extended to support direct access to dBASE *II* data base files. Through this interface, the system provides a rule-based expert system the capability to use the power of Pascal (or other languages) for complex algorithmic computing as well as relational data base access and manipulation. The system is capable of handling up to two thousand rules which is considered sufficient for risk analysis. A portable microcomputer was used during the interviews with contractors and bonding companies to get feedback from experts. The major components of the risk management system are described in the following section.

Risk Management Knowledge Base:

The knowledge base is a repository of basic knowledge and rules of construction risk management. The knowledge was collected from three basic sources: 1) Interviews with contractors; 2) Journal papers, and 3) Text books. The basic framework was established based on the last two parts, and the system was modified by contractors. At the beginning, a small system was developed, and then incrementally a significant testable system was built. First, the specification of goals, and constraints was defined. Second, a general description and classification of construction risk, in terms of hypotheses, data, and intermediate reasoning concepts was constructed as shown in Figure 2. Third, the identified elements were represented in a rule-based (IF-THEN) format (1,3,5,12, and 17). Then, the system was tested against more complex and real cases. Many adjustments of the elements and their relationships were a result of these tests.

All the contractors interviewed had at least ten years of construction experience and a yearly volume of less than $50 million. One of the most important considerations of every firm was the amount of time allowed by the owner for completion as related to the type and amount of liquidated damages in the contract. A contract with heavy liquidated damages combined with a very short time allowed for completion presented a large and almost unacceptable risk. Another item was the client/contractor relationship. A good strong client relationship was highly valued and sought after when the contractor is considering new work. Such a relationship will mitigate or dramatically lessen a contractor's risk in such areas as poorly written contract language or vague project drawings. Other contractor considerations also included existing workload, repeat clients, and project location.

The foremost consideration of the surety companies is the financial stability of the general contractor. A contractor wishing to become bonded for a project or to increase his bonding capacity

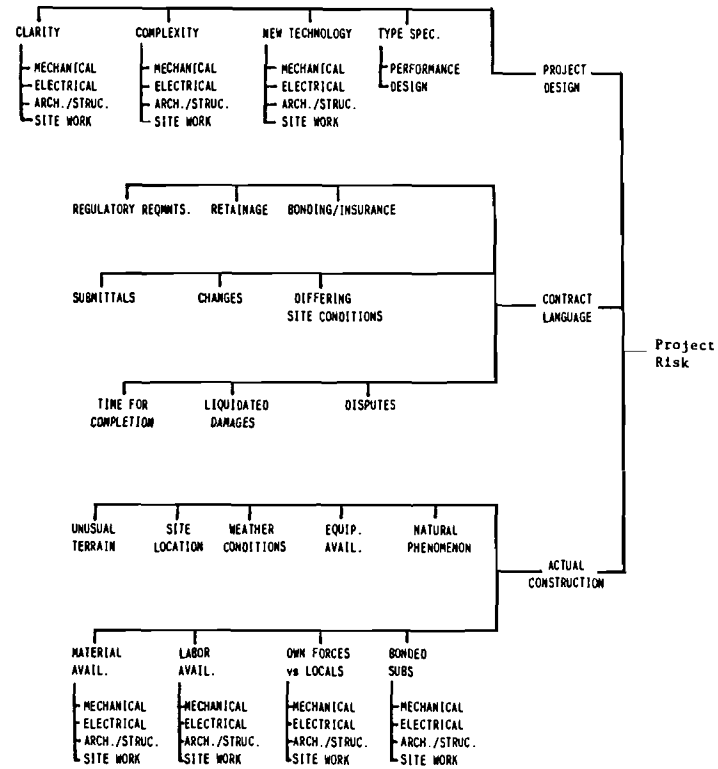

FIG. 2.- Inference Chain of Uncertainty Elements

must furnish the surety with copies of his company's financial statements, letters or proof of credit, and tax records. Next, the surety looks at the company's performance history. Such things as bankruptcy and failure of performance on previous jobs, and size of jobs performed by the contractor over the last few years. The surety will then want to know who the general contractor will assign as the project supervisors for the job and their technical qualifications. The type of work is also another major element. The results of these interviews were then presented in rule-based format to enhance the risk management knowledge base.

User Interface:

The user interface provides capability for the user (e.g., project manager, estimator, and others) to monitor the performance of the system, and provides input concerning construction work conditions, sources of uncertainty, confidence levels, cost and economic data, type of contract, information about subcontractors, and etc.

The system provides the user with trace or display of system operation by listing all rules fired and the names of all subroutines called. The system also provides menus of risk factors for the user to select from when inputing the requested information. The risk management expert system also explains to users how it reached particular conclusions.

This system provides the user a mechanism for editing. This is just a standard text editor for modifying rules and data by hand. It also provides an UNKNOWN function which allows the user to bypass the unknown questions, and continue with the process of trying to reach a conclusion from the information it can obtain.

DIFFICULTIES IN DEVELOPING AN EXPERT SYSTEM FOR RISK MANAGEMENT:

There are several types of difficulties in developing an expert system for risk management: 1) lack of resources; 2) limitations of expert systems, and 3) time required to build.

The lack of resources needed for the job consists of two elements: a) Personnel; and b) Expert system tools. The personnel required to build an expert system consists of at least a knowledge engineer and an expert. It was found that knowledge acquisition for risk management is the most difficult part of the system. The knowledge engineer must be familiar with the concepts of construction management, and the expert should provide a sufficient time to build the system. The expert system tools are still in the stage of development and only few of the high-level support tools and languages are fully developed or reliable. In fact, many of them are new and untested.

Current expert systems and expert system tools have limitations, many of which will gradually disappear as AI researchers advance the state of the art. Expert systems have a very narrow domain of expertise and hence their operation is not as robust as the users might want. They also have difficulty dealing with inconsistent knowledge.

Finally, building an expert system takes time. The actual time required to build a system depends on problem complexity and number of people assigned to the effort.

SUMMARY AND CONCLUSION:

Construction management risk analysis expert system is developed to assist management with complex decision-making under uncertainty. Expert systems will make it possible to develop quick answers for management problems. It will also help contractors to solve their productivity problems. Contractors can reorganize themselves into more efficient and effective organizations. Management will be able to monitor projects more effectively, and secure their profit by managing and forecasting the uncertainty factors. In summary, the construction industry will become much more rational. More information will be gathered, synthesized, and put into useful form more rapidly than has ever before been possible.

During the next four to five years many small knowledge systems and narrow expert systems will be developed for decision-making under uncertainty. The more complex hybrid systems, the integration of natural language, and the development of intelligent workstations that incorporate a large number of different knowledge systems in a microcomputer will be developed at the end of this decade.

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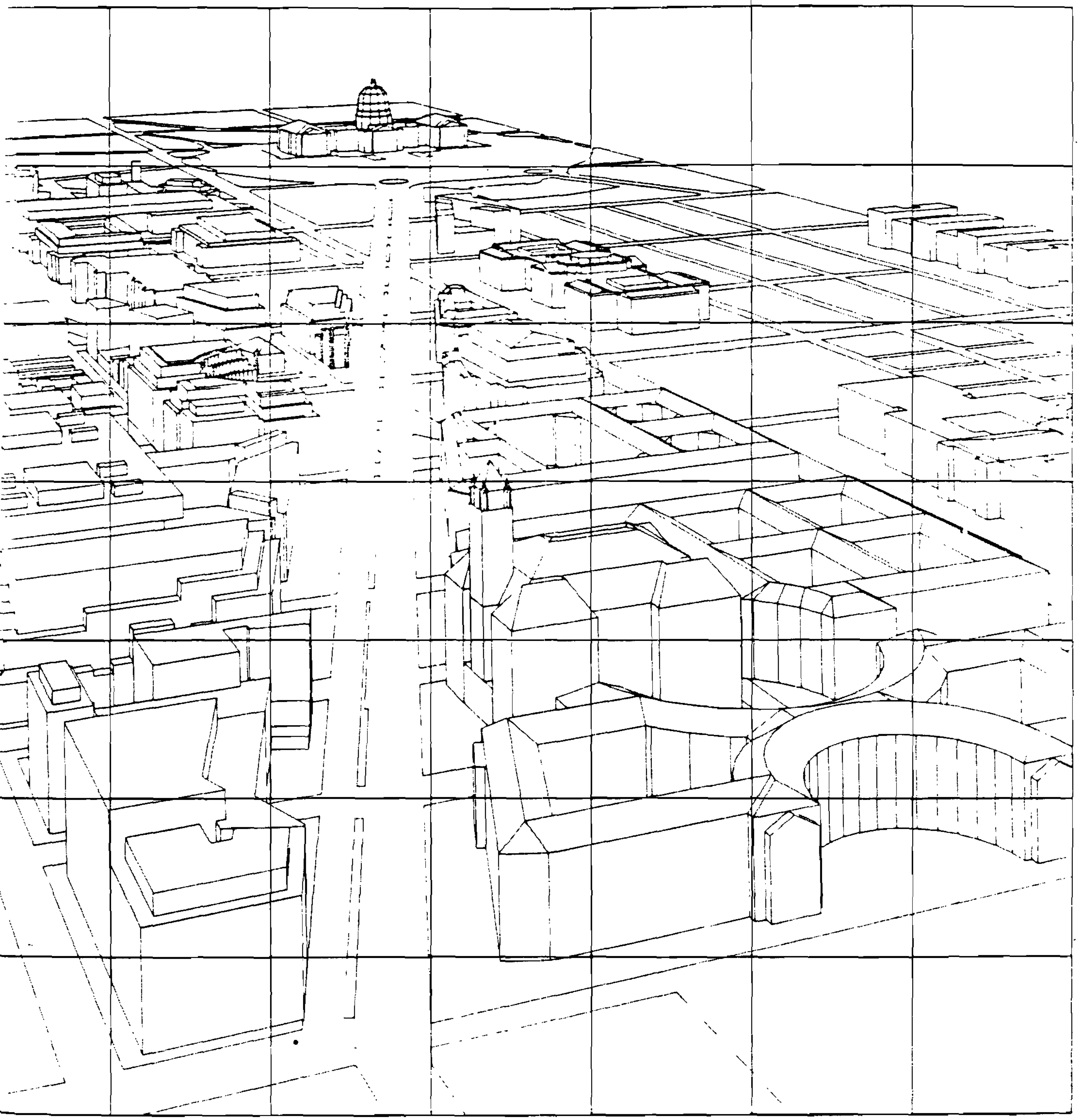
Computer Data Bases and Information Services

Knowledge-based Expert Systems to Aid Decision Making



Systèmes experts basés sur la connaissance pour l'analyse des risques de la construction.

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MOTS CLEFS:

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Sommaire:

La construction et la gestion comprennent un grand nombre de problèmes complexes qui demandent des prises de décision concernant la gestion des ressources, le calcul et le contrôle des frais, l'étude des procédés de construction, la prévision des risques, et divers autres problèmes associés à la gestion de la construction. La plupart de ces tâches dépendent en grande partie du jugement de l'ingénieur. L'entrepreneur, pour résoudre certains problèmes, se voit dans l'obligation d'utiliser des méthodes empiriques et des évaluations subjectives. Traditionnellement, les modèles de gestion de la construction sont basés sur des analyses algorithmiques explicites et sur des programmes d'optimisation. Dans le cas de ces modèles, l'élément créatif de la gestion de la construction a été grandement ignoré. Dans le monde réel de la construction, un grand nombre de décisions sont prises en se basant sur les suppositions, les limitations, les méthodes empiriques et le style de gestion d'un expert, et non sur des lois mathématiques. Cet expert possède une grande expérience des opérations de construction, est capable d'identifier les conditions existantes et de prendre les mesures appropriées. Le principal objectif de cet exposé est la présentation d'un système expert basé sur la connaissance en vue de l'analyse des risques de la construction, système qui permettra aux ingénieurs de chantier ayant peu d'expérience à leur actif de prendre les mêmes décisions que s'ils bénéficiaient des conseils et des directives d'un expert en construction. Le modèle décrit comment les professionnels utilisent, intègrent et combinent les éléments d'information et de connaissance dont ils disposent dans le but de développer un modèle efficace et innovateur concernant les prises de décisions en matière de gestion.

INTRODUCTION

A construction project is continuously influenced by uncertainty factors. These uncertainty factors have high financial and social impact on major parties involved in the project. Some of these uncertain or risk factors can be managed in advance. However, most of them can not be eliminated. Therefore, construction engineering and management involves many complex decision-making tasks under uncertainty (Ref. 1). Contractors use rules of thumb and subjective evaluations to analyze the uncertainty factors. A successful construction risk management system requires a significant amount of empirical knowledge from construction experts and specialists.

Traditional construction risk management systems are developed based on algorithmic analysis. In these models the creative component of the construction risk analysis has been largely ignored. In the real construction world, construction management rules are not based on mathematical laws, but are based on the contractor's assumptions, limitations, rules of thumb, and management style. The traditional algorithmic risk management models have not fully incorporated the significance of empirical knowledge. Emprical knowledge plays a major role at every stage of construction decision-making. Many risk analysis models have failed due to the lack of expert support for novice or semi-experienced model users (Ref. 2).

The objectives of this paper are to explore the application of expert systems in construction risk management, and to develop a prototype expert system for decision-making under uncertainty. This paper is focused on risk analysis from contractors viewpoint.

CONSTRUCTION RISK ANALYSIS

Risk is commonly defined as chance of injury, damage, or loss. Although these definitions are easy to understand, they are not suitable for risk analysis since they can be interpreted in different ways and are not explicit enough to allow measurement. The subject of risk is very complex and no single method of risk analysis is free of weakness. This paper defines risk as dispersion of outcomes around the expected value (Ref. 3).

The identification and effective evaluation of risk is an important requirement for successful project selection. Continued growth and complexity of construction projects require fundamental knowledge concerning the identification and evaluation of project risk by contractors. The construction industry is becoming a more changing, uncertain environment than before. As the underlying conditions are changing, the available information that indicates the trends, cycles, or seasonal fluctuations should be taken into account.

There are many reasons which justify expert system development effort in risk analysis. First, risks associated with construction projects are potentially serious and have significant financial and social impact on contractors; therefore, there is a reasonable possibility of high payoff when an expert system is developed. Second, for an inexperienced engineer an expert system can act as an advisor when the professional experts are unavailable. Expert systems are justified especially when significant expertise is being lost to a construction company through personnel changes (e.g., retirement, job transfers, etc.). Finally, expert system development in construction risk management is justified because of the dynamic, ill-structured, and high risk environment of construction field which requires quick decision-making.

RISK ANALYSIS BY EXPERT SYSTEMS

To apply expert systems in construction risk analysis, first, the characteristics of uncertainty management must be explored. One of the most important characteristics is that people with an extremely high level of expertise exist in the construction management area. They have many years of professional construction experience, and can provide the knowledge necessary to build expert systems. Many of these people are able to articulate and explain the methods that they use to analyze risk. The second aspect which makes construction risk management appropriate for expert system is that risk management is cognitive, and does not require physical skills. The third characteristic is that risk analysis is not too difficult or too complex for a knowledge engineer to approach. Many sources of information (e.g., papers, books, and etc.) are available in this area which can establish the basic framework for knowledge acquisition. Therefore, it can be concluded that construction risk management is an appropriate area for expert systems since it requires symbolic reasoning, and it is heuristic in nature, that is, it requires the use of rules of thumb to solve problems. Risk management is not easy to model, it takes a human years of study or practice to achieve the status of an expert. Finally, it is of manageable size to be handled adequately by expert systems, and it has a practical value.

KNOWLEDGE ENGINEERING

Any intelligent analysis of risk requires appropriate knowledge. It can be said that knowledge is information that the computer can think about. The objective of this section is to present and describe the main components of the Micro Construction Risk Management Expert System.

The first step was to select an appropriate expert system shell. The next question was whether a large system designed to run on a large mainframe or a microcomputer shell program should be implemented. For many reasons it was decided to work with micro programs. The first reason was familiarity with micro systems. The second reason was low cost of resources, and the third reason was the type of application which was anticipated (Ref. 4).

Figure 1 shows a schematic view of the construction risk management expert system. The system helps contractors to identify the uncertainty factors, and provides a risk index for the overall project. The system is implemented in INSIGHT 2, a microcomputer knowledge engineering language for rule-based representation. The knowledge base systems created with INSIGHT 2 are complete knowledge and information processing systems capable of applying heuristic knowledge to direct the control and

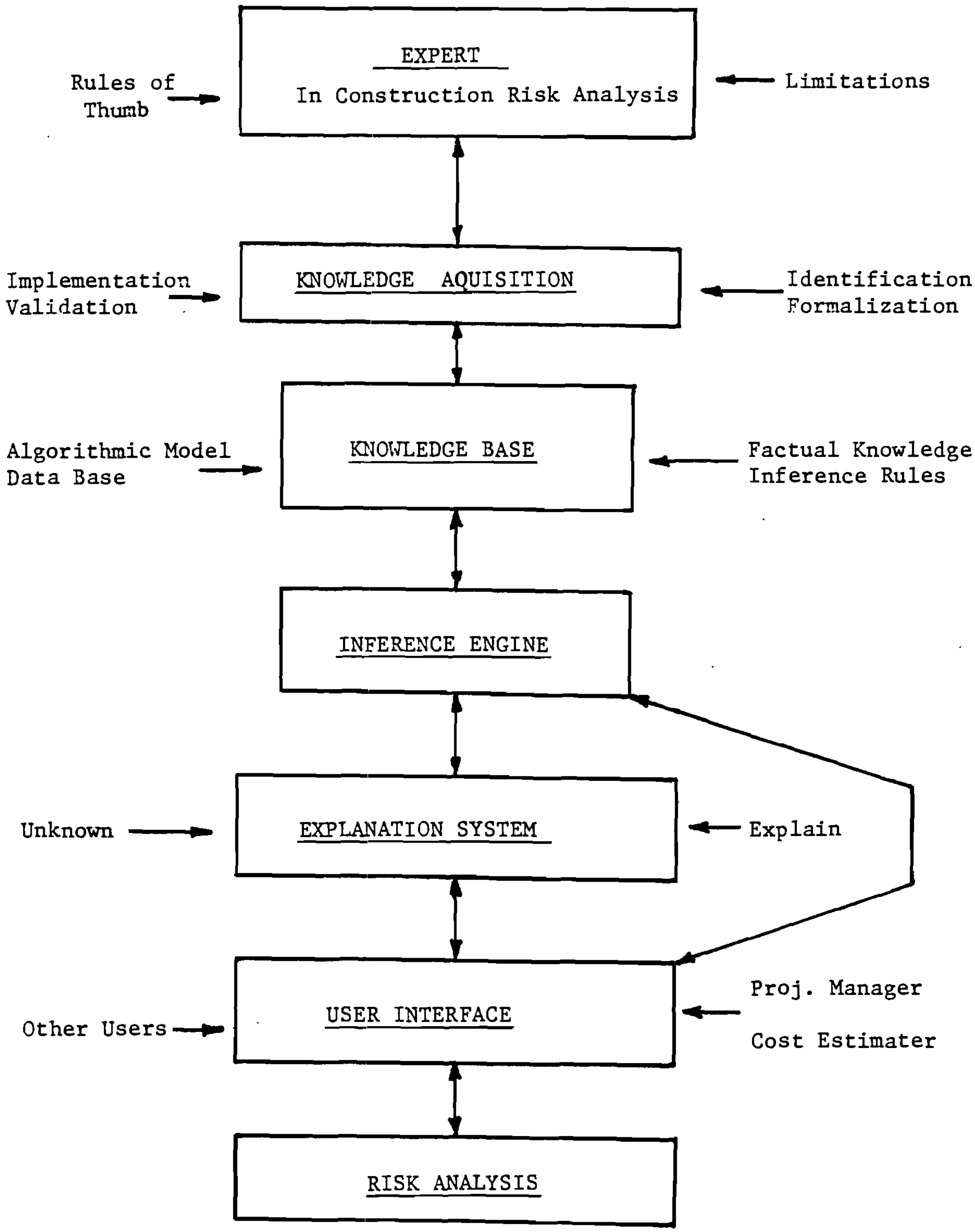

Fig. 1- General Feature of Risk Analysis Expert System

management of conventional programs with data bases. The system's control structure makes use of backward and forward chainings. Numeric data can be expressed as real numbers and variables and can be manipulated with the basic relational and arithmetic operations. Each supporting condition and conclusion of a rule can have its own confidence factor. Each knowledge base has a variable threshold of acceptability which is used to evaluate the viability of a path of reasoning. The system provides the facility for the activation of other programs written in any language during the execution of a knowledge base. The system also contains an interface to a Pascal programming environment which is extended to support direct access to dBASE II data base files. Through this interface, the system provides a rule-based expert system the capability to use the power of Pascal (or other languages) for complex algorithmic computing as well as relational data base access and manipulation. The system is capable of handling up to two thousand rules which is considered sufficient for risk analysis. A portable microcomputer was used during the interviews with contractors and bonding companies to get feedback from experts.

KNOWLEDGE BASE

One of the major components of a construction risk management expert system is the knowledge base. The knowledge base as shown in Figure 1 is that portion of expert system that contains the knowledge (information) of risk management. The knowledge was collected from various sources such as: interviews with contractors, journal papers about construction risk analysis, and text books. The basic framework was established based on the last two parts, and the system was modified by contractors. At the beginning, a small system was developed, and then incrementally a significant testable system was built. First, the specification of goals, and constraints was defined. Second, a general description and classification of construction risk, in terms of hypotheses, data, and intermediate reasoning concepts was constructed as shown in Figure 2. Third, the identified elements were represented in a rule-based (IF-THEN) format (Refs. 5, 6, and 7). Then, the system was tested against more complex and real cases. Many adjustments of the elements and their relationships were a result of these tests.

All the contractors interviewed had at least ten years of construction experience and a yearly volume of less than $50 million. One of the most important considerations of every firm was the amount of time allowed by the owner for completion as related to the type and amount of liquidated damages in the contract. A contract with heavy liquidated damages combined with a very short time allowed for completion presented a large and almost unacceptable risk. Another item was the client/contractor relationship. A good strong client relationship was highly valued and sought after when the contractor is considering new work. Such a relationship will mitigate or dramtically lessen a contractor's risk in such areas as poorly written contract language or vague project drawings. Other contractor considerations also included existing workload, repeat clients, and project location.

The foremost consideration of the surety companies is the financial stability of the general contractor. A contractor wishing to become

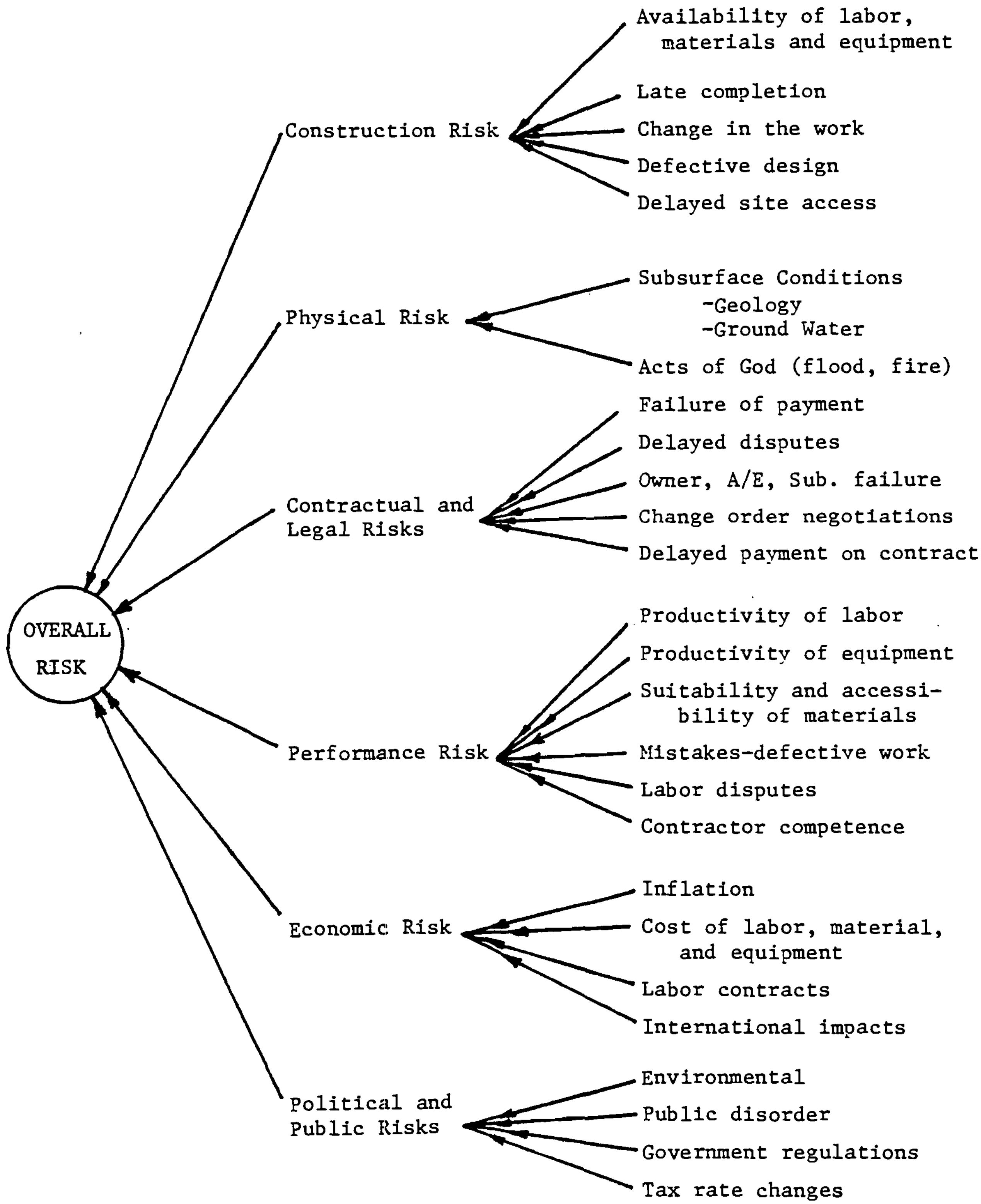

Fig. 2- Risk Management Inference Chain

bonded for a project or to increase his bonding capacity must furnish the surety with copies of his company's financial statements, letters or proof of credit, and tax records. Next, the surety looks at the company's performance on previous jobs, and size of jobs performed by the contractor over the last few years. The surety will then want to know who the general contractor will assign as the project supervisors for the job and their technical qualifications. The type of work is also another major element. The results of these interviews were then presented in rule-based format to enhance the risk management knowledge base.

MICROCOMPUTER APPLICATION

Primary motivations for implementing the construction risk management expert system on microcomputers were: 1) low cost of software programs; 2) availability of microcomputers by contractors in the field and main office; and 3) transportability of micros to construction sites (i.e., portable microcomputers). Overall, it appears that a primary advantage of implementing expert systems on microcomputers is that these computers provide potential users with a low risk opportunity to bring expert systems capabilities in construction site.

Although large scale expert systems have been providing themselves on minicomputers and mainframes for several years, AI developers are just beginning to develop programs for personal computers. Many micro expert system shells such as: Exsys (Exsys Inc.); Expert-Easte (Human Edge Software Corp.); Insight 2 (Level Five Research Inc.); KDS (KDS Corp.); KES (Software Architecture and Engineering Inc.); M.1 (Teknowledge Inc.); MicroExpert (McGraw-Hill Co.); Personal Consultant (Texas Instruments Inc.); and TIMM-PC (General Research Corp.) are commercially available (Ref. 8). These programs allow sophisticated users to build their own small expert systems without having to learn specialized programming languages such as LISP.

SUMMARY AND CONCLUSION

Expert systems are appropriate computer programs for construction risk analysis. These programs typically represent knowledge symbolically, examine and explain their reasoning processes, and address problem areas that require special education and experience. Expert systems will make it possible to develop quick answers for management problems. It will also help contractors to solve their productivity problems. Contractors can reorganize themselves into more efficient and effective organizations. Management will be able to monitor projects more effectively, and secure their profit by managing and forecasting the uncertainty factors. In summary, the construction industry will become much more rational. More information will be gathered, synthesized, and put into useful form more rapidly than has ever before been possible.

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