CHAPTER V

APPLICATION OF RISK ASSESSMENT INTEGRATED WITHIN RANDOM–FUZZY NETWORK (RAIRFNET) TO A TUNNELING CONSTRUCTION PROJECT

This section is to illustrate the calculations performed using the concept of random–fuzzy variables incorporated in the risk assessment and to interpret a given degree of risk. It is also used to show how to integrate the risk assessment results into the schedule network. First, the characteristics of a tunneling project employed to demonstrate the applications is described. As some data are unavailable, any assumption and adjustment are provided in order for the demonstrative example to apply the proposed RAIRNET. Then, outputs provided by applying the RAIRFNET to the tunneling project are discussed in detail. Next, results obtained from the proposed methods including the RAIRFNET using the Salicone's method processed on data associated with duration of project activities, the RAIRFNET using the neurofuzzy metamodel trained on data associated with duration of project activities, the Salicone's method processed on data associated with project completion times, the neurofuzzy metamodel trained on data associated with project completion times and Monte Carlo simulation are compared.

5.1 Example Project

To perform the demonstrative application of RAIRFNET, details of an actual drainage water tunneling project being constructed in Bangkok. are discussed in this section. This project is adopted from the literature (Sarutirattanaworakun, 2005). Based on the available information, the main tunneling operation of this project is composed of three main processes: 1) tunnel excavation by an EPB machine, 2) tunnel lining installation, and 3) muck and lining transportation. There are 14 activities (i.e., toloadsoil, loadsoil, excavate, returntoshaft, locoout, unloadsoil, TBMinstallsl, TBMinspsl, loadsl, locoin, outofshaft, totunnel, and unloadsl) presented through the network shown in Figure 5.1. .

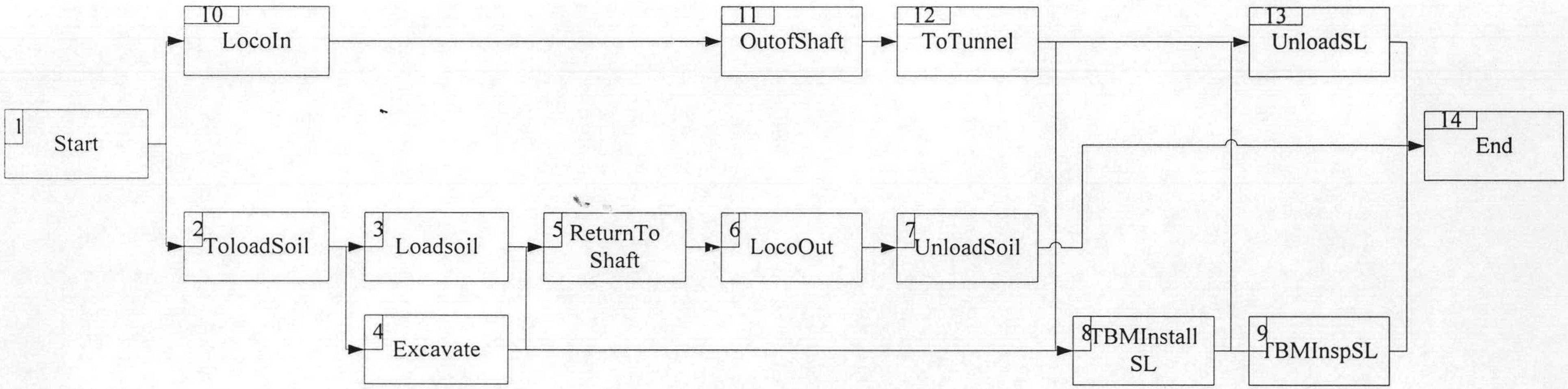

Figure 5.1 A scheduling network of a tunneling construction project

The precedence logic of tunneling processes was developed by integrating the sequence of the tunneling processes with technical and resource constraints. The network and its detailed description are also presented by using a time – scaled arrow network. The main activities are decomposed into 28 sub-activities. To develop a simulation model to capture the sequence of tunneling process, this process is investigated and summarized. The probabilistic scheduling network of the tunneling construction process established by Sarutirattanaworakun (2005) as shown in Figure 5.2 is analyzed by using the STROBOSCOPE simulation system (Martinez, 1996).

The tunnel construction is used to present the application of the RAIRFNET as it is one of the most complex and risky types of construction projects. It does not only involve a large number of interrelated operations, but it is also affected by several uncontrollable factors. The uncontrollable factors accordingly make the durations of activities and the project completion time for the future become very uncertain.

Simulation models were developed based on different construction scenarios to yield realistic results. Uncertainty associated with tunneling processes was assimilated through random process duration. The parameters of the time equations were assessed by using the PERT method. The optimistic, most likely, and pessimistic speeds of the train in this project were estimated.

To apply the RAIRFNET, the activity duration and attributes of a risk factor are considered as random–fuzzy variables. The means and variances of representing the random part of these random–fuzzy variables are obtained by executing simulation models. The corresponding membership functions of the random–fuzzy variables are developed by using the probability–possibility transformation method (Silicone, 2007) and alternatively the neurofuzzy metamodel. As all input data required by the RAIRFNET cannot be obtained from Sarutirattanaworakun (2005), some assumptions are made together the use of the identified risk factors and available information associated with their attributes obtained from the literature (Pongmee, 2006).

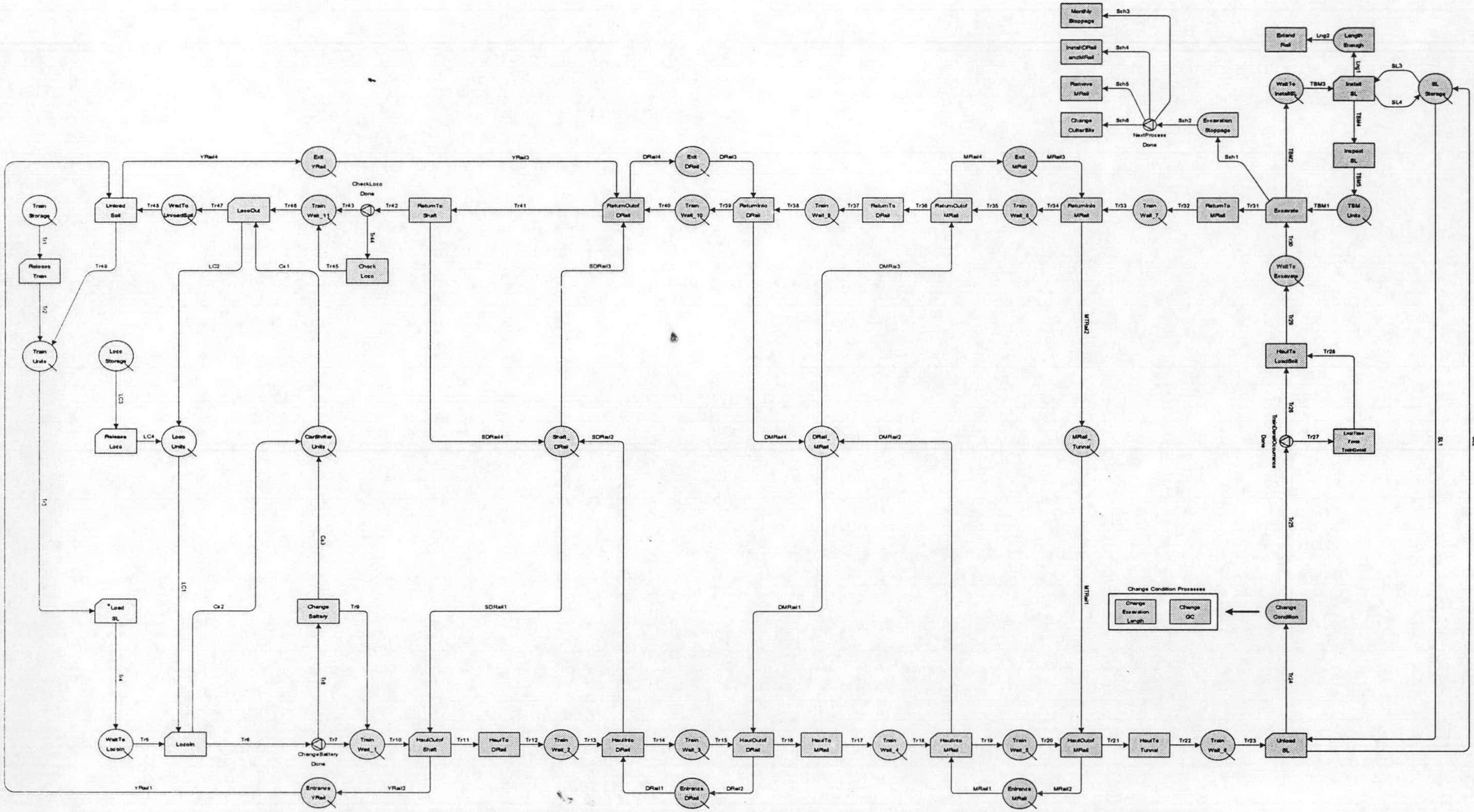

Figure 5.2 A scheduling network of tunneling process Sarutirattanaworakun (2005)

5.2 Demonstration of RAIRFNET Calculations for a Tunneling Project

The step – by – step calculations performed by applying the RAIRFNET to a tunneling project are presented which includes risk weight calculation using FAHP, comparison between FAHP and AHP methods, demonstration of the risk assessment method, development of probability distribution functions and membership functions of activity duration and risk factors, and RAIRFNET calculation.

5.2.1 Risk Weight Calculation

A collection of historical data required to calculate weights of risk factors was obtained from the literature (Pongmee, 2006). To simplify a demonstration, only three significant risk factors having impact on the tunnel lining installation activity are determined which are composed of (1) a work stoppage by an unanticipated design change, (2) an unanticipated change of working rules, and (3) a work stoppage by a fault in design drawing. The significant risk factors affecting other activities, such as the excavating activity which include (1) a work stoppage by an unanticipated design change, (2) an unanticipated change of working rules, and (3) a work stoppage by a fault in design drawing, are determined following steps applied to the tunnel lining installation.

In a demonstrative application of the FAHP, the linguistic terms are expressed with triangular fuzzy numbers. The evaluation is made by using triangular fuzzy conversion scale given in Table 4.1 (data from Büyüközkan, 2007). Table 4.1 also presents the decision aids for the risk assessment proposed by Georgy (2005) which are employed to assign the linguistic risk evaluating scale.

The evaluations were provided based on the information supplied by the twelve experts who have in-depth knowledge about problems and a good understanding of risk factors and adverse consequence. The risk factors were classified into operation risk and management risk in order to highlight risk factors having significant impacts on the activity level and project level. To determine weights w_k of the risk factors or to identify the comparison structure among risk factors, the experts were asked to provide judgement of the relative significance of these risk factors. The determination of the relative significance of three risk factors affecting the tunnel lining installation activity is provided as an example. A tentative assessment of the relative significance is performed regarding the following statements

(1) A work stoppage by an unanticipated design change is far more significant than an unanticipated change of working rules
(2) A work stoppage by a fault in design drawing is particularly significant comparing to an unanticipated change of working rules
(3) A work stoppage by an unanticipated change is as significant as a work stoppage by a fault in design drawing.

Based on the assessment and the resulting comparison matrix $[A]_{3\times3}$ of the relative significance of three risk factors affecting the tunnel lining installation activity, the step by step in the weight calculation is provided by using the fuzzy numbers, the fuzzy evaluation matrix is constructed in the form as given below

$$[A]_{3\times3} = \begin{bmatrix} 1.0 & a_{12} & a_{13} \\ a_{21} & 1.0 & a_{23} \\ a_{31} & a_{32} & 1.0 \end{bmatrix} = \begin{bmatrix} (1,1,1) & \left(\frac{1}{2},1,\frac{3}{2}\right) & \left(1,\frac{3}{2},2\right) \\ \left(\frac{1}{2},1,\frac{3}{2}\right) & (1,1,1) & \left(1,\frac{3}{2},2\right) \\ \left(\frac{1}{4},\frac{3}{4},\frac{5}{4}\right) & \left(\frac{1}{4},\frac{3}{4},\frac{5}{4}\right) & (1,1,1) \end{bmatrix}$$

Then the weight vector is calculated as follows:

$$S_{Dr} = (2.00, 3.50, 3.84) \otimes \left(\frac{1}{9.51},\frac{1}{9.50},\frac{1}{5.00}\right) = (0.14, 0.37, 1.00)$$

$$S_{Ddr} = (2.00, 3.50, 2.50) \otimes \left(\frac{1}{9.51},\frac{1}{9.50},\frac{1}{5.00}\right) = (0.14, 0.37, 1.00)$$

$$S_{Ds} = (1.00, 2.50, 3.17) \otimes \left(\frac{1}{9.51},\frac{1}{9.50},\frac{1}{5.00}\right) = (0.07, 0.26, 0.80)$$

Using these vectors to find relative weights

$V(S_{Dr} \geq S_{Ddr}) = 1.0$

$V(S_{Dr} \geq S_{Ds}) = 1.0$

$V(S_{Ddr} \geq S_{Dr}) = 1.0$

$V(S_{Ddr} \geq S_{Dds}) = 1.0$

$V(S_{Dds} \geq S_{Dr}) = 0.86$, and

$V(S_{Dds} \geq S_{Ddr}) = 0.86$

Finally, weight of each factor is computed as follows

$d'(Dr) = V(S_{Dr} \geq S_{Ddr}, S_{Dds}) = \min(0.0, 0.0) = 1.00$

$d'(Ddr) = V(S_{Ddr} \geq S_{Dr}, S_{Dds}) = \min(1.0, 1.0) = 1.00$

$d'(Dds) = V(S_{Dds} \geq S_{Dr}, S_{Ddr}) = \min(1.0, 0.5) = 0.86$

Therefore, $W' = (1.00, 1.00, 0.86)^T$. The weight vector of the risk factors affecting the tunnel lining installation activity is calculated by normalizing W'. Then, $W = (0.35, 0.35, 0.30)^T$. Weight vectors of other risk factors affecting other activities can be also computed following steps explained above.

The weights w_k of risk factors are obtained with the consensus of the evaluators as shown in Table 5.1. As the average weight vector represents the most likely values for the calculated comparison structure, the average weight vector is particularly used to represent the weight vectors provided by twelve experts. Let a_{ij}^k be the fuzzy number (weight) assigned by $expert_i$ or A_i for the risk factor k, then the average of fuzzy number across all the experts can be expressed as $A_{ij}^k = (1/p) \times (a_{i1}^k + a_{i2}^k + ... + a_{ip}^k)$, where p = number of experts involved in the evaluation process.

Table 5.1 Relative significance of risk factors

Risk factor	Relative significance of risk factors evaluated by $expert_i$									
	1	2	3	4	5	6	7	...	12	average
I	0.35	0.34	0.34	0.34	0.36	0.34	0.33	...	0.35	0.34
II	0.35	0.32	0.34	0.33	0.34	0.33	0.35	...	0.35	0.34
III	0.30	0.34	0.32	0.33	0.29	0.33	0.33	...	0.30	0.32

Note: I = a work stoppage by an unanticipated design change, II = an unanticipated change of working rules, and III = a work stoppage by a fault in design drawing.

The FAHP method provides a crisp value of weight (relative significance of risk factors) based on the input fuzzy numbers. The resulting weights show that the significant risk factors associated with the operation risk are composed of the occurrence of high water pressure, geologic uncertainty, a decline in the tunnel ring, and a work stoppage by unanticipated design changes, respectively.

5.2.2 Comparison between FAHP and AHP Methods

Previous section presents the illustrative examples of the evaluation of the weights of risk factors using the fuzzy numbers incorporated with the FAHP. For comparison purposes, AHP together with a simple additive weighting method are applied to provide the weights of the risk factors being considered by using the crisp numbers rather than the fuzzy numbers. The following discussion is provided to present the comparisons between the FAHP method and the AHP method based on results obtained from the demonstrative applications of these methods to the tunnel construction project, which are divided into the calculating process based comparison and the result based comparison.

Uncertainties are inevitably associated with the mapping of a decision maker's perception (or judgement) to a number. The uncertainties cannot be properly and exactly presented by the discrete scale. The use of a fuzzy scale presenting in the form of a fuzzy number is more appropriate to represent uncertainty which is usually attributed to the level of complexity and imprecision particularly characterizing the risk assessment. This study uses the fuzzy number to present the uncertainty and vagueness from the subjective perception and experience of humans in the pairwise comparison and employs the Büyüközkan's extent analysis method to derive the significance weight.

Following the definition of the fuzzy synthetic degree value which is the basis of fuzzy values for the extent analysis of each object, the value of fuzzy synthetic extent is defined as a ratio of between-group sum to total sum. The weight calculated by using the AHP method, by contrast, is a ratio of between-group sum to within-group sum. These two values are different by their definitions. Therefore, the calculated weights obtained from these two methods are conceptually different. The weights provided by using the AHP method are crisp numbers so that they can be linearly ordered by $\leq$. On the other hand, the values of the fuzzy synthetic extents are fuzzy numbers which cannot be linearly ordered. The fuzzy ranking method is required for ordering the fuzzy numbers. In addition, final results or the normalized weights vary based on the fuzzy numbers and the selected fuzzy ranking method. Figure 5.3 shows the fuzzy synthetic extents of the weights of the risk factors. It can be seen that these fuzzy numbers bring about an ill-posed problem which requires a sophisticated ranking method to order the weights of the risk factors.

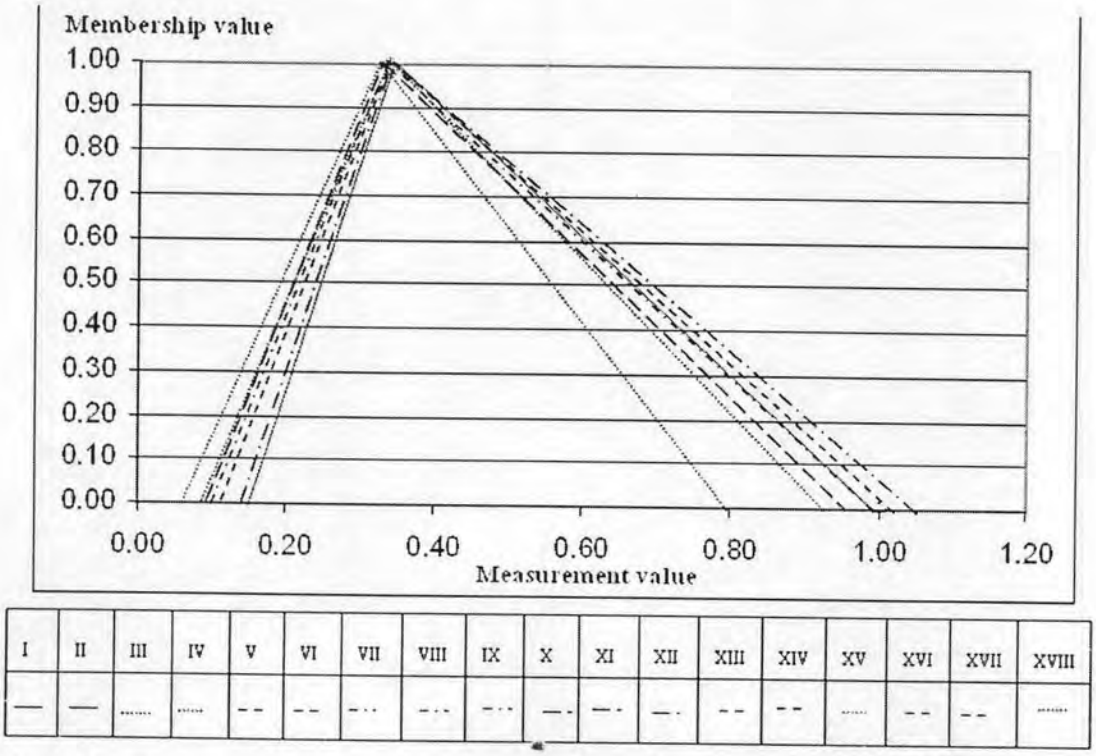

Figure 5.3 Fuzzy synthetic extents of the weights of the risk factors (i.e., I, II, ..., XVII) evaluated by $expert_1$

Most resulting weights obtained from both the FAHP and AHP are consistent which shows that the significant risk factors associated with the operation risk are composed of the occurrence of high water pressure, geologic uncertainty, a decline in the tunnel ring, and a work stoppage by unanticipated design changes. The demonstrative examples of the obtained results are shown in Table 5.2. However, the proposed approach is particularly suitable for subjective data and its results are more meaningful and interpretable. The calculated scores of risk factors can assist a decision maker in investigating the risk factors causing the increment or reduction of the total score of risk factors in order to manage and control any pitfall by assigning the appropriate corrective measures to reduce impact of risk factors.

Table 5.2 Comparison between total scores obtained from methods using crisp and fuzzy numbers

Tunnel lining installation activity							
FAHP method				AHP method			
Experts from construction firms				Experts from consulting firms			
Risk	Risk factor	Value	TS	Risk	Risk factor	Value	TS
Operation risk	I	0.94		Operation risk	I	1.59	
	II	0.84			II	1.36	
	III	0.67	2.45		III	0.97	3.92
Management risk	VII	0.92		Management risk	VII	1.52	
	VIII	V0.85			VIII	1.35	
	IX	0.85	2.61		IX	1.35	4.23
Excavate activity							
FAHP method				AHP method			
Experts from construction firms				Experts from consulting firms			
Risk	Risk factor	Value	TS	Risk	Risk factor	Value	TS
Operation risk	IV	0.79		Operation risk	IV	1.25	
	V	0.76			V	1.18	
	VI	0.73	2.28		VI	1.12	3.56
Management risk	X	0.89		Management risk	X	1.47	
	XI	0.79			XI	1.23	
	XII	0.79	2.46		XII	0.24	2.95

5.2.3 Demonstrative Application of Risk Assessment Method

This subsection presents a demonstrative application of the proposed method to the subjective risk assessment. Data is also adopted from the literature (Pongmee, 2006). As input data required by the RAIRFNET cannot be acquired from the literature, the original definition of $l_{i(j)}$ was adjusted based on available data. The subjective assessment was performed to find the likelihood of occurrence of each risk factor j. Although a set of risk factors had impact on the activity duration, the subjective assessment was performed based on the determination of a particular risk factor. The twelve experts were asked to assess the likelihood of occurrence, adverse consequence, and extended duration for each level of consequence by using the linguistic terms. To demonstrate the application of the proposed approach to the risk assessment based on available data, the assigned linguistic terms are later transformed into the triangular membership functions. By applying the product operation to Eq (3.15), the values of risk factors would take the form: $l_{i(j)} \otimes c_{i(j)} \otimes e_{i(j)}$, where $l_{i(j)}$ is the likelihood of occurrence, $c_{i(j)}$ is adverse consequence, and $e_{i(j)}$ is duration of project activities affected by risk factors. The minimum, mode, and maximum values of $P_{i(j)}$ were used to determine the optimistic, most likely, and pessimistic values of $l_{i(j)}$. For example, if the maximum values of $P_{i(j)}$ of the work stoppage by an unanticipated design change was "highly likely", the derived pessimistic likelihood $l_{i(j)} = Wt \times P_{i(j)} = 0.35 \times \frac{1}{24 \times 60} = 0.00024$, where the weight (0.35) of the work stoppage by an unanticipated design change was calculated by using the FAHP, $P_{i(j)}$ was of level 4, the quantitative likelihood was of 0.00069 occurrence per minute. Level 4 was the work stoppage by an unanticipated design change occurring at least once every day. The calculated values of risk factors are defuzzified and shown in Table 5.3.

Table 5.3 Values of risk factors

Risk factor	Value of risk factors									
	1	2	3	4	5	6	7	...	12	average
I	0.38	0.36	0.35	0.38	0.43	0.38	0.31	...	0.38	0.37
II	0.38	0.29	0.35	0.31	0.36	0.31	0.38	...	0.38	0.34
III	0.23	0.36	0.29	0.31	0.21	0.31	0.31	...	0.23	0.29

Note: I = a work stoppage by an unanticipated design change, II = an unanticipated change of working rules, and III = a work stoppage by a fault in design drawing.

The values of the risk factors which reference the values of risk factors to some tunnel construction norms are determined for comparison purposes. As the average value vector represents the most likely values for the assessed risk factors, the reference value of the risk factor is represented by the average value vector of risk factors. The reference value is then used to depict the most likely values of the risk factors of the available dataset. The reference values of the significant risk factors are also shown in Table 5.3.

5.2.4 Establishing Distributions of Activity Duration and Attributes of Risk Factors

Based on available data from the literature, impacts of a risk factor were determined in terms of the decreased advance rate and duration increased due to waiting or rectification. This research assumes that the impacts (i.e., decreased advance rate and duration increased due to waiting or rectification) are associated with the same likelihood of occurrence. The subjective impact evaluations were performed. The quantitative values of impacts were derived based on the definitions of the selected subjective expressions. A number of assessors were asked to subjectively evaluate impacts of each risk factor. The minimum, mode, and maximum values of $C_{i(j)}$ were used to determine the optimistic, most likely, and pessimistic values for the three – point estimations. For example, if the maximum values of $C_{i(j)}$ or the decreased advance rate and duration increased due to waiting or rectification resulting from the work stoppage by an unanticipated design change is "catastrophic" and "minor", the derived impact (i.e., decreased advance rate) $E_{i(j)}$ = 0.6 meter per minute and the impact (i.e., increased duration) $E_{i(j)}$ = 60 minutes, respectively. The values of the minimum and mode are derived by using the same procedure. Then, the triang'.lar distribution of impacts (i.e., decreased advance rate, increased duration) was developed. The values of $E_{i(j)}$ and $C_{i(j)}$ are randomly drawn based on the corresponding triangular distributions. In regard to the impacts of the work stoppage by an unanticipated design change, duration of the tunnel lining installation activity is recalculated from a function of the likelihood of occurrence of the work stoppage by an unanticipated design change, the extended duration (%), and the initially estimated duration. Duration of the tunnel lining installation activity is extended due to the work stoppage by an unanticipated design change: $\frac{q}{(a-0.6)}+60$, where q is work quantity and a is the initially estimated advance rate, 0.6 is the reduced advance rate, 60 is the increased duration.

The most likely and minimum values of $E_{i(j)}$ due to the work stoppage by an unanticipated design change and the maximum, most likely and minimum values of $E_{i(j)}$ due to other risk factors affecting other activities can be calculated following the above steps. The distribution of activity duration is established by using the three – point estimation. Conceptually, the distribution of activity duration affected by all risk factors is established by adding the activity duration initially estimated without a consideration about risk factors into the sum of the individual distributions of activity duration affected by risk factors. The proposed method uses simulation to generate data and develops the probability distribution of activity duration affected by risk factors and the probability distribution of risk variables. Activity duration affected by each risk factor is drawn randomly based on its derived distribution. Then, the initially estimated activity duration plus the sum of the activity durations affected by all risk factors is calculated. The obtained result represents the random contribution to uncertainty associated with activity duration. Table 5.4 shows the simulated values of duration and the product of attributes of each risk factor for Drilling, Cage installation, and Concrete pouring activities. To simplify the demonstration of simulated data, only four simulation replications are presented in Table 5.4.

5.2.5 Developing the Membership Functions of Activity Duration and Attributes of Risk Factors

This section is to demonstrate how random and nonrandom parts of random–fuzzy variables (i.e., duration of project activities and attributes of risk factors) are represented by membership functions. Two probability–possibility transformation methods including the Salicone's method and the neurofuzzy metamodel are used to transform the probability distributions into the membership functions representing the random part. The development of the probability distribution is described above. The transformed membership functions of duration of project activities obtained from Salicone's method and neurofuzzy metamodel for nil, rectangular, and triangular internal membership functions are also presented in Table 5.5 and 5.6.

To display membership functions of project activities consisting of different numbers of sub – activities, Figure 5.4 to 5.5 show membership functions and probability distributions of duration of TBMExcavate and UnloadSoil activities, respectively. Figure 5.6 and 5.7 show membership functions and probability distributions of

LocoOut and LocoIn which have two sub – activities including LocoOut and CheckLoco for LocoOut activity and LocoIn and ChangeBattery for LocoIn activity. The probability distributions of LocoOut and LocoIn are developed from durations of their sub – activities drawn randomly based on their derived probability distributions. Figure 5.8 and 5.9 present membership functions and probability distributions of ReturnToShaft and OutofShaft activities. Sub – activities in association with the ReturnToShaft are composed of ReturnToMRail, ReturnIntoMRail, ReturnOutofMRail, ReturnToDRail, ReturnIntoDRail, ReturnOutofDRail, ReturnToShaft.

Table 5.4 Simulated data of activity durations (minute)

Activity	R_1	R_2	R_3	...	R_{9000}	Average	Standard deviation
ToLoadSoil	1.31	1.41	1.07	...	1.02	1.29	0.16
TBMExcavate	20.74	21.41	21.63	...	22.67	25.83	31.89
ReturnToShaft	2.02	2.04	2.03	...	2.17	27.53	14.96
LocoOut	7.09	8.46	7.80	...	6.46	7.78	0.84
UnloadSoil	45.48	42.11	43.19	...	47.48	42.91	5.51
TBMInstallSL	55.28	51.60	50.64	...	55.91	53.66	3.58
TBMInspSL	3.88	3.66	3.70	...	3.34	3.59	0.34
LoadSL	8.37	8.90	7.58	...	7.85	8.41	1.14
LocoIn	15.92	16.36	16.81	...	14.86	15.65	1.67
OutofShaft	1.62	1.80	1.71	...	1.91	27.06	14.91
ToTunnel	0.48	0.47	0.50	...	0.49	5.23	2.50
UnloadSL	4.95	5.07	4.44	...	6.21	5.21	0.88

R_j = simulation replication j

Table 5.5 Membership functions obtained from Salicone's method and neurofuzzy metamodel for nil and rectangular internal membership functions

Activity	NS				NN				RS				RN			
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
ToLoadSoil	0.8	1.3	1.3	1.8	0.0	1.3	1.3	5.1	0.8	1.3	2.3	2.7	0.0	1.3	6.4	10.2
TBMExcavate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ReturnToShaft	0.0	26.2	26.2	133.7	26.2	26.2	26.2	832.0	0.0	26.2	159.8	267.3	26.2	26.2	832.0	1637.9
LocoOut	0.0	27.7	27.7	90.1	27.7	27.7	27.7	172.3	0.0	27.7	117.8	180.2	27.7	27.7	172.3	317.0
UnloadSoil	5.3	7.8	7.8	10.5	4.9	7.8	7.8	14.1	5.3	7.8	13.0	15.8	4.9	7.8	17.0	23.3
TBMInstallSL	18.9	43.5	43.5	68.1	5.2	43.5	43.5	60.9	18.9	43.5	92.6	117.2	5.2	43.5	99.2	116.6
TBMInspSL	37.2	53.9	53.9	74.1	32.0	53.9	53.9	68.4	37.2	53.9	90.7	110.9	32.0	53.9	90.3	104.8
LoadSL	2.6	3.6	3.6	4.6	1.0	3.6	3.6	7.0	2.6	3.6	5.6	6.6	1.0	3.6	9.6	13.0
LocoIn	5.1	8.4	8.4	11.8	3.2	8.4	8.4	12.7	5.1	8.4	15.1	18.5	3.2	8.4	17.9	22.1
OutofShaft	10.6	15.6	15.6	21.0	0.0	15.6	15.6	33.5	10.6	15.6	25.9	31.3	0.0	15.6	49.2	67.1
ToTunnel	0.0	27.3	27.3	89.9	0.0	27.3	27.3	74.3	0.0	27.3	117.2	179.9	0.0	27.3	101.6	148.6
UnloadSL	0.0	5.3	5.3	12.8	0.0	5.3	5.3	14.0	0.0	5.3	18.0	25.6	0.0	5.3	19.3	28.0

Note NS is nil membership function developed by using Salicone's method
NN is nil membership function developed by using a neurofuzzy metamodel
RS is rectangular membership function developed by using Salicone's method
RN is rectangular membership function developed by using a neurofuzzy metamodel
a is minimum value, b and c is most likely value, and d is maximum value

Table 5.6 Membership functions obtained from Salicone's method and neurofuzzy metamodel for trapezoidal and triangular internal membership functions

Activity	TS1				TN1				TS2				TN2			
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
ToLoadSoil	0.3	1.3	2.3	3.2	0.0	1.3	6.4	12.8	0.3	1.3	1.3	2.3	0.0	1.3	1.3	7.7
TBMExcavate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ReturnToShaft	0.0	26.2	159.8	334.2	0.0	26.2	832.0	2040.8	0.0	26.2	26.2	200.5	0.0	26.2	26.2	1234.9
LocoOut	0.0	27.7	117.8	225.3	0.0	27.7	172.3	389.3	0.0	27.7	27.7	135.2	0.0	27.7	27.7	244.6
UnloadSoil	2.6	7.8	13.0	18.4	0.3	7.8	17.0	27.9	2.6	7.8	7.8	13.2	0.3	7.8	7.8	18.7
TBMInstallSL	0.0	43.5	92.6	141.8	0.0	43.5	99.2	144.5	0.0	43.5	43.5	92.6	0.0	43.5	43.5	88.8
TBMInspSL	18.8	53.9	90.7	129.4	13.8	53.9	90.3	123.0	18.8	53.9	53.9	92.5	13.8	53.9	53.9	86.6
LoadSL	1.6	3.6	5.6	7.5	0.0	3.6	9.6	16.0	1.6	3.6	3.6	5.6	0.0	3.6	3.6	10.0
LocoIn	1.7	8.4	15.1	21.9	0.0	8.4	17.9	26.9	1.7	8.4	8.4	15.1	0.0	8.4	8.4	17.4
OutofShaft	5.5	15.6	25.9	36.4	0.0	15.6	49.2	83.8	5.5	15.6	15.6	26.1	0.0	15.6	15.6	50.3
ToTunnel	0.0	27.3	117.2	224.9	0.0	27.3	101.6	185.8	0.0	27.3	27.3	134.9	0.0	27.3	27.3	111.5
UnloadSL	0.0	5.3	18.0	32.0	0.0	5.3	19.3	35.0	0.0	5.3	5.3	19.2	0.0	5.3	5.3	21.0

Note TS1 is trapezoidal membership function developed by using Salicone's method
TN1 is trapezoidal membership function developed by using a neurofuzzy metamodel
TS2 is triangular membership function developed by using Salicone's method
TN2 is triangular membership function developed by using a neurofuzzy metamodel
a is minimum value, b and c is most likely value, and d is maximum value

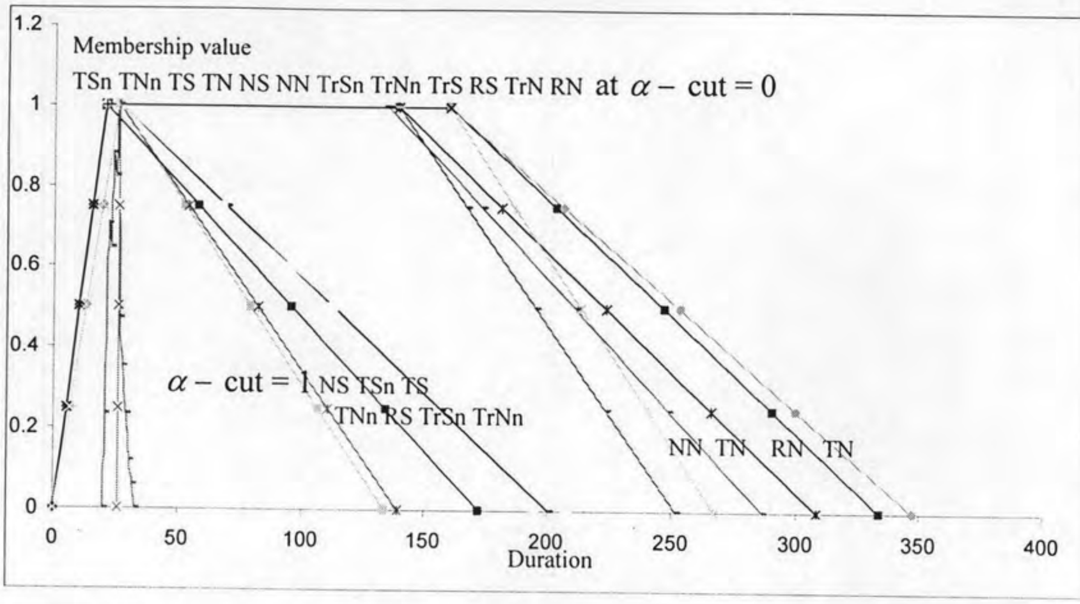

Figure 5.4 Comparison of simulation results for membership functions obtained from the neurofuzzy metamodel and Salicone's method and triangular distribution based durations of TBMexcavate activity

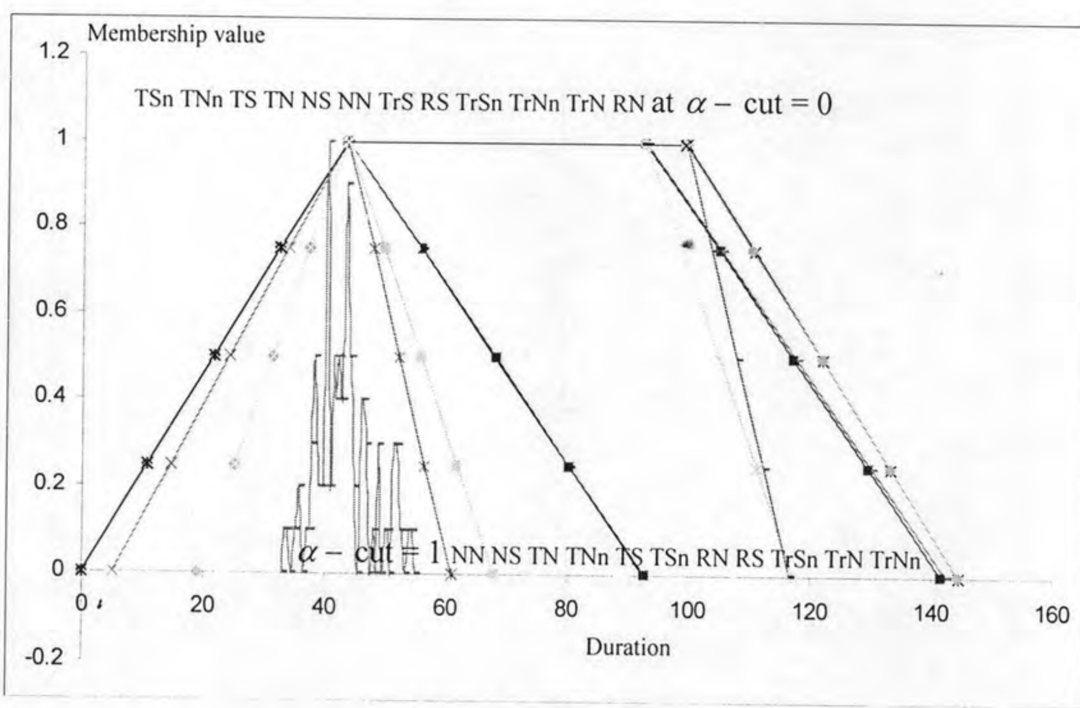

Figure 5.5 Comparison of simulation results for membership functions obtained from the neurofuzzy metamodel and Salicone's method and triangular distribution based durations of UnloadSoil activity

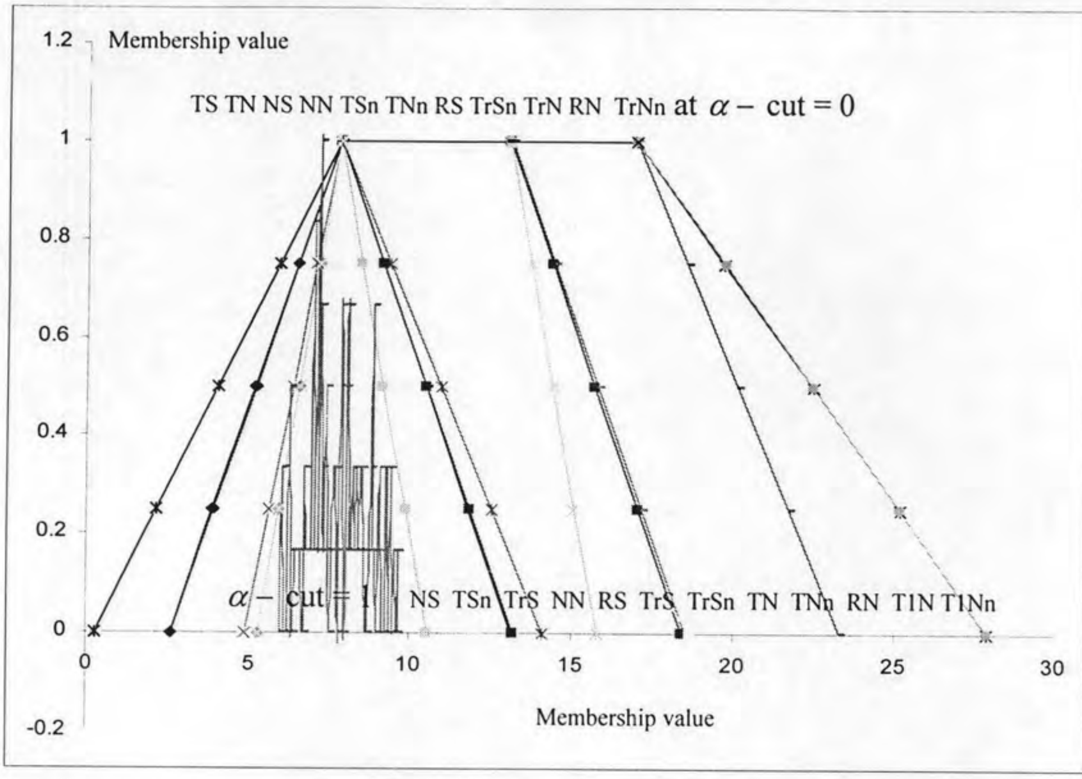

Figure 5.6 Comparison of simulation results for membership functions obtained from the neurofuzzy metamodel and Salicone's method and triangular distribution based durations of LocoOut activity

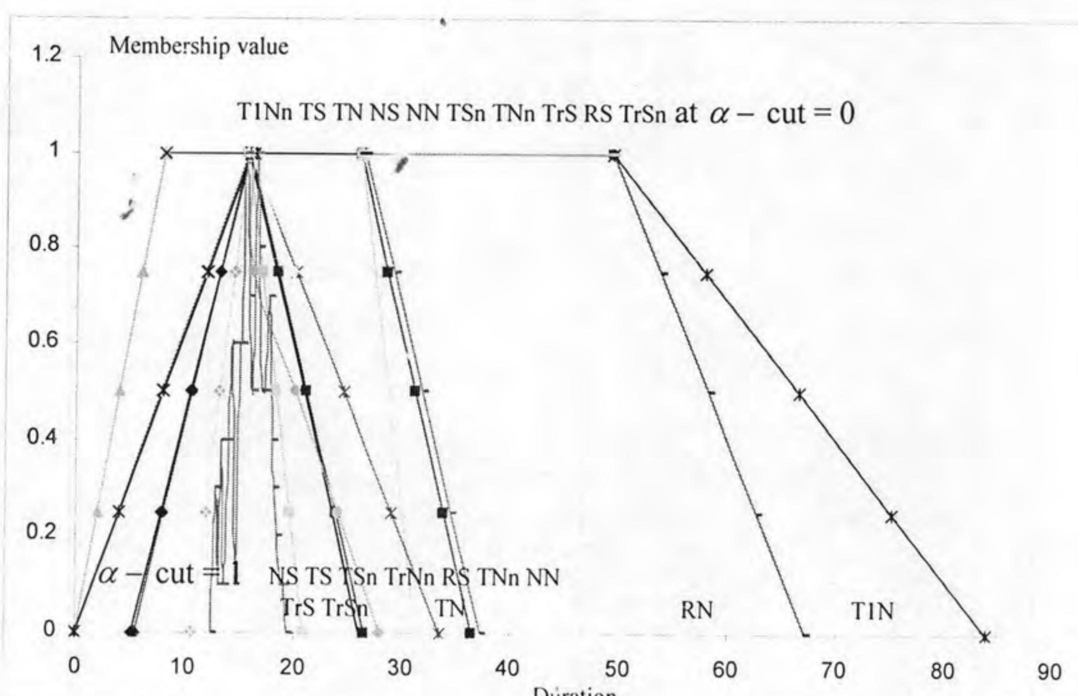

Figure 5.7 Comparison of simulation results for membership functions obtained from the neurofuzzy metamodel and Salicone's method and triangular distribution based durations of LocoIn activity

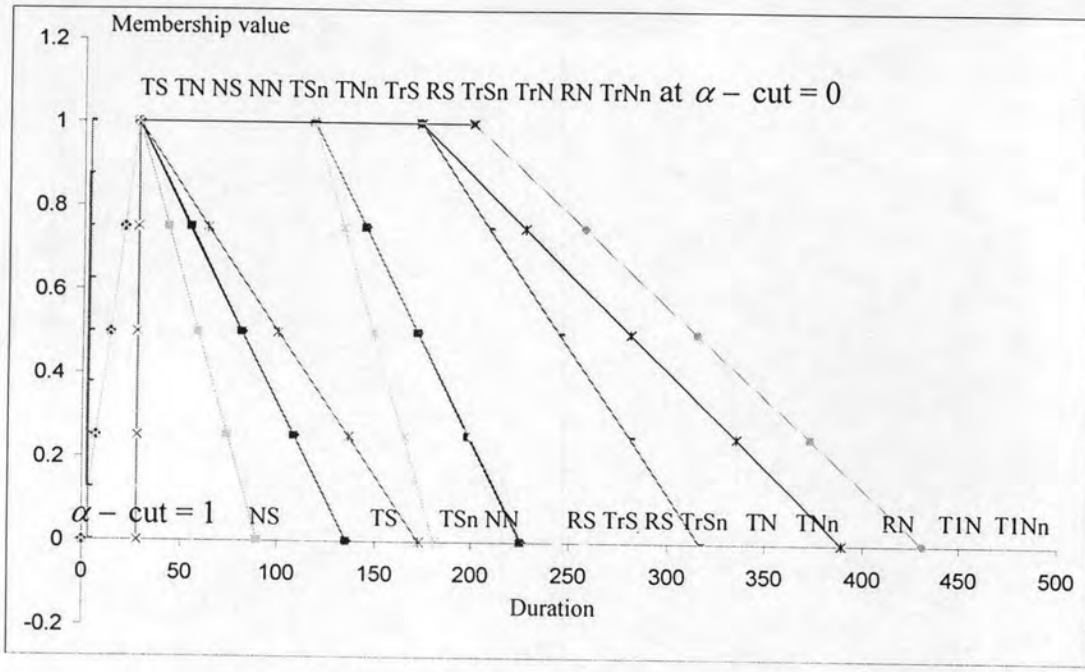

Figure 5.8 Comparison of simulation results for membership functions obtained from the neurofuzzy metamodel and Salicone's method and triangular distribution based durations of ReturnToShaft activity

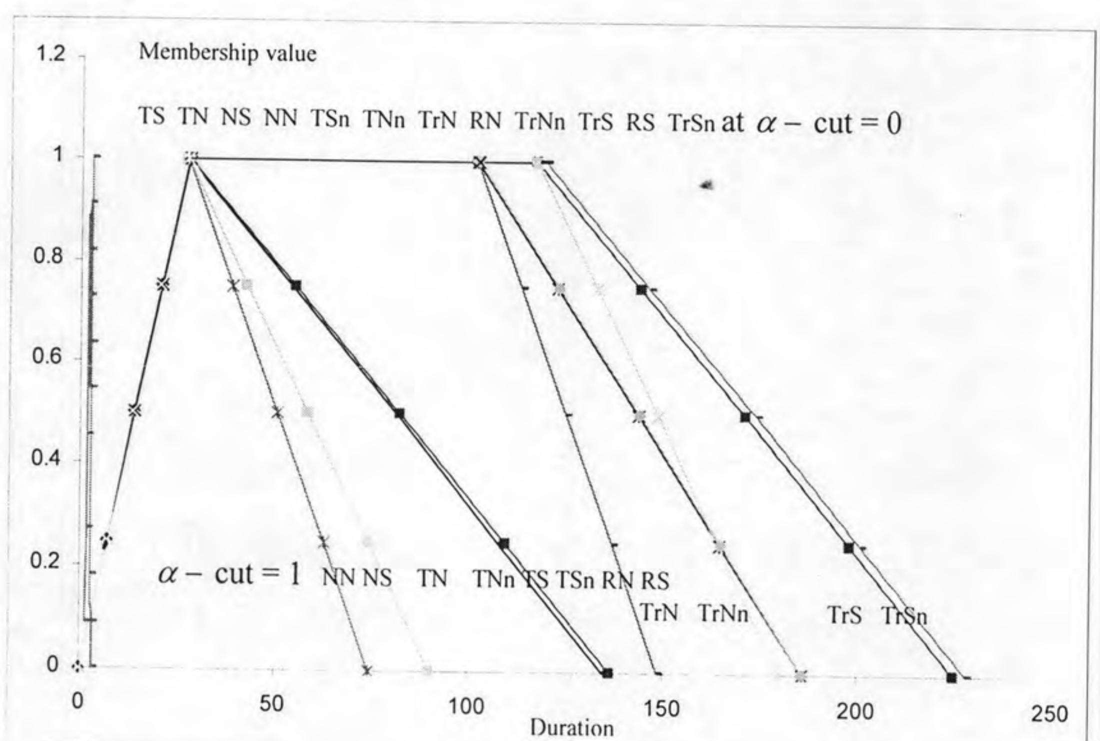

Figure 5.9 Comparison of simulation results for membership functions obtained from the neurofuzzy metamodel and Salicone's method and triangular distribution based durations of OutofShaft activity

The OutofShaft activity is decomposed into HaulOutofShaft, HaulToDRail, HaulIntoDRail, HaulOutofDRail, HaulToMRail, HaulIntoMRail, HaulOutofMRail, HaulToTunnel, where NS, RS, TS, TrS are the Salicone's method using nil, rectangular, triangular, and trapezoidal internal membership functions, NN, RN, TN, TrN are the neurofuzzy metamodel using nil, rectangular, triangular, and trapezoidal internal membership functions, NSn, RSn, TSn, TrSn are the Salicone's method using nil, rectangular, triangular, and trapezoidal internal membership functions developed disregarding impact of risk factors, NNn, RNn, TNn, TrNn are the neurofuzzy metamodel using nil, rectangular, triangular, and trapezoidal internal membership functions developed disregarding impact of risk factors.

To compare the simulation results obtained from the probability distributions with the fuzzy number, the frequencies of the activity durations are normalized by dividing them with the maximum frequency. To enable the comparison between the random–fuzzy numbers representing and not representing the systematic and unknown contributions, there are four types of the internal membership function including nil, rectangular, trapezoidal and triangular internal membership functions.

5.2.6 RAIRFNET Calculation

This section is to recalculate and update the schedule in terms of fuzzy early and late times, and determine a project completion time. To give a demonstrative application of the proposed methods, results from the network calculation using the RAIRFNET using Salicone's method to develop the membership function of activity duration and the RAIRFNET using neurofuzzy metamodel to develop the membership function of activity duration for a nil internal membership function at $\alpha -$ cut = 0 are summarized. Table 5.7 and 5.8 present the corresponding outputs of the RAIRFNET using Salicone's method for the first and the tenth units, while Table 5.9 and 5.10 show the RAIRFNET using neurofuzzy metamodel for the first and the tenth units. Table 5.11 shows fuzzy early and late times for the tenth unit obtained from these two methods using four shapes of internal membership function including nil, rectangular, trapezoidal, and triangular membership functions.

The comparison between results based FNET and RAIRFNET methods for different shapes of internal membership functions is provided. The calculated early finish times obtained from these two methods are compared to the simulated early finish times provided by executing simulation. As noted, different methods are used to develop the membership functions of duration of project activities. For the case that impact of risk factors on duration of project activities is not determined, Table 5.12 presents the fuzzy start and finish times calculated by using the RAIRFNET for the tenth units based on the activity durations obtained from the Salicone's method and the neurofuzzy metamodel using four shapes of internal membership functions including nil, rectangular, triangular and trapezoidal membership functions.

The percent deviations of random–fuzzy durations regarding uncertainties due to risk factors from random–fuzzy durations regardless uncertainties due to risk factors for all shapes of internal membership functions range from 0% to 15%. Table 5.13 shows the fuzzy start and finish times calculated by using the FNET for the tenth unit based on the activity durations obtained from the Salicone's method and the neurofuzzy metamodel using four shapes of internal membership function including nil, rectangular, triangular and trapezoidal membership functions. The percent deviations of random–fuzzy duration from fuzzy duration range from 0.57% to 2.37% for the overestimated values where the random–fuzzy duration is smaller than the fuzzy duration.

The comparing results confirm that impact of risk factors could extend project completion times. In addition, the project completion times provided by FRAIRNET are affected by the central limit theorem, which theoretically compensates the random contribution regardless shapes of membership functions representing duration of project activities. As a result, the random–fuzzy durations are smaller than the fuzzy durations calculated using the fuzzy arithmetic algorithms, which does not compensate the random contribution and eliminate the systematic and unknown contributions.

Table 5.7 The calculated start and finish times (minute) for the first unit using Salicone's method for nil internal membership function

Activity	duration				ES				EF				LF				LS			
1	0	0	0	0	0	0	0	0	0	0	0	0	79	79	79	79	79	79	79	79
2	1	1	1	2	0	0	0	0	1	1	1	2	80	81	81	81	79	79	79	80
3	0	0	0	0	1	1	1	2	1	1	1	2	36	37	37	52	36	37	37	49
4	0	26	26	134	1	1	1	2	1	27	27	119	63	90	90	168	63	64	64	168
5	0	28	28	90	1	27	27	119	1	55	55	188	43	97	97	214	43	70	70	208
6	5	8	8	11	1	55	55	188	6	63	63	182	32	89	89	195	21	81	81	180
7	19	44	44	68	6	63	63	182	25	106	106	237	38	119	119	240	38	76	76	213
8	37	54	54	74	16	57	57	122	53	110	110	190	53	110	110	207	53	57	57	162
9	3	4	4	5	53	110	110	190	56	114	114	190	57	116	116	214	53	112	112	203
10	5	8	8	12	0	0	0	0	5	8	8	12	5	8	8	18	5	0	0	11
11	11	16	16	21	5	8	8	12	16	24	24	33	16	24	24	38	16	8	8	27
12	0	27	27	90	16	24	24	33	16	51	51	115	16	51	51	121	16	24	24	121
13	0	5	5	13	16	51	51	115	16	57	57	122	16	57	57	133	3	51	51	126
14	3	5	5	8	53	110	110	190	56	116	116	193	56	116	116	215	48	110	110	204
15	0	0	0	0	56	116	116	237	56	116	116	225	56	116	116	215	56	116	116	207

Note act is activity, 1 is start, 2 is ToLoadSoil, 3 is LoadSoil, 4 is TBMExcavate, 5 is ReturnToShaft, 6 is LocoOut, 7 is UnloadSoil, 8 is TBMInstallSL, 9 is TBMInspSL, 10 is LoadSL, 11 is LocoIn, 12 is OutToShaft, 13 is ToTunnel, 14 is UnloadSL, and 15 is Finish; ES is early start, EF is early finish, LF is late finish, LS is late start

Table 5.8 The calculated start and finish times (minute) for the tenth unit using Salicone's method for nil internal membership function

Activity	duration				ES				EF				LF				LS			
1	500	1041	1041	1631	0	0	0	0	500	1041	1041	1621	605	1147	1147	1719	605	106	106	1219
2	1	1	1	2	500	1041	1041	1631	501	1043	1043	1623	606	1148	1148	1721	605	1147	1147	1714
3	0	0	0	0	501	1043	1043	1623	501	1043	1043	1615	536	1078	1078	1644	536	1078	1078	1639
4	0	26	26	134	501	1043	1043	1623	501	1069	1069	1732	582	1150	1150	1793	449	1124	1124	1793
5	0	28	28	90	501	1069	1069	1732	501	1096	1096	1795	555	1151	1151	1828	465	1123	1123	1818
6	5	8	8	11	501	1096	1096	1795	506	1104	1104	1784	539	1137	1137	1800	528	1129	1129	1781
7	19	44	44	68	506	1104	1104	1784	525	1148	1148	1835	541	1164	1164	1838	473	1120	1120	1808
8	37	54	54	74	515	1098	1098	1732	553	1152	1152	1794	553	1152	1152	1799	479	1098	1098	1753
9	3	4	4	5	553	1152	1152	1794	555	1155	1155	1790	557	1157	1157	1807	552	1153	1153	1794
10	5	8	8	12	500	1041	1041	1631	505	1050	1050	1633	524	1069	1069	1644	512	1060	1060	1633
11	11	16	16	21	505	1050	1050	1633	515	1065	1065	1646	526	1076	1076	1650	505	1061	1061	1635
12	0	27	27	90	515	1065	1065	1646	515	1093	1093	1722	515	1093	1093	1713	426	1065	1065	1712
13	0	5	5	13	515	1093	1093	1722	515	1098	1098	1724	515	1098	1098	1726	503	1093	1093	1717
14	3	5	5	8	553	1152	1152	1794	555	1157	1157	1793	555	1157	1157	1807	547	1152	1152	1794
15	0	0	0	0	555	1157	1157	1835	555	1157	1157	1819	555	1157	1157	1807	555	1157	1157	1797

Note act is activity, 1 is start, 2 is ToLoadSoil, 3 is LoadSoil, 4 is TBMExcavate, 5 is ReturnToShaft, 6 is LocoOut, 7 is UnloadSoil, 8 is TBMInstallSL, 9 is TBMInspSL, 10 is LoadSL, 11 is LocoIn, 12 is OutToShaft, 13 is ToTunnel, 14 is UnloadSL, and 15 is Finish; ES is early start, EF is early finish, LF is late finish, LS is late start

Table 5.9 The calculated start and finish times (minute) for the first unit using neurofuzzy metamodel for nil internal membership function

Activity	duration				ES				EF				LF				LS			
1	0	0	0	0	0	0	0	0	0	0	0	0	157	157	157	157	157	157	157	157
2	0	1	1	5	0	0	0	0	0	1	1	5	156	158	158	161	152	156	156	161
3	0	0	0	0	0	1	1	5	0	1	1	4	17	18	18	21	17	18	18	21
4	26	26	26	139	0	1	1	5	26	27	27	120	159	160	160	234	28	134	134	207
5	28	28	28	172	26	27	27	120	54	55	55	243	138	139	139	288	0	111	111	260
6	5	8	8	14	54	55	55	243	59	63	63	218	103	107	107	231	89	100	100	202
7	5	44	44	61	59	63	63	218	64	106	106	252	81	124	124	248	20	80	80	222
8	32	54	54	68	26	57	57	126	58	110	110	188	58	110	110	213	0	57	57	169
9	1	4	4	7	58	110	110	188	59	114	114	189	61	116	116	221	54	112	112	210
10	3	8	8	13	0	0	0	0	3	8	8	13	3	8	8	31	0	0	0	24
11	0	16	16	34	3	8	8	13	3	24	24	46	3	24	24	64	0	8	8	60
12	0	27	27	74	3	24	24	46	3	51	51	116	3	51	51	134	0	24	24	131
13	0	5	5	14	3	51	51	116	3	57	57	126	3	57	57	147	0	51	51	140
14	1	5	5	9	58	110	110	188	59	116	116	191	59	116	116	222	50	110	110	211
15	0	0	0	0	64	116	116	252	64	116	116	234	64	116	116	221	64	116	116	210

Note act is activity, 1 is start, 2 is ToLoadSoil, 3 is LoadSoil, 4 is TBMExcavate, 5 is ReturnToShaft, 6 is LocoOut, 7 is UnloadSoil, 8 is TBMInstallSL, 9 is TBMInspSL, 10 is LoadSL, 11 is LocoIn, 12 is OutToShaft, 13 is ToTunnel, 14 is UnloadSL, and 15 is Finish; ES is early start, EF is early finish, LF is late finish, LS is late start

Table 5.10 The calculated start and finish times (minute) for the tenth unit using neurofuzzy metamodel for nil internal membership function

Activity	duration				ES				EF				LF				LS			
1	575	1041	1041	1574	0	0	0	0	575	1041	1041	1560	768	1234	1234	1742	-801	193	193	1167
2	0	1	1	5	575	1041	1041	1574	575	1043	1043	1565	768	1235	1235	1746	762	1234	1234	1737
3	0	0	0	0	575	1043	1043	1565	575	1043	1043	1553	617	1085	1085	1586	617	1085	1085	1579
4	26	26	26	139	575	1043	1043	1565	601	1069	1069	1669	759	1227	1227	1799	622	1200	1200	1773
5	28	28	28	172	601	1069	1069	1669	629	1096	1096	1784	729	1197	1197	1839	557	1169	1169	1805
6	5	8	8	14	629	1096	1096	1784	634	1104	1104	1752	688	1158	1158	1769	674	1151	1151	1736
7	5	44	44	61	634	1104	1104	1752	639	1148	1148	1780	661	1169	1169	1776	600	1126	1126	1746
8	32	54	54	68	601	1098	1098	1669	633	1152	1152	1723	633	1152	1152	1733	565	1098	1098	1687
9	1	4	4	7	633	1152	1152	1723	634	1155	1155	1719	636	1157	1157	1742	629	1153	1153	1728
10	3	8	8	13	575	1041	1041	1574	578	1050	1050	1573	592	1063	1063	1575	579	1055	1055	1564
11	0	16	16	34	578	1050	1050	1573	578	1065	1065	1595	581	1068	1068	1589	547	1052	1052	1582
12	0	27	27	74	578	1065	1065	1595	578	1093	1093	1657	578	1093	1093	1655	504	1065	1065	1649
13	0	5	5	14	578	1093	1093	1657	578	1098	1098	1660	578	1098	1098	1668	564	1093	1093	1658
14	1	5	5	9	633	1152	1152	1723	634	1157	1157	1721	634	1157	1157	1742	625	1152	1152	1728
15	0	0	0	0	639	1157	1157	1780	639	1157	1157	1758	639	1157	1157	1741	639	1157	1157	1727

Note act is activity, 1 is start, 2 is ToLoadSoil, 3 is LoadSoil, 4 is TBMExcavate, 5 is ReturnToShaft, 6 is LocoOut, 7 is UnloadSoil, 8 is TBMInstallSL, 9 is TBMInspSL, 10 is LoadSL, 11 is LocoIn, 12 is OutToShaft, 13 is ToTunnel, 14 is UnloadSL, and 15 is Finish; ES is early start, EF is early finish, LF is late finish, LS is late start

Table 5.11 Calculated random–fuzzy start and finish times for the tenth unit using RAIRFNET

M	ES				EF				LF				LS			
NS	555	1157	1157	1835	555	1157	1157	1819	555	1157	1157	1807	555	1157	1157	1797
NN	639	1157	1157	1780	639	1157	1157	1758	639	1157	1157	1741	639	1157	1157	1727
RS	555	1157	3855	4545	555	1157	3855	4527	555	1157	3855	4512	555	1157	3855	4501
RN	639	1157	4339	4973	639	1157	4339	4949	639	1157	4339	4930	639	1157	4339	4915
TrS	276	1157	3855	4884	276	1157	3855	4853	276	1157	3855	4829	276	1157	3855	4810
TrN	276	1157	3855	4884	276	1157	3855	4853	276	1157	3855	4829	276	1157	3855	4810
TS	276	1157	1157	2174	276	1157	1157	2146	276	1157	1157	2123	276	1157	1157	2106
TN	138	1157	1157	2364	138	1157	1157	2325	138	1157	1157	2294	138	1157	1157	2270

Note ES is early start, EF is early finish, LF is late finish, LS is late start, M is methods including NS (nil internal membership function for Salicone's method), NN (nil internal membership function for neurofuzzy metamodel), RS (rectangular internal membership function for Salicone's method), RN (rectangular internal membership function for neurofuzzy metamodel), TrS (trapezoidal internal membership function for Salicone's method), TrN (trapezoidal internal membership function for neurofuzzy metamodel), TS (triangular internal membership function for Salicone's method), TN (triangular internal membership function for neurofuzzy metamodel)

Table 5.12 Calculated fuzzy start and finish times for the tenth unit using RAIRFNET regardless impact of risk factors

M	ES				EF				LF				LS			
NS	550	1165	1165	1837	550	1165	1165	1825	550	1165	1165	1816	550	1165	1165	1809
NN	726	1165	1165	1745	726	1165	1165	1716	726	1165	1165	1693	726	1165	1165	1675
RS	550	1165	3617	4308	550	1165	3617	4292	550	1165	3617	4280	550	1165	3617	4270
RN	726	1165	4793	5393	726	1165	4793	5359	726	1165	4793	5333	726	1165	4793	5312
TS	265	1165	3617	4647	265	1165	3617	4620	265	1165	3617	4599	265	1165	3617	4582
TN	521	1165	4793	5696	521	1165	4793	5642	521	1165	4793	5600	521	1165	4793	5566
TrS	265	1165	1165	2176	265	1165	1165	2153	265	1165	1165	2135	265	1165	1165	2121
TrN	521	1165	1165	2049	521	1165	1165	1999	521	1165	1165	1960	521	1165	1165	1929

Note ES is early start, EF is early finish, LF is late finish, LS is late start, M is methods including NS (nil internal membership function for Salicone's method), NN (nil internal membership function for neurofuzzy metamodel), RS (rectangular internal membership function for Salicone's method), RN (rectangular internal membership function for neurofuzzy metamodel), TrS (trapezoidal internal membership function for Salicone's method), TrN (trapezoidal internal membership function for neurofuzzy metamodel), TS (triangular internal membership function for Salicone's method), TN (triangular internal membership function for neurofuzzy metamodel)

Table 5.13 Calculated fuzzy start and finish times for the tenth unit using FNET regardless impact of risk factors

M	ES				EF				LF				LS			
NS	555	1157	1157	1835	555	1157	1157	1835	555	1157	1157	1819	555	1157	1157	1819
NN	639	1157	1157	1780	639	1157	1157	1780	639	1157	1157	1758	639	1157	1157	1758
RS	555	1157	3855	4545	555	1157	3855	4545	555	1157	3855	4527	555	1157	3855	4527
RN	639	1157	4339	4973	639	1157	4339	4973	639	1157	4339	4949	639	1157	4339	4949
TrS	276	1157	3855	4884	276	1157	3855	4884	276	1157	3855	4853	276	1157	3855	4853
TrN	276	1157	3855	4884	276	1157	3855	4884	276	1157	3855	4853	276	1157	3855	4853
TS	276	1157	1157	2174	276	1157	1157	2174	276	1157	1157	2146	276	1157	1157	2146
TN	138	1157	1157	2364	138	1157	1157	2364	138	1157	1157	2325	138	1157	1157	2325

Note ES is early start, EF is early finish, LF is late finish, LS is late start, M is methods including NS (nil internal membership function for Salicone's method), NN (nil internal membership function for neurofuzzy metamodel), RS (rectangular internal membership function for Salicone's method), RN (rectangular internal membership function for neurofuzzy metamodel), TrS (trapezoidal internal membership function for Salicone's method), TrN (trapezoidal internal membership function for neurofuzzy metamodel), TS (triangular internal membership function for Salicone's method), TN (triangular internal membership function for neurofuzzy metamodel)

Considering impact of the selected shapes of internal membership functions of durations of project activities on the corresponding project completion times, based on results presented above, the trapezoidal internal membership functions of project completion times representing either fuzzy or random–fuzzy numbers provide the widest range of uncertainty, while the nil internal membership functions show the smallest range of uncertainty. This is because the largest values of uncertainty due to systematic and unknown contributions is presented through the trapezoidal internal membership functions of duration of project activities.

To simplify the illustration of the comparison between project completion times represented by the random–fuzzy numbers within a certain time, the degree of belief of project completion times is calculated in the RAIRFNET using Salicone's method to develop the membership function of activity duration and the RAIRFNET using neurofuzzy metamodel to develop membership function of activity duration utilizing AI and C_{eq}. A number of project durations are computed using these two methods. Table 5.14 presents the credibility coefficients C_{gr}, C_{lo}, and C_{eq}, and AI for network paths which are calculated by utilizing the RAIRFNET using Salicone's method and the RAIRFNET using neurofuzzy metamodel for nil, rectangular, trapezoidal, and triangular internal membership functions of durations. It can be seen from Table 5.14 that the values of the C_{eq} and AI are less than 1. The values of the C_{eq} and AI are consistent for both RAIRFNET using Salicone's method and RAIRFNET using neurofuzzy metamodel for every shape of membership functions.

For both RAIRFNET using Salicone's method and RAIRFNET using neurofuzzy metamodel, some paths contain high C_{eq} and AI values which indicates that there are more than one nearly – critical path. Most values of C_{eq} and AI are consistent. Path 3 is considered to be the most critical (i.e., for the RAIRFNET using Salicone's method for the nil internal membership function: AI = 0.94, C_{eq} =0.7.9). Path 1 and 6 exhibit less criticality than the path 3. A project manager should therefore keep an eye on the activities on path 1, 3, and 6.

Table 5.14 Criticality measures for network paths of the first unit

M	Path	Activity								a1	a2	a3	a4	$C_{lo}(A,B)$	$C_{gr}(A,B)$	$C_{eq}(A,B)$	AI
NS	1	1	2	4	8	14	15			41.4	87.8	87.8	168.1	0.0	0.5	0.5	0.6
NS	2	1	2	4	8	9	15			41.4	86.2	86.2	164.9	0.0	0.5	0.5	0.6
NS	3	1	2	4	5	6	7	15		25.8	107.7	107.7	228.9	0.0	0.2	0.8	0.9
NS	4	1	2	3	5	6	7	15		25.8	81.5	81.5	151.1	0.0	0.6	0.4	0.5
NS	5	1	10	11	12	13	14	15		23.3	70.2	70.2	132.3	0.0	0.7	0.3	0.4
NS	6	1	10	11	12	13	8	14	15	60.6	124.1	124.1	201.5	0.0	0.2	0.8	0.8
NN	1	1	2	4	8	14	15			58.9	87.8	87.8	158.6	0.0	0.5	0.5	0.5
NN	2	1	2	4	8	9	15			59.1	86.2	86.2	156.1	0.0	0.5	0.5	0.5
NN	3	1	2	4	5	6	7	15		63.9	107.7	107.7	233.7	0.0	0.1	0.9	0.9
NN	4	1	2	3	5	6	7	15		37.8	81.5	81.5	172.1	0.0	0.5	0.5	0.6
NN	5	1	10	11	12	13	14	15		7.7	70.2	70.2	142.0	0.0	0.7	0.3	0.4
NN	6	1	10	11	12	13	8	14	15	39.7	124.1	124.1	212.1	0.0	0.3	0.7	0.8
RS	1	1	2	4	8	14	15			41.4	87.8	265.5	345.8	0.0	0.5	0.5	0.6
RS	2	1	2	4	8	9	15			41.4	86.2	260.6	339.3	0.0	0.5	0.5	0.6
RS	3	1	2	4	5	6	7	15		25.8	107.7	387.8	509.0	0.0	0.1	0.9	1.0
RS	4	1	2	3	5	6	7	15		25.8	81.5	227.9	297.5	0.0	0.6	0.4	0.5
RS	5	1	10	11	12	13	14	15		23.3	70.2	201.9	264.0	0.0	0.7	0.3	0.4
RS	6	1	10	11	12	13	8	14	15	60.6	124.1	292.6	370.0	0.0	0.3	0.7	0.7
RN	1	1	2	4	8	14	15			58.9	87.8	255.3	326.0	0.0	0.6	0.4	0.5
RN	2	1	2	4	8	9	15			59.1	86.2	251.7	321.6	0.0	0.6	0.4	0.5
RN	3	1	2	4	5	6	7	15		63.9	107.7	440.3	566.3	0.0	0.0	1.0	1.0
RN	4	1	2	3	5	6	7	15		37.8	81.5	301.3	391.9	0.0	0.4	0.6	0.6
RN	5	1	10	11	12	13	14	15		7.7	70.2	219.0	290.8	0.0	0.7	0.3	0.4
RN	6	1	10	11	12	13	8	14	15	39.7	124.1	309.3	397.3	0.0	0.4	0.6	0.6
TrS	1	1	2	4	8	14	15			19.5	87.8	265.5	394.2	0.0	0.4	0.6	0.6
TrS	2	1	2	4	8	9	15			21.1	86.2	260.6	386.1	0.0	0.4	0.6	0.6

Table 5.14 Criticality measures for network paths of the first unit (con't)

M	Path	Activity								a1	a2	a3	a4	$C_{lo}(A,B)$	$C_{gr}(A,B)$	$C_{eq}(A,B)$	AI
TrS	3	1	2	4	5	6	7	15		3.3	107.7	387.8	573.8	0.0	0.1	0.9	1.0
TrS	4	1	2	3	5	6	7	15		3.3	81.5	227.9	341.4	0.0	0.5	0.5	0.5
TrS	5	1	10	11	12	13	14	15		8.9	70.2	201.9	299.4	0.0	0.6	0.4	0.4
TrS	6	1	10	11	12	13	8	14	15	27.7	124.1	292.6	419.5	0.0	0.3	0.7	0.7
TrN	1	1	2	4	8	14	15			19.5	87.8	265.5	394.2	0.0	0.4	0.6	0.6
TrN	2	1	2	4	8	9	15			21.1	86.2	260.6	386.1	0.0	0.4	0.6	0.6
TrN	3	1	2	4	5	6	7	15		3.3	107.7	387.8	573.8	0.0	0.1	0.9	1.0
TrN	4	1	2	3	5	6	7	15		3.3	81.5	227.9	341.4	0.0	0.5	0.5	0.5
TrN	5	1	10	11	12	13	14	15		8.9	70.2	201.9	299.4	0.0	0.6	0.4	0.4
TrN	6	1	10	11	12	13	8	14	15	27.7	124.1	292.6	419.5	0.0	0.3	0.7	0.7
TS	1	1	2	4	8	14	15			19.5	87.8	87.8	216.6	0.0	0.4	0.6	0.7
TS	2	1	2	4	8	9	15			21.1	86.2	86.2	211.7	0.0	0.4	0.6	0.6
TS	3	1	2	4	5	6	7	15		3.3	107.7	107.7	293.7	0.0	0.1	0.9	0.9
TS	4	1	2	3	5	6	7	15		3.3	81.5	81.5	195.0	0.0	0.5	0.5	0.6
TS	5	1	10	11	12	13	14	15		8.9	70.2	70.2	167.7	0.0	0.5	0.5	0.5
TS	6	1	10	11	12	13	8	14	15	27.7	124.1	124.1	251.0	0.0	0.2	0.8	0.8
TN	1	1	2	4	8	14	15			13.8	87.8	87.8	219.1	0.0	0.4	0.6	0.6
TN	2	1	2	4	8	9	15			13.8	86.2	86.2	216.1	0.0	0.4	0.6	0.6
TN	3	1	2	4	5	6	7	15		0.3	107.7	107.7	339.8	0.0	0.1	0.9	0.9
TN	4	1	2	3	5	6	7	15		0.3	81.5	81.5	242.6	0.0	0.4	0.6	0.6
TN	5	1	10	11	12	13	14	15		0.0	70.2	70.2	175.9	0.0	0.6	0.4	0.5
TN	6	1	10	11	12	13	8	14	15	13.8	124.1	124.1	259.1	0.0	0.3	0.7	0.7

Note N, R, Tr, and T are nil, rectangular, trapezoidal and triangular internal membership functions, while S and N are Salicone's method and neurofuzzy metamodel, 1 is start, 2 is ToLoadSoil, 3 is LoadSoil, 4 is TBMExcavate, 5 is ReturnToShaft, 6 is LocoOut, 7 is UnloadSoil, 8 is TBMInstallSL, 9 is TBMInspSL, 10 is LoadSL, 11 is LocoIn, 12 is OutToShaft, 13 is ToTunnel, 14 is UnloadSL, and 15 is Finish

The C_{eq} and AI are able to present the critical activities as presented in Table 5.15. For the criticality at the activity level, the Excavate activity is used to provide a demonstrative example. The Excavate activity is presented on path 1, 2, and 3. The variation of credibility coefficients due to the variation of the relative positions of the fuzzy path durations and fuzzy project completion time can be considered as membership functions. The degrees of belief associated with the statements that the durations of considered paths are greater, lower, or equal to the designed project completion time can be computed. The determination about the degree that the current activity is ahead of schedule, behind schedule can be performed. A decision maker can seek the critical activities, whenever the criticality of an activity presented on more than one path is considered by using the membership functions of the values of the credibility coefficients together with fuzzy inference. By doing so, the calculation of the criticality at the activity level is systematically and logically provided. For the first unit, the membership values of $C_{eq}(A,B)$ from path 1 to 6 obtained by applying the RAIRFNET using the Salicone's method for the nil internal membership functions are 0.60, 0.58, 0.94, 0.50, 0.40 and 0.79, respectively. Using the maximum operation in the fuzzy inference, the criticality of this activity is 0.94.

Table 5.15 AI and credibility coefficients C_{gr}, C_{lo}, and C_{eq} for project activities

Method	Measure	2	3	4	5	6	7	8	9	10	11	12	13	14
NS	AI	2.6	0.5	2.1	1.4	1.4	1.4	1.2	0.6	1.2	1.2	1.2	1.2	1.8
	Ceq	2.3	0.4	1.9	1.2	1.2	1.2	1.1	0.5	1.1	1.1	1.1	1.1	1.7
NN	AI	2.4	0.6	1.9	1.5	1.5	1.5	1.0	0.5	1.2	1.2	1.2	1.2	1.7
	Ceq	2.3	0.5	1.8	1.4	1.4	1.4	1.0	0.5	1.0	1.0	1.0	1.0	1.5
RS	AI	2.6	0.5	2.2	1.5	1.5	1.5	1.2	0.6	1.1	1.1	1.1	1.1	1.6
	Ceq	2.4	0.4	2.0	1.3	1.3	1.3	1.1	0.5	1.0	1.0	1.0	1.0	1.6
RN	AI	2.5	0.6	1.9	1.6	1.6	1.6	0.9	0.5	1.0	1.0	1.0	1.0	1.5
	Ceq	2.4	0.6	1.8	1.5	1.5	1.5	0.9	0.4	0.9	0.9	0.9	0.9	1.4
TrS	AI	2.7	0.5	2.2	1.5	1.5	1.5	1.2	0.6	1.1	1.1	1.1	1.1	1.7
	Ceq	2.5	0.5	2.1	1.4	1.4	1.4	1.1	0.6	1.1	1.1	1.1	1.1	1.6
TrN	AI	2.7	0.5	2.2	1.5	1.5	1.5	1.2	0.6	1.1	1.1	1.1	1.1	1.7
	Ceq	2.5	0.5	2.1	1.4	1.4	1.4	1.1	0.6	1.1	1.1	1.1	1.1	1.6
TS	AI	2.8	0.6	2.2	1.5	1.5	1.5	1.3	0.6	1.3	1.3	1.3	1.3	1.9
	Ceq	2.7	0.5	2.1	1.4	1.4	1.4	1.3	0.6	1.2	1.2	1.2	1.2	1.9
TN	AI	2.7	0.6	2.0	1.5	1.5	1.5	1.1	0.6	1.1	1.1	1.1	1.1	1.7
	Ceq	2.6	0.6	2.0	1.5	1.5	1.5	1.1	0.6	1.1	1.1	1.1	1.1	1.7

Note N, R, Tr, and T are nil, rectangular, trapezoidal and triangular internal membership functions, while S and N are Salicone's method and neurofuzzy metamodel

The cumulative degree of criticality provides other useful information which can be derived from either the credibility coefficients or AI. The cumulative degree of criticality can also present the degree of being a bottle – neck activity which can later affect the project schedule. The project manager should pay attention to activities having higher cumulative criticality values as their delays can significantly affect the project completion time.

The ToLoadSoil activity is the most critical activity having the highest cumulative AI, and the highest cumulative C_{eq}. Every method and measure provide the consistent result. The cumulative AI decreases and tends to be lower than the cumulative C_{eq} when the rectangular, triangular, and trapezoidal internal membership function are used. The more uncertain activity duration is determined, the lower cumulative values of AI are obtained. It can show that the use of the cumulative C_{eq} is more suitable for any case.

To enable the comparisons between results obtained from the RAIRFNET using Salicone's method and the RAIRFNET using neurofuzzy metamodel for nil, rectangular, trapezoidal, and triangular internal membership functions, the calculation of the cumulative degree of criticality represented in terms of C_{eq} and AI is performed on four types of internal membership functions.

The comparing results for four shapes of internal membership functions for the RAIRFNET using Salicone's method and the RAIRFNET using neurofuzzy metamodel are presented in Figure 5.10, where N, R, Tr, and T are nil, rectangular, trapezoidal and triangular internal membership functions; S and N are Salicone's method and neurofuzzy metamodel. The membership function of project completion times only for the nil internal membership function produced by RAIRFNET using the Salicone's method is reasonably close to the corresponding result generated by Monte Carlo simulation as both considers only a random effect and eliminates the systematic and unknown effects. The project completion times provided by RAIRFNET using the neurofuzzy metamodel for any type of the internal membership functions are consistent. The differences between the project completion times produced by RAIRFNET using neurofuzzy metamodel and simulation outputs are larger than the differences between the project completion times produced by RAIRFNET using the Salicone's method and the simulation results. The Salicone's method gives scheduling outputs based theoretically on the means and variances of probability density functions using the probabilistic methods. Thus, both simulation and Salicone's method compensate the random contribution and eliminate the systematic and unknown contributions. The results of RAIRFNET using the neurofuzzy metamodel on the other hand depend only on uncertainty in the simulated data.

The comparison between the project completion time calculated by using the FNET based on the fuzzy arithmetic algorithms and the project completion time provided by using the RAIRFNET based on the mathematics for random–fuzzy variables is provided by using the cumulative degree of criticality presented in terms of C_{eq} and AI. The comparing results for nil internal membership function for the RAIRFNET and FNET using Salicone's method and the RAIRFNET and FNET using neurofuzzy metamodel are presented in Figure 5.11 as examples where AI (NS, RAIRFNET) and C_{eq} (NS, RAIRFNET) are agreement index and credibility coefficient analyzing results obtained from the RAIRFNET using the Salicone's method for nil internal membership function, AI (NS, FNET) and C_{eq} (NS, FNET) are agreement index and credibility coefficient analyzing results obtained from the FNET using the Salicone's method for nil internal membership function. The comparing results in association with other shapes of membership functions are consistent to the ones shown in these two figures that values of AI and C_{eq} which are calculated by using FNET tend to be larger than the ones provided by using RAIRFNET when the project durations are smaller than the calculated means and otherwise beyond the means.

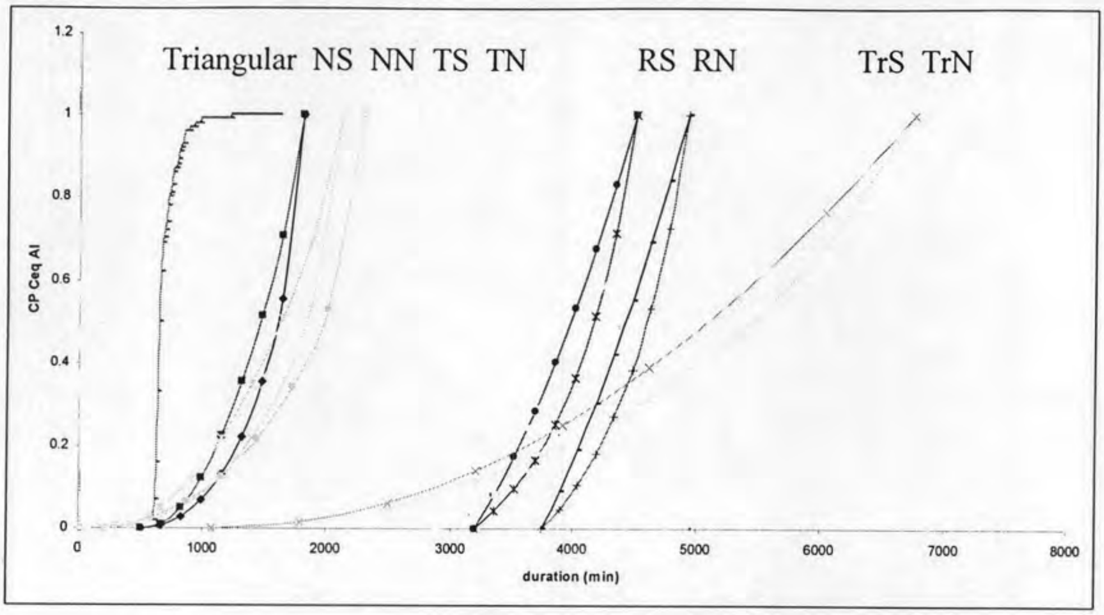

Figure 5.10 CP, C_{eq} and AI for random–fuzzy duration using RAIRFNET using Salicone's method and RAIRFNET using neurofuzzy metamodel for four types of membership functions

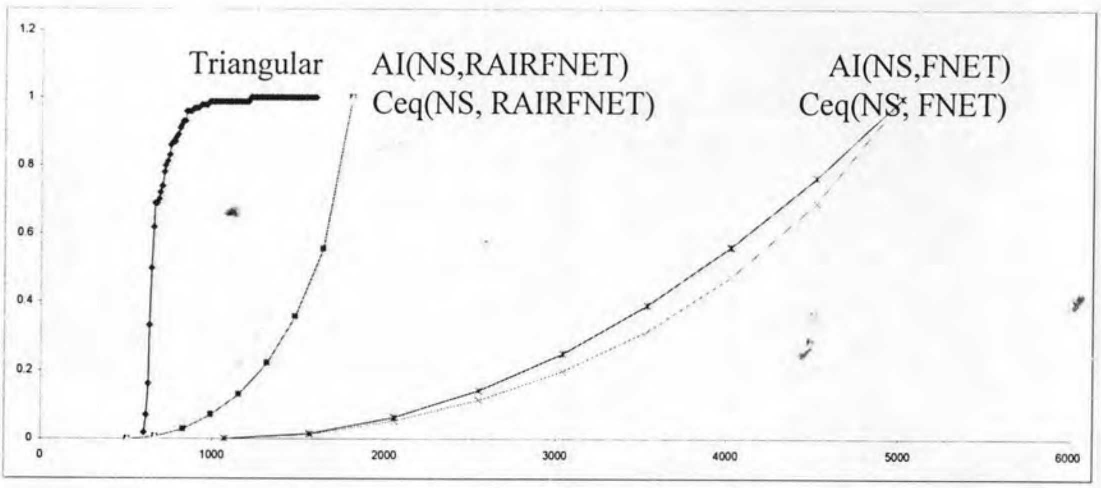

Figure 5.11 CP, C_{eq} and AI for random–fuzzy duration obtained from RAIRFNET and fuzzy duration obtained from FNET

Based on the results generated by AI and C_{eq} presented above, for the same shapes of membership functions of fuzzy and random–fuzzy durations, the fuzzy number based methods provide the wider range of uncertainty than the random–fuzzy number based methods. In general, the random–fuzzy numbers (i.e., random–fuzzy duration) are in association with the means and variances of probability distribution functions because the membership functions representing the random part of the random fuzzy variables are transformed from the probability distribution functions. The developed membership function of project duration is accordingly affected by the central limit theorem, which theoretically compensates the random contribution and eliminate the systematic and unknown contributions. The shape of fuzzy project durations calculated using the fuzzy arithmetic algorithms, on the contrary, does not compensate the random contribution and eliminate the systematic and unknown contributions. In addition, the fuzzy and random–fuzzy project completion times depend on the selected shapes of internal membership functions of duration of project activities. Based on results presented above, the trapezoidal internal membership functions of project durations representing either fuzzy or random–fuzzy numbers provide the widest range of uncertainty, while the nil internal membership functions show the smallest range of uncertainty.

5.3 Comparison among RAIRFNET, Neurofuzzy Metamodel, and Probabilistic Results

To enable the comparisons among project completion times provided by RAIRFNET, neurofuzzy metamodel, and probabilistic method, the considered methods are classified into three categories. The first category presents the comparisons between project completion times obtained from the RAIRFNET using the Salicone's method to develop the membership function of activity duration and the RAIRFNET using the neurofuzzy metamodel to develop the membership function of activity duration. Shapes of the internal membership function include nil, rectangular, trapezoidal and triangular internal membership functions.

The membership functions of project completion times are alternatively developed by using the simulation data associated with project completion times. The application of these two methods is different from the use of the Salicone's method and the neurofuzzy metamodel in the RAIRFNET (the first category) because none of network calculation is required for calculating the project completion time. The Salicone's method uses means and the maximum and minimum duration to develop the membership function of random–fuzzy project completion time. The neurofuzzy metamodel depends mainly on simulation data used to train the knowledge network. The membership functions are created based on a range of uncertain duration presented by the minimum and maximum values obtained from the trained knowledge network and the means obtained from the simulation. Uncertainty due to the random contribution initially represented by a probability distribution is represented in the form of a membership function. The comparison between the first and second categories is provided by using four shapes of the internal membership functions of the project completion times include nil, rectangular, trapezoidal and triangular internal membership functions.

The application of Monte Carlo simulation to produce the project completion time is demonstrate in the third category. The average project durations are obtained with the Monte Carlo simulation which are drawn based on different types of probability distributions of durations of project activities. Figure 4.12 shows eight comparison categories of results of the proposed methods and simulation results.

To simplify the illustration of the comparison between project completion times represented by the probability distributions and the random–fuzzy numbers within a certain time, the probability of project completion times is calculated in Monte Carlo simulation using CP and in the Salicone's method, the neurofuzzy metamodel and the RAIRFNET (and FNET) method using AI and C_{eq}. A number of project durations are computed using these three methods. To enable the comparisons among the results obtained from these three methods, eight comparison categories are presented as follows:

5.3.1 Comparison between Project Completion Times Obtained from Simulation and Salicone's Method Processed on Data Associated with Project Completion Times

The results from Monte Carlo simulation expressed by means of activity duration on a critical path are obtained by executing simulation. A large number of simulation runs is necessary to produce the statistical analysis. The random–fuzzy project durations obtained using the Salicone's method are represented by four types of internal membership functions (i.e., nil, rectangular, trapezoidal and triangular). The percent deviations of random–fuzzy durations from durations obtained from the probabilistic methods range from -49.82% to -40.02% for the underestimated values where the random–fuzzy durations are smaller than the probabilistic result, and 59.62% and 19.61% for the overestimated values. The Salicone's method in association with the trapezoidal and nil internal membership functions provides the highest and lowest deviation for the overestimated values. The difference between random–fuzzy duration and duration obtained from the probabilistic methods depends on the assigned values of epistemic uncertainty due to systematic and unknown contributions.

Figure 5.12 depicts AI, C_{eq}, and CP values of project completion times where NS, RS, TrS, TS are the Salicone's method using nil, rectangular, trapezoidal, and triangular internal membership functions, NN, RN, TrN, TN are the neurofuzzy metamodel using nil, rectangular, trapezoidal, and triangular internal membership functions. It can be seen that the membership functions of project completion times for the nil internal membership function produced by the Salicone's method are closest to the corresponding results generated by Monte Carlo simulation. The use of the trapezoidal internal membership function provided the longest distance between values of CP and values of AI and C_{eq}. For every shape of internal membership functions, values of AI and C_{eq} which are calculated by the Salicone's method are smaller than their respective CP values of Monte Carlo simulation when durations are smaller than modes. The calculated values of AI and C_{eq} are consistent. The values of AI tend to be larger than the C_{eq} for any project completion time.

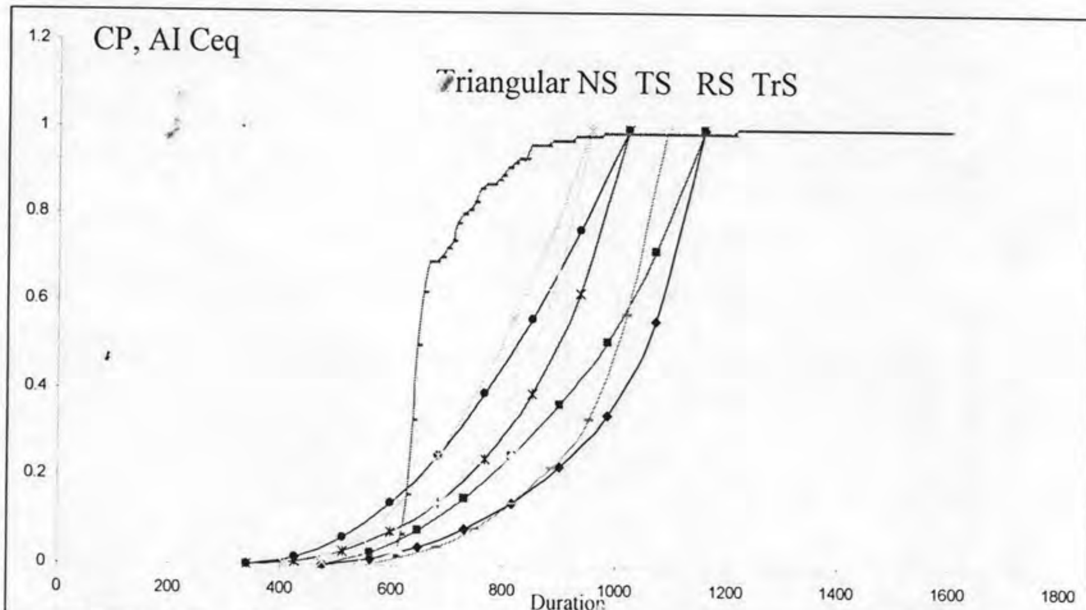

Figure 5.12 CP, AI and C_{eq} for results from the Salicone's method for four shapes of internal membership functions

5.3.2 Comparison between Project Completion Times Obtained from Simulation and Neurofuzzy Metamodel Trained on Data Associated with Project Completion Times

The comparisons between project completion times obtained from simulation and neurofuzzy metamodel trained on simulated data associated with project completion times are analogous to the ones presented above. By training the neurofuzzy metamodel on the same set of simulation data associated with project completion times used in the previous section, the neurofuzzy metamodels provide results represented by four types of internal membership functions (i.e., nil, rectangular, trapezoidal and triangular). The percent deviations of random–fuzzy durations from durations obtained from the probabilistic methods is -100% for every type of internal membership function for the underestimated values where the random–fuzzy duration are smaller than the probabilistic results, and 328% to 360% for the overestimated values.

It can be investigated that the membership functions of project completion times for any type of the internal membership function produced by the neurofuzzy metamodel behave in a similar way towards the corresponding results generated by Monte Carlo simulation. Figure 5.13 presents a wider range for the project duration associated with the neurofuzzy metamodel and a smaller range associated with Monte Carlo simulation. For every type of internal membership functions, values of AI and C_{eq} which are calculated by the neurofuzzy metamodel tend to be larger than their respective values of CP of Monte Carlo simulation when the project durations are smaller than the calculated means and otherwise beyond the means. Values of AI tend to be larger than the C_{eq} values for any project duration.

It can be also seen from the obtained results that the random–fuzzy durations given by the neurofuzzy metamodel are able to explain every uncertainty which cannot be fully determined by the probabilistic method. The assigned values of epistemic uncertainty due to systematic and unknown contributions have great impact on the difference between random–fuzzy duration and duration obtained from the probabilistic methods.

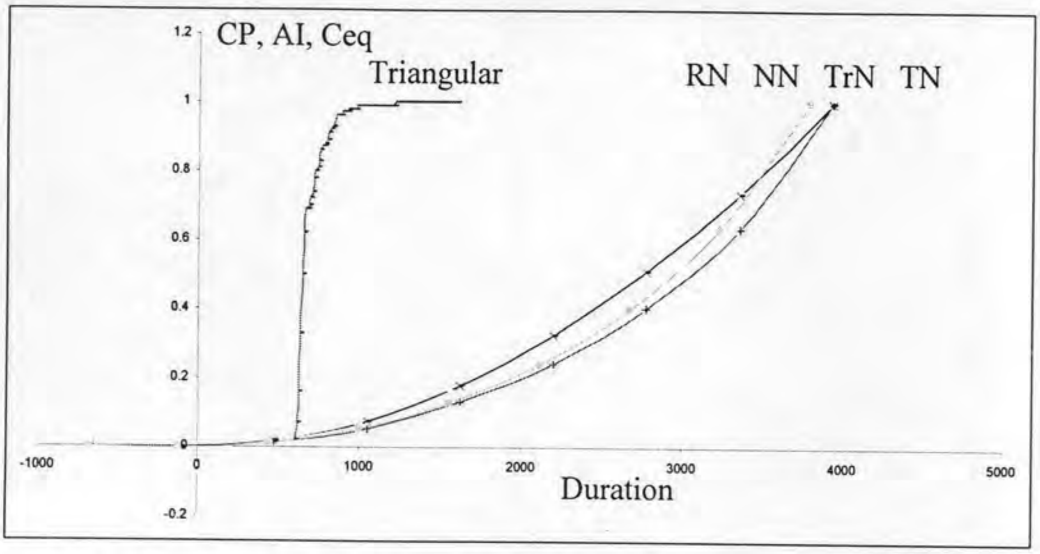

Figure 5.13 CP, AI and C_{eq} for results from the neurofuzzy metamodel for four shapes of internal membership functions

5.3.3 Comparison between Project Durations Obtained from RAIRFNET Using Salicone's Method and Simulation

Simulation results are used to compare with the results provided by RAIRFNET using Salicone's method to provide the membership functions of duration of project activities for the network calculation. The RAIRFNET provides the project completion times presented by four shapes of internal membership functions (i.e., nil, rectangular, trapezoidal and triangular). The shapes are designed based on the assigned values of uncertainty due to the systematic and unknown contributions.

The ranges of minimum and maximum percent deviations are 0% to 62.85%, and 0% to 86.04%. The lowest and highest deviations are obtained from the method having the nil and trapezoidal internal membership functions, at the level $\alpha = 0$, respectively. The comparing results indicate that the random–fuzzy durations can explain every uncertainty that cannot be determined by the probabilistic methods. The obtained results show that the difference between random–fuzzy duration and duration obtained from the probabilistic methods is influenced by the assigned values of epistemic uncertainty due to systematic and unknown contributions and the mathematics for random–fuzzy variables.

Working durations (i.e., minimum and maximum duration) for each unit of a product are displayed in Figure 5.14 where NS1a, NS1d are optimistic and pessimistic durations of activity Start, and NS15a, NS15d are optimistic and pessimistic durations of activity Finish obtained from the RAIRFNET using the Salicone's method to develop the nil internal membership function and the definitions of RS1a, RS1d, RS15a, RS15d, TrS1a, TrS1d, TrS15a, TrS15d, TS1a, TS1d, TS15a, TS15d are provided analogous to the definitions of NS1a, NS1d, NS15a, NS15d where R, Tr, T are rectangular, trapezoidal, and triangular internal membership functions.

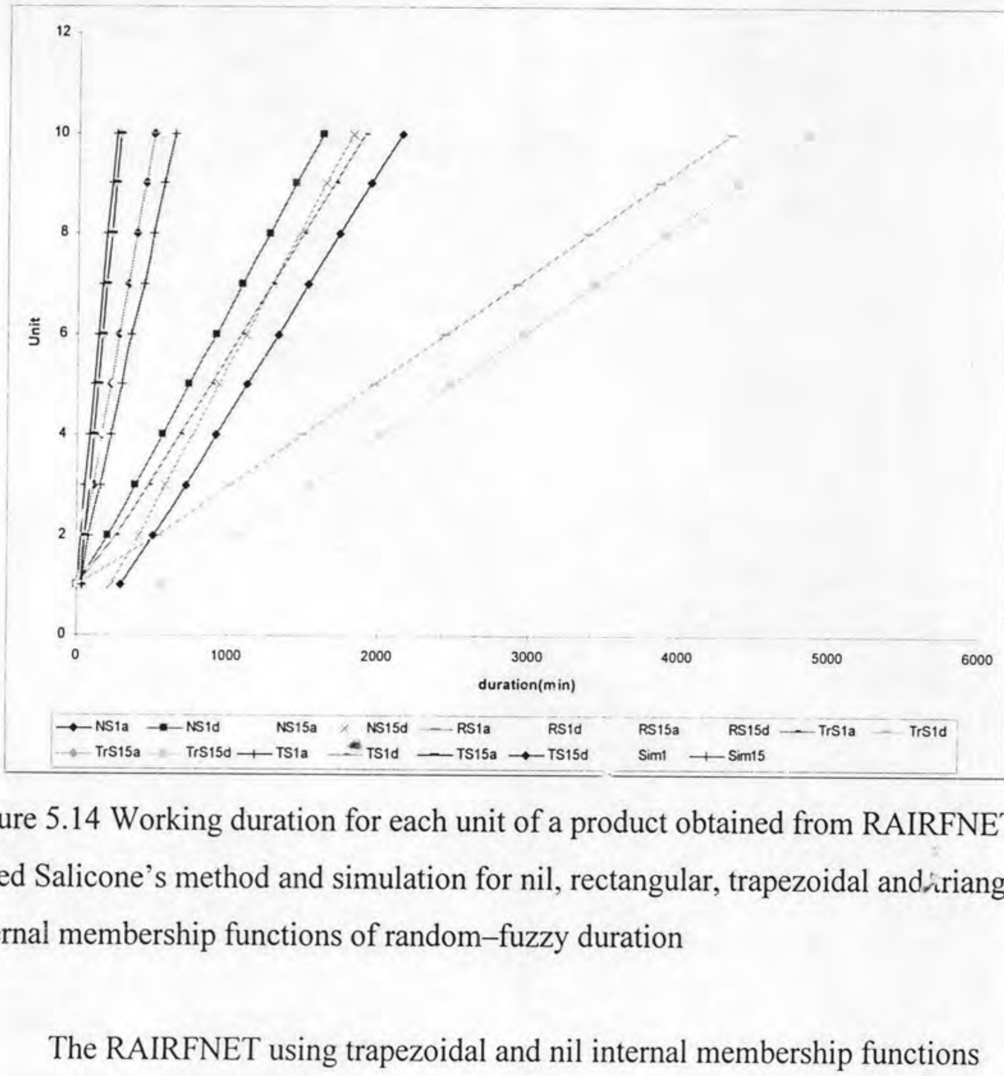

Figure 5.14 Working duration for each unit of a product obtained from RAIRFNET based Salicone's method and simulation for nil, rectangular, trapezoidal and triangular internal membership functions of random–fuzzy duration

The RAIRFNET using trapezoidal and nil internal membership functions provides the largest and smallest range of project completion times, while the one using rectangular and triangular internal membership functions provides the project completion times failing in the middle of those methods because every uncertainty is considered in the network calculation. The results also confirm that the RAIRFNET using the nil internal membership function produces the project completion time closer to the one provided by simulation as both of them determine only uncertainty due to the random contribution. The range of the calculated project completion times does not depend only on the types of internal membership functions, but also the assigned confidence level ($\alpha -$ cut level). The large confidence interval dramatically increases the range of the calculated project completion times when the most uncertain durations of project activities which are represented by the trapezoidal internal membership functions are determined.

Figure 5.15 shows the values of CP of project completion times, AI and C_{eq} particularly for duration. Although the membership functions of project completion times for any shape of the internal membership function produced by RAIRFNET using the Salicone's method represent the uncertainty in a similar way, the one for the trapezoidal and rectangular internal membership functions gives the larger ranges of project completion times. For every shape of internal membership functions, values of CP tend to be located within the values of AI and C_{eq}. Values of CP tend to be smaller than the values of AI and C_{eq} when the project durations are smaller than the calculated means and otherwise beyond the means. The values of AI and values of C_{eq} are consistent. The values of AI tend to be larger than the C_{eq} for any project duration because C_{eq} is more sensitive to the relevance between the compared fuzzy numbers. The membership function of project completion times can be predetermined as it depends on those of the membership functions of duration of project activities. Values of AI and values of C_{eq} obtained from the RAIRFNET using nil internal membership functions is found to be the nearest to values of CP given by Monte Carlo simulation because only the random contribution to uncertainty is determined. The obtained results present that the calculated values of AI and C_{eq} depend on the assigned values of epistemic uncertainty due to the systematic and unknown contributions, while the computed values of CP are not influenced by the assigned values of epistemic uncertainty.

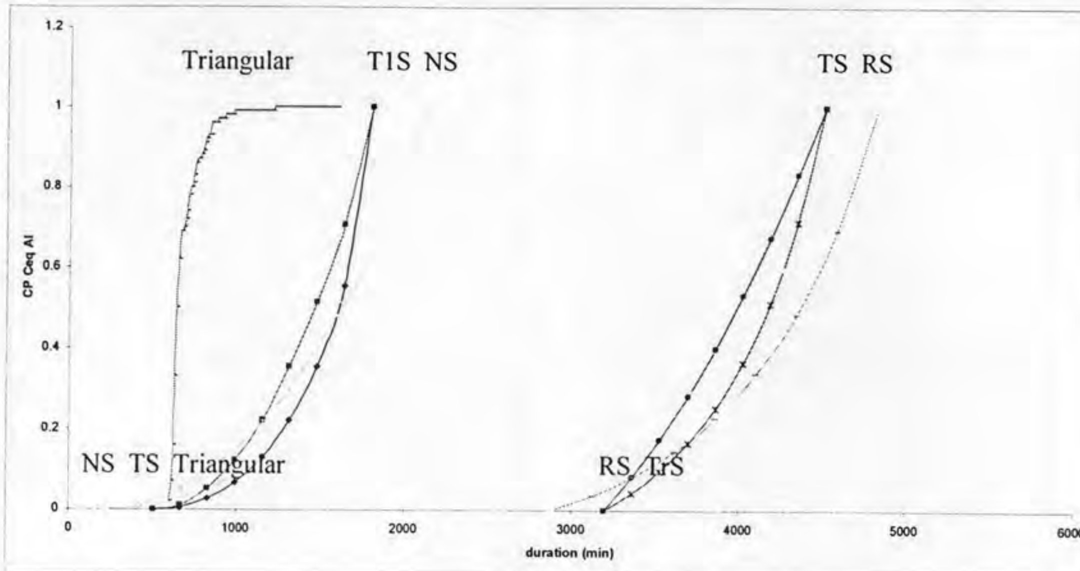

Figure 5.15 CP, AI and C_{eq} for results from RAIRFNET using Salicone's method processed on activity duration data

5.3.4 Comparison between Project Durations Obtained from RAIRFNET Using Neurofuzzy Metamodel and Simulation

The comparison between Simulation results and the results provided by RAIRFNET using neurofuzzy metamodel to provide the membership functions of activity duration is presented in this section. Four shapes of internal membership functions (i.e., nil, rectangular, trapezoidal and triangular) are determined which are established based on the assigned values of uncertainty due to the systematic and unknown contributions.

The minimum percent deviations ranges from 0% to 62.85%, while the maximum percent deviations ranges from 0% to 86.04%. The applications of nil and trapezoidal internal membership functions, at the level $\alpha = 0$, give the highest and lowest deviations, respectively. Differences between optimistic, mode, and pessimistic random–fuzzy durations and simulated duration of all activities are computed. The comparison between the working durations (i.e., minimum and maximum duration) for each unit of a product estimated by applying the RAIRFNET using Salicone's method and the ones provided by running simulation is performed. The comparing results including the nil, rectangular, trapezoidal and triangular internal membership functions used to present random–fuzzy duration are shown in Figure 5.16. The comparing results are consistent with the ones given by other comparing methods. The largest and smallest ranges of project completion times are provided by employing RAIRFNET using trapezoidal and nil internal membership functions, respectively. The RAIRFNET using rectangular internal membership functions provides the project completion times which is close to the RAIRFNET using trapezoidal one, while the use of the triangular internal membership function produces the outputs close to the application of the nil internal membership function. These results depend mainly on the values of systematic and unknown contributions which are assigned during establishing the internal membership functions. As only the random contribution is determined, the application of RAIRFNET using the nil internal membership function produces the project completion time closer to the one provided by simulation.

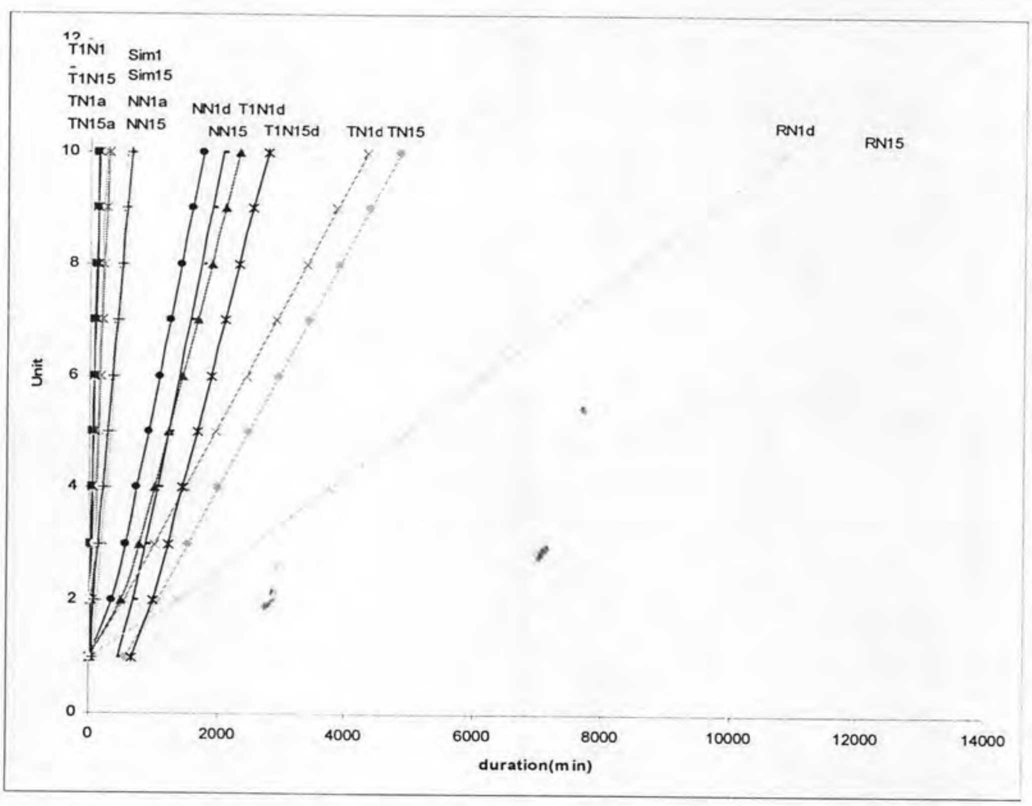

Figure 5.16 Working duration for each unit of a product obtained from RAIRFNET based neurofuzzy metamodel and simulation for nil, rectangular, trapezoidal and triangular internal membership functions of random–fuzzy duration

The widest range of uncertainty is presented at $\alpha -$ cut level = 0. Based on the obtained results, a range of project completion times is based on either shapes of internal membership functions or the assigned confidence levels ($\alpha -$ cut levels). When the most uncertain durations of project activities represented by the trapezoidal internal membership functions are considered, the large confidence interval considerably raises the range of project completion times.

The values of CP of project completion times examined at five $\alpha-$ cut levels, AI and C_{eq} particularly for durations are presented through Figure 5.17. It can be seen that the membership functions of project completion times for any shape of the internal membership function produced by RAIRFNET using the neurofuzzy metamodel are consistent. The application of the trapezoidal and rectangular internal membership functions provides the larger ranges of project completion times than the application of the nil and triangular internal membership functions. The range of CP are located within the range of AI and C_{eq}. The values of AI and C_{eq} are larger than the values of CP when the project durations are smaller than the calculated means and otherwise beyond the means. The values of AI are also larger than the values of C_{eq} for every project completion time because C_{eq} is considerably influenced by the relevance between the compared fuzzy numbers.

The assigned values of uncertainties due to systematic and unknown effects have significant impact on the differences between values of CP and values of AI and C_{eq} obtained from the RAIRFNET using rectangular, trapezoidal, and triangular internal membership functions. The RAIRFNET using the nil internal membership function provides the smallest differences between these values because none of the systematic and unknown effects are involved in the establishment of a probability distribution and a nil internal membership function.

5.3.5 Comparison between Project Completion Times Obtained from Salicone's Method and Neurofuzzy Metamodel Trained on Data Associated with Project Completion Times

The comparison between the random–fuzzy project durations provided by using the Salicone's method and the ones provided by neurofuzzy metamodel trained on data associated with project completion times is provided in this section. Four shapes of internal membership functions (i.e., nil, rectangular, trapezoidal and triangular) are determined. The percent deviations of random–fuzzy durations provided by the Salicone's method from durations obtained from the probabilistic methods (i.e., -49.82% to 59.62%) are smaller than the ones provided by the neurofuzzy metamodel (i.e., -100% to 359.89%).

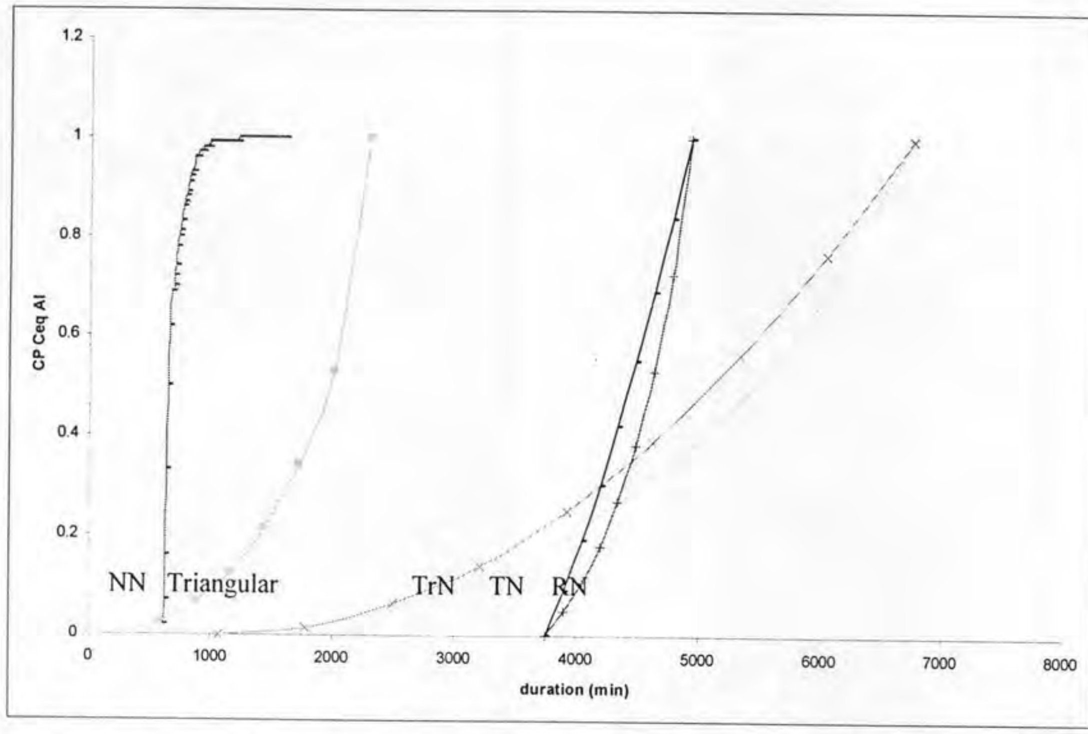

Figure 5.17 CP, AI and C_{eq} for results from RAIRFNET using neurofuzzy metamodel trained on data associated with duration of project activities

Values of CP of project completion times calculated by the probabilistic methods, values of AI and values of C_{eq} are presented in Figure 5.18. The membership function of project completion times only for the nil internal membership function produced by the Salicone's method is reasonably close to the corresponding result generated by Monte Carlo simulation as both considers only a random effect and eliminates the systematic and unknown effects. The project completion times provided by the neurofuzzy metamodel for any type of the internal membership functions are consistent to the simulation results, although the differences are larger than the differences between the project completion times produced by the Salicone's method and the simulation results. This is because theoretically the Salicone's method produces scheduling outputs based on the means and variances of a probability density function using the probabilistic methods.

The fuzzy rule base obtained from the knowledge network learnt by using the neurofuzzy metamodel makes the results obtained from the neurofuzzy metamodel become more interpretable and applicable to construction projects than the results provided by the Salicone's method. Specifically, the Salicone's method gives only membership functions representing project completion times and the values of attributes of risk factors. The neurofuzzy metamodel, on the other hand, offers the fuzzy rule base together with the membership functions of input – output variables (i.e., risk variables and project completion time), which in practice the establishment of the rule base can not be provide in a simply manner as it requires so much time and a lot of efforts to examine the logical relationships between input – output variables. The use of any traditional rule base development method to complement the Salicone's method can help create the fuzzy rule base, but additional data are required. Such data are usually unavailable and depend on human subjectivity. Although the application of the neurofuzzy metamodel is more suitable, the results of the neurofuzzy metamodel depend on uncertainty in the training data.

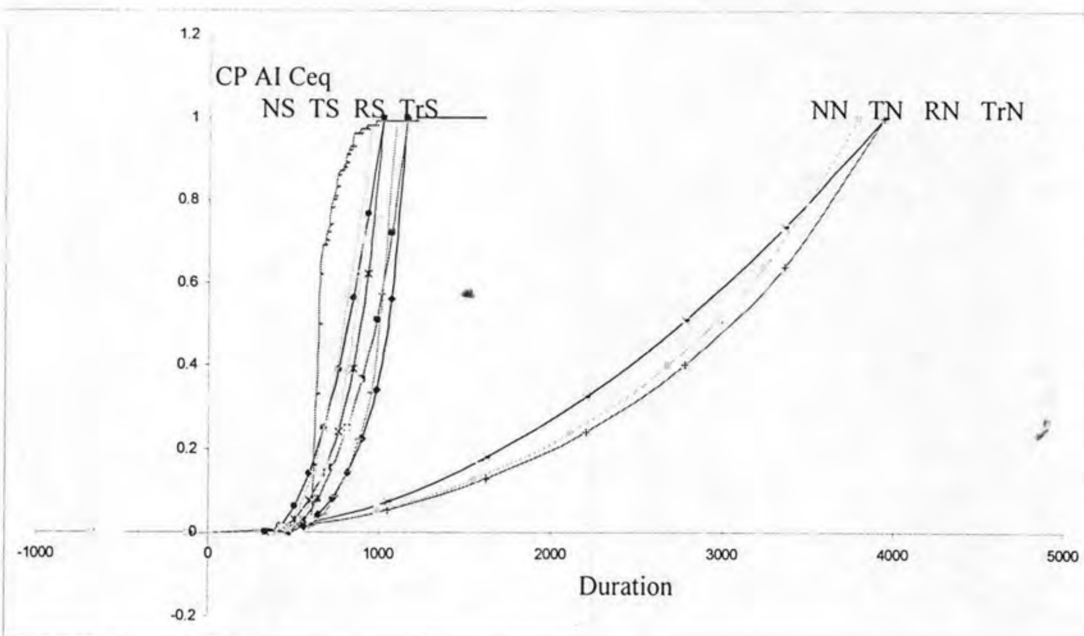

Figure 5.18 CP, AI and C_{eq} for results from the Salicone's method and the neurofuzzy metamodel for a triangular distribution

5.3.6 Comparison between Project Completion Times Obtained from Salicone's Method Processed on Data Associated with Project Completion Times and RAIRFNET Using Salicone's Method Processed on Data Associated with Activity Duration

The performance of the Salicone's method applied by using different data sets including data associated with project completion times and data associated with activity duration is determined in this section. After applying the Salicone's method to transform a probability distribution function into a membership function representing the random contribution, uncertainty due to the systematic and unknown contributions is examined and presented by four shapes of internal membership functions (i.e., nil, rectangular, trapezoidal and triangular). The random–fuzzy durations of project activities are inputted into the network calculation in order to estimate the project completion time.

The use of the Salicone's method processed on data associated with project completion times is different from the application of RAIRFNET utilizing the Salicone's method processed on data associated with duration of project activities as none of network calculation is performed for computing the project completion time. The ranges of minimum and maximum percent deviations are -32.53% to 92.29%, and 35.79% to 465.52%. The lowest deviations are obtained from the method having the triangular and trapezoidal internal membership functions. The highest deviations are obtained from the method having the rectangular and trapezoidal internal membership functions.

The spread of project completion times provided by the Salicone's method processed on data associated with project completion times is of three times of the spread of the project completion time obtained from the Monte Carlo simulation. The obtained results are consistent to the designed concept that the difference between the optimistic and pessimistic project durations or the spread of project completion times obtained from the Salicone's method processed on data associated with project completion times is larger than the standard deviation of the project completion time computed by using the statistical method.

The spread of project completion times obtained from the RAIRFNET using Salicone's method is larger than the spreads of the project completion times obtained from the Monte Carlo simulation and the Salicone's method processed on data associated with project completion times. The membership function of random–fuzzy duration of project activities developed based on the designed concept would make the cumulative assigned value of epistemic uncertainty associated with activity duration become larger than the assigned value of epistemic uncertainty associated with the project completion time by using the Salicone's method processed on data associated with project completion times. The spread of project completion times provided by the RAIRFNET also depends on the mathematics for the random–fuzzy numbers which are able to simultaneously analyze either the random contribution or the systematic and unknown contributions to uncertainty.

Values of CP of project durations examined at five $\alpha-$ cut levels, values of AI and C_{eq} are depicted in Figure 5.19 where NS, RS, TrS, TS are the Salicone's method processed on data associated with the project completion times for nil, rectangular, trapezoidal and triangular internal membership function and NS_R, RS_R, TrS_R, TS_R are the RAIRFNET using the Salicone's method processed on data associated with duration of project activities for nil, rectangular, trapezoidal and triangular internal membership function. The results show that values of AI and C_{eq} of project completion times and the spread of random–fuzzy project completion times for any shape of the internal membership functions (i.e., nil, rectangular, trapezoidal and triangular) produced by RAIRFNET using the Salicone's method are mostly larger than the ones obtained from the Salicone's method processed on data associated with project completion times when the project durations are smaller than the modes and otherwise beyond the modes. When the durations are smaller than the calculated modes, the random–fuzzy durations provided by the former overestimate the random–fuzzy duration obtained from the later which shows that the former provides more uncertain results than the later.

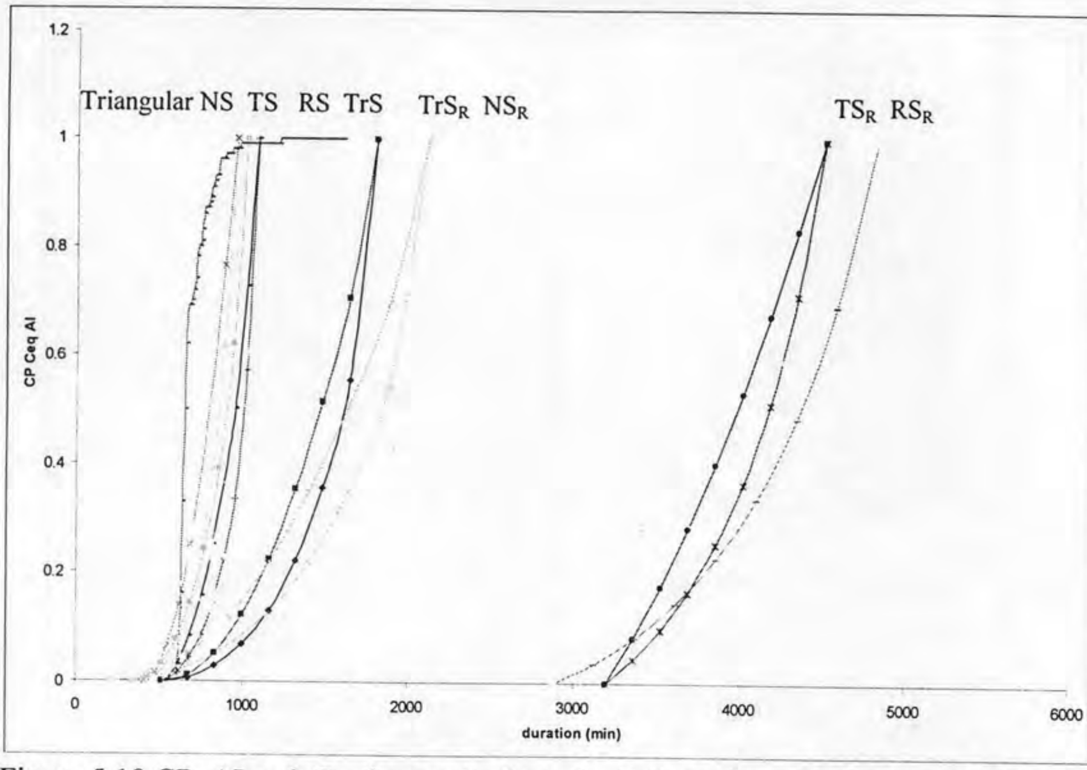

Figure 5.19 CP, AI and C_{eq} for results from the Salicone's method ad RAIRFNET using the Salicone's method and simulation using triangular probability distribution

5.3.7 Comparison between Project Completion Times Obtained from Neurofuzzy Metamodel Trained on Data Associated with Project Completion Times and RAIRFNET Using Neurofuzzy Metamodel Trained on Data Associated with Activity Duration

This section is to present the comparison between the performance of the neurofuzzy metamodel trained on data related to project completion times and the RAIRFNET using the neurofuzzy metamodel trained on data related to durations of project activities by determining different aspects. The neurofuzzy metamodels are trained on data using in the previous subsection to apply of the Salicone's methods. The comparisons are provided based on different shapes (i.e., nil, rectangular, and triangular) of internal membership functions. The project completion time is computed by performing the network calculation following the steps in the neurofuzzy metamodel and using durations of project activities represented by membership functions produced by the neurofuzzy metamodels. By using the neurofuzzy metamodel trained on data associated with project completion times, the project completion time can be obtained for given input values without performing the network calculation.

The ranges of minimum and maximum percent deviations are -40% to 140%, and 68.43% to 640.52%. The lowest percent deviations are obtained from the applications of the triangular and trapezoidal internal membership functions, while the highest percent deviations are provided by applying the rectangular and trapezoidal internal membership functions.

Values of CP of project durations, values of AI and C_{eq} are expressed in Figure 5.20 where NN, RN, TrN, TN are the neurofuzzy metamodel trained on data associated with the project completion times for nil, rectangular, trapezoidal and triangular internal membership function and NN_R, RN_R, TrN_R, TN_R are the RAIRFNET using the neurofuzzy metamodel trained on data associated with duration of project activities for nil, rectangular, trapezoidal and triangular internal membership function. The results show that for any shape of the internal membership functions (i.e., nil, rectangular, trapezoidal and triangular) values of AI and C_{eq} of project completion times and the spread of random–fuzzy project completion times produced by RAIRFNET using the neurofuzzy metamodel are mostly larger than the ones obtained from the neurofuzzy metamodel trained on data associated with project completion times when the project durations are smaller than the modes and otherwise beyond the modes. The random-fuzzy durations of the RAIRFNET using the neurofuzzy metamodel overestimate the random–fuzzy durations of the neurofuzzy metamodel trained on data associated with project completion times when the durations are smaller than the calculated modes, which means that the more uncertain durations are obtained from the application of the RAIRFNET using the neurofuzzy metamodel.

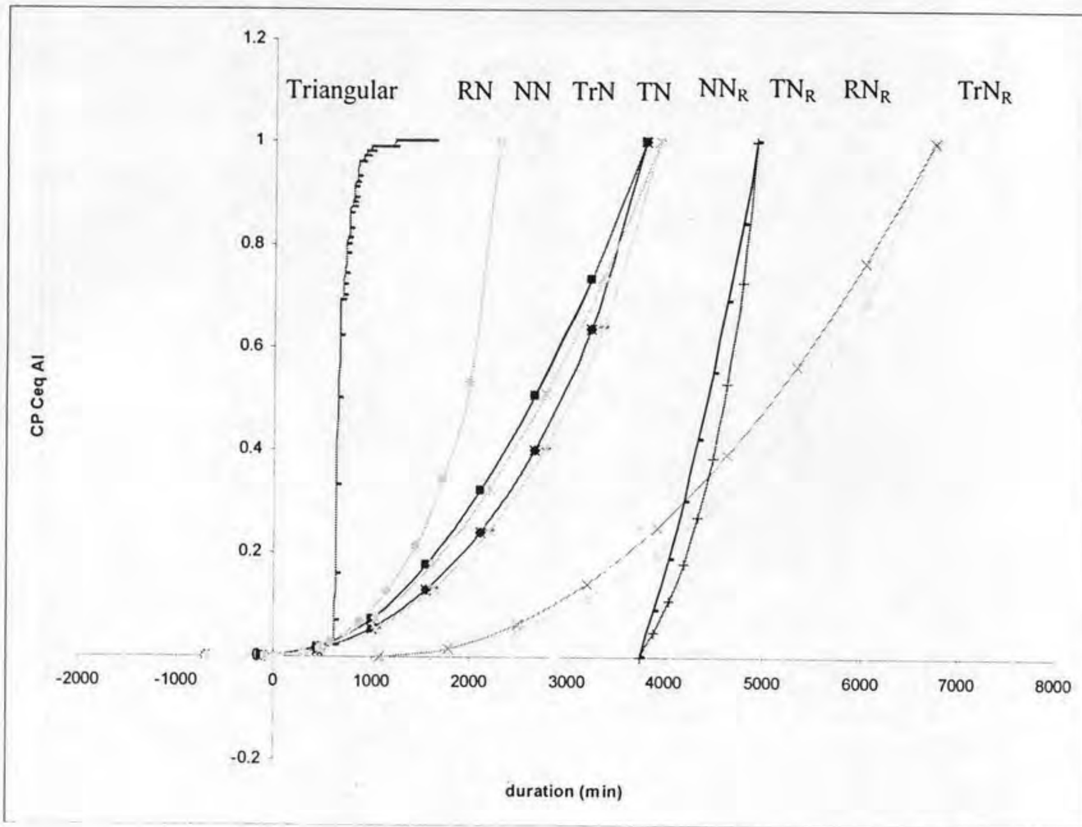

Figure 5.20 CP, AI and C_{eq} for results from RAIRFNET using the neurofuzzy metamodel trained on activity duration data and the neurofuzzy metamodel trained on project duration data derived from triangular probability distribution

Simulation results are compared with results obtained from these two methods, the results of the neurofuzzy metamodel trained on data associated with project completion times are closer the simulation results simulation data are used to train the neurofuzzy metamodel. The spread of project completion times obtained from the RAIRFNET using neurofuzzy metamodel is larger than the spreads of the project completion times obtained from the neurofuzzy metamodel trained on data associated with project completion times, while the spreads of project completion times obtained from the RAIRFNET using neurofuzzy metamodel and the neurofuzzy metamodel trained on data associated with project completion times are larger than the spread of project completion times achieved from the Monte Carlo simulation. The obtained results are consistent to the concept used to develop the membership functions of random–fuzzy durations of project activities for the RAIRFNET. The cumulative assigned values of epistemic uncertainty involved in durations of project activities due to systematic and unknown contributions whish is larger than the value of epistemic uncertainty determined in the development of the internal membership function of the project completion time in the case of the application of the neurofuzzy metamodel trained on data associated with the project completion times. The RAIRFNET using mathematics for the random–fuzzy numbers to simultaneously examine the random and nonrandom part of duration of project activities also leads to the deviations.

5.3.8 Comparison between Project Completion Times Obtained from RAIRFNET Using Salicone's Method and RAIRFNET Using Neurofuzzy Metamodel Trained on Data Associated with Activity Duration

This section is to present the random–fuzzy project completion times obtained from the RAIRFNET using the Salicone's method and the RAIRFNET using neurofuzzy metamodel trained on data associated with duration of project activities. Four shapes of internal membership functions (i.e., nil, rectangular, trapezoidal and triangular) are determined in the comparisons between the project completion times provided by the RAIRFNET and also the comparison between results obtained from the RAIRFNET and simulation. Once simulation data are processed by using the Salicone's method and the neurofuzzy metamodel, the percent deviations of random–fuzzy durations obtained from the RAIRFNET using the Salicone's method are smaller than the percent deviations of random–fuzzy durations obtained from the RAIRFNET using the neurofuzzy metamodel.

This subsection is to show the comparing results related to working durations for each unit of a product estimated by applying the RAIRFNET using the Salicone's method, the RAIRFNET using the neurofuzzy metamodel, and simulation which are illustrated in Figure 5.21 and 5.22 for the optimistic and pessimistic durations, respectively. The smallest and widest ranges of project completion times are obtained from the RAIRFNET using the Salicone's method utilizing nil and trapezoidal internal membership functions, respectively. The RAIRFNET using neurofuzzy metamodel provides the same results. The RAIRFNET using the Salicone method utilizing trapezoidal and rectangular internal membership functions provides the similar range of project completion times. The RAIRFNET using neurofuzzy metamodel utilizing rectangular internal membership function provides the smaller range of project completion time. It can be investigated from the obtained results that generally the trapezoidal internal membership function is suitable for presenting every uncertain involved in duration.

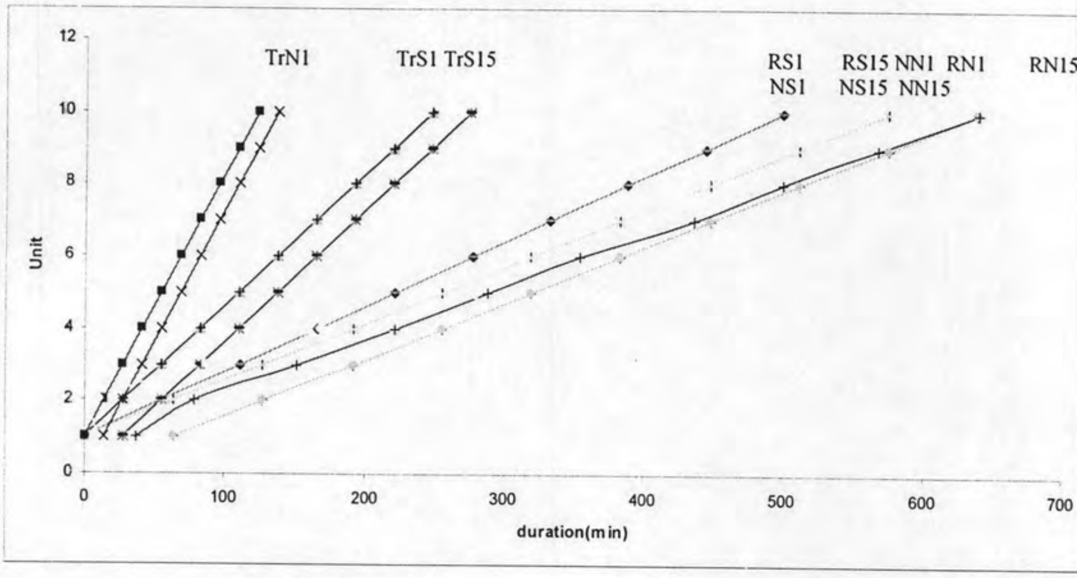

Figure 5.21 Working duration for each unit of a product obtained from RAIRFNET using Salicone's method and RAIRFNET using neurofuzzy metamodel for the optimistic duration

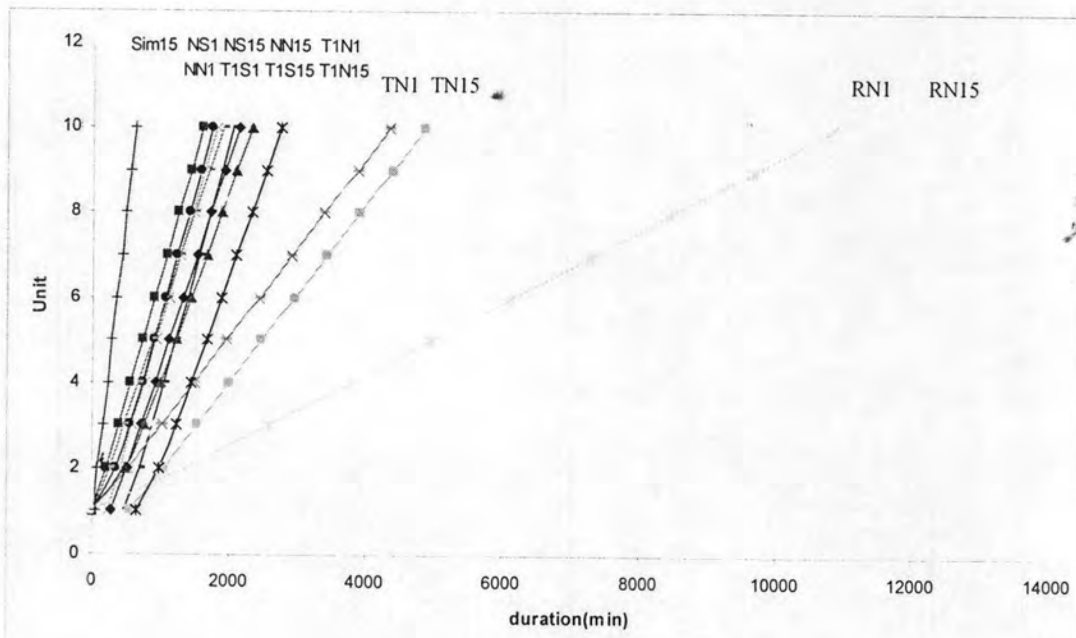

Figure 5.22 Working duration for each unit of a product obtained from RAIRFNET using Salicone's method and RAIRFNET using neurofuzzy metamodel for the pessimistic duration

The application of the RAIRFNET using the neurofuzzy metamodel for nil internal membership function provides the project completion times closer to the simulation results comparing to the use of other shapes of internal membership functions because these two methods consider only the random contribution. The RAIRFNET using Salicone's method for the nil internal membership function provides the project completion times that are much closer to the simulation results comparing to the results obtained from the RAIRFNET using the neurofuzzy metamodel. All results are consistent to the results presented previously based on the determination of working duration of each unit of a product and the values of CP, AI and C_{eq}. As the RAIRFNET using the Salicone's method produces scheduling outputs based theoretically on the means and variances of a probability density function using in the probabilistic methods, the applications of simulation and RAIRFNET using Salicone's method for nil internal membership function disregard the systematic and unknown effects and compensate the random contribution, but, by contrast, the results obtained from the RAIRFNET using the neurofuzzy metamodel depend only on uncertainty in the simulated data.

5.4 Summary

Duration estimating is of paramount importance in every phase of construction projects from planning to execution. This research tries to produce an estimate that is an accurate reflection of reality by using three data acquiring approaches to provide an estimator the best information available to estimate duration for performing the required works using the selected resources. Data used in the duration estimating are composed of subjective data from professional experience and judgment, historical data, and simulation data. The used information is therefore the calculations based on detailed analysis of the construction process combining with the estimator's best guess of time. The proposed method uses data from past projects with knowledge of the resemblance between past projects and the ongoing project. As a result, the proposed method provides an accurate estimate which covers actual duration and reflect the realities of the project in investigation.

The comparisons among alternative methods proposed in this research and current methods typically used to perform risk assessment and network calculation are provided. The Salicone's method processed on data associated with project completion times, neurofuzzy metamodel trained on data associated with project completion times, RAIRFNET using Salicone's method processed on data associated with activity duration to develop membership function of activity duration, and RAIRFNET using neurofuzzy metamodel trained on data associated with activity duration are alternative methods proposed in this research. The performance of a method based the probability theory (i.e., simulation) is compared with the performance of alternative methods by using data from the tunneling project.

Different shapes of the internal membership functions (i.e., nil, rectangular, trapezoidal and triangular) representing the fuzzy part of random–fuzzy durations are used to present the project completion times. The probability based method presents the project completion times in the statistical form of frequency or cumulative frequency. The frequencies of the project durations are normalized by dividing them with the maximum frequency. Other measurement methods (i.e., CP, AI, credibility coefficients) are also used in the comparison between the computed project completion times.

The results obtained from the proposed methods are consistent. The project completion times produced by the RAIRFNET using the neurofuzzy metamodel are mostly larger than the ones produced by the RAIRFNET using the Salicone's method when durations are smaller than the calculated modes and otherwise beyond the modes. The RAIRFNET method provides the more uncertain project completion times than the Salicone's method and neurofuzzy metamodel trained on data associated with project completion times. The proposed methods provide project completion times having larger ranges than the simulation results.

Based on the results obtained from using the proposed RAIRFNET, the proposed random–fuzzy network calculation is not only able to determine every uncertainty, but it is also address uncertainties associated with the network calculation process. The cumulative value of uncertainties of duration of project activities is considered in the calculation of the project completion time.

Considering the project completion times obtained from the Salicone's method and neurofuzzy metamodel trained on data associated with project completion times, the results are based mainly on the training data capturing behaviors and relationships between the temporal variable and risk variables. Based on the comparing results between project completion times provided by these two methods and the ones obtained from the RAIRFNET, it can indicate that data associated with the project completion time and values of risk variables that are used as the training data cannot represent all uncertainties involved. On the other hand, the uncertainty associated with duration of project activities and uncertainty associated with the network calculation which are ignored by these two methods are taken into account in the application of the RAIRFNET method.

It can be seen from the comparing results that the proposed methods which are based on the random–fuzzy concept are able to address uncertainties associated with the estimation of the project completion times. As uncertainties due to random and fuzzy effects associated with activity duration are examined, the proposed methods give the larger results comparing to results obtained from the probability theory based methods because the epistemic uncertainty due to systematic and unknown contributions is not determined.

In this research, the rectangular, triangular, and trapezoidal internal membership functions are used to represent the assigned values of uncertainties due to systematic and unknown contributions. The smallest uncertain project completion time is achieved by using nil internal membership functions to represent durations of project activities because only uncertainty due to a random contribution is determined in the network calculation. The methods using the nil internal membership function, therefore, provide the results that are close the simulation results as both of them determine only uncertainty due to the random contribution but these two methods cannot provide results covering the actual duration. The methods determining uncertainty due to fuzzy effects in the development of the membership functions of activity duration provide the more accurate project duration. However, the calculated project duration depends mainly on the assigned values of uncertainty due to the fuzzy effects.