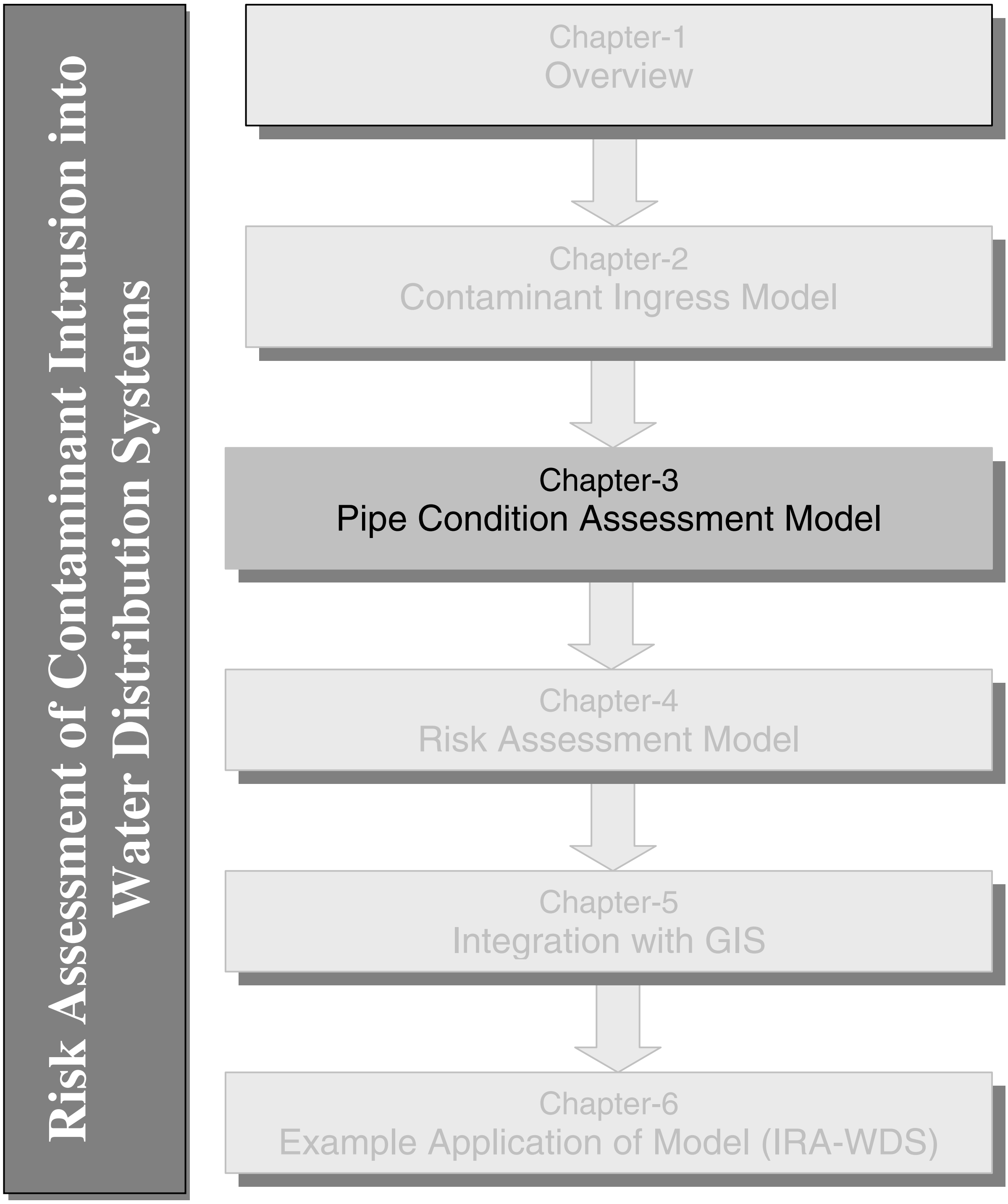
CHAPTER THREE

Pipe Condition Assessment Model


Risk Assessment of Contaminant Intrusion into Water Distribution Systems
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Chapter 3: Pipe Condition Assessment Model

3.1 Introduction

This chapter presents details of the pipe condition assessment model component of IRA-WDS. As the name implies, this model considers all pipes in a water distribution system and estimates their relative condition (see Figure 3.1).

The outputs from the model presented in this chapter are therefore a measure of relative condition of each pipe in the water distribution system being studied. Figure 3.12 and Table 3.17 at the end of this chapter give a typical example of the outputs.

The purpose of this chapter is to provide an insight into the background and the techniques that underpin the pipe condition model. This should enable the user of IRA-WDS to appreciate the significance of the data required and also aid in interpreting the results of the model. On completion of this chapter, the user should be able to complete Tables 3.1 to 3.8, which form the input data required to run the pipe condition assessment model of IRA-WDS. Information on the data that needs to be developed in order to complete Tables 3.1–3.8 is given in this chapter.

It should be noted, however, that to use IRA-WDS the user is not required to have a detailed understanding of the technical component of the model presented in this chapter.

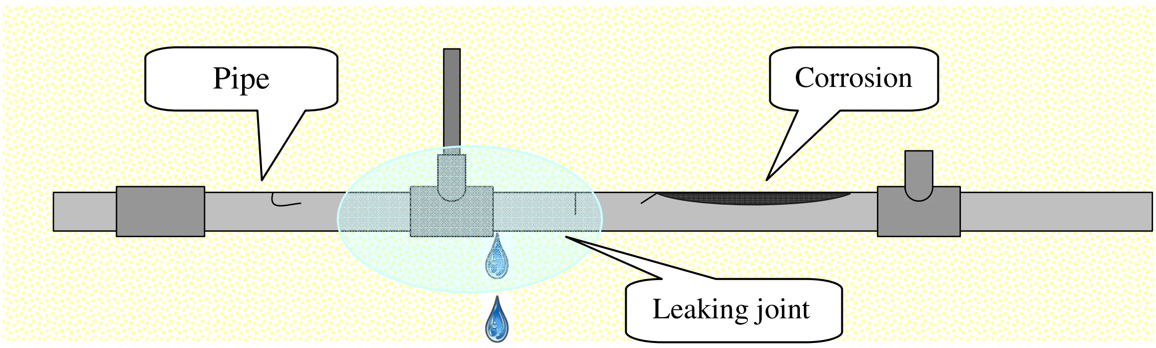

Figure 3.1. Water distribution pipe deterioration

The condition of each pipe is assessed by means of numerous indicators related to physical, environmental and operational aspects of water distribution system. These indicators are combined to give a single measure of the relative condition of each pipe. The relative condition of each pipe, coupled with its section in the contaminant zone and the contaminant loading along this section (outputs from the contaminant ingress model presented in Chapter 2), provides an estimate of the potential pollutant load entering each pipe.

Table 3.1. Properties of water distribution network

Parameter	**Unit**	**Value**
Network map ***For each pipe of network***	*Shape file*	
Length of pipe	*m*	
Joint method	Linguistic *(rubber, leadite …)*	
Material type	Linguistic *(CI, DI, RCC, PVC …)*	
Traffic load	Linguistic *(busy, medium, quiet…)*	
Surface type	Linguistic *(hard, grassed, water body…)*	
Internal protection	Linguistic *(good, medium, bad…)*	
External protection	Linguistic *(good, medium, bad…)*	
Bedding condition	Linguistic *(good, medium, bad…)*	
Workmanship	Linguistic *(good, medium, bad…)*	
Diameter of pipe	*mm*	
Installation year	*(year)*	
Bury depth of start node	*m*	
Bury depth of start node	*m*	
No. of connections	-	
No. of breaks per year	-	
Leakage rate	*lps*	
No. of valves	-	
Duration of water supply per day	*hrs*	
No. of times water supplied per day	-	

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Table 3.2. Properties of different pipe materials			
Property	**Unit**	**value**	
Pipe material: ________			
Corrosion index	Linguistic *(good, medium, bad…)*		
Maximum pressure	*kg/cm^2*		
Maximum load	*m-kg/m*		
Design life	*years*		
Maximum diameter	*mm*		
Minimum diameter	*mm*		
Hazen-William Roughness Coefficient, C		Age, years	Value
		0-10	
		11-20	
		21-30	
		31-40	
		41-50	
		51-60	
		61-70	
		71-80	
		81-90	
		91-100	

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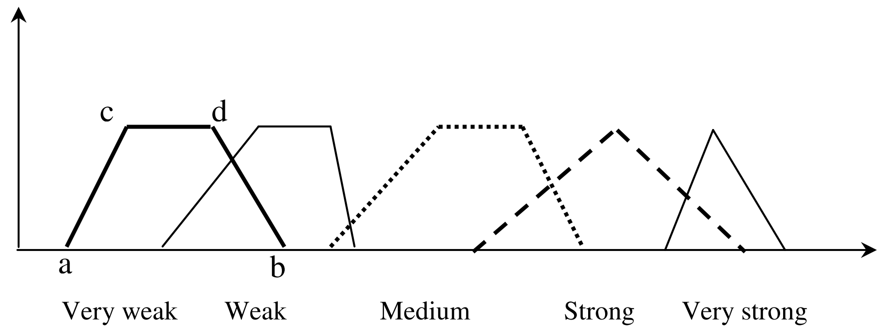
Table 3.3. Membership Functions

Sample of membership functions



Corrosive Index (normalized values)

	a	b	c	d
Very weak				
Weak				
Medium				
Strong				
Very strong				

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Internal Protection (normalized values)

	a	b	c	d
Very bad				
Bad				
Medium				
Good				
Very good				

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External Protection (normalized values)

	a	b	c	d
Very bad				
Bad				
Medium				
Good				
Very good				

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Soil Corrosivity (ohm-m)				
	a	b	c	d
Non-corrosive				
Mildly corrosive				
Corrosive				
Highly corrosive				
Extremely corrosive				
Surface Permeability (normalized values)				
	a	b	c	d
Very hard				
Hard				
Grassed				
Open land				
Water body				
Groundwater Fluctuations (normalized values)				
	a	b	c	d
Very bad				
Bad				
Medium				
Good				
Very good				
Joint Method (normalized values)				
	a	b	c	d
Very bad				
Bad				
Medium				
Good				
Very good				
Bedding condition (normalized values)				
	a	b	c	d
Very bad				
Bad				
Medium				
Good				
Very good				

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Workmanship (normalized values)				
	a	b	c	d
Very bad				
Bad				
Medium				
Good				
Very good				
Traffic density (Vehicles/hr)				
	a	b	c	d
Very busy				
Busy				
Medium				
Quiet				
Very quiet				
Maximum pressure (m)				
	a	b	c	d
Very high				
High				
Medium				
Low				
Very low				

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Table 3.4. Soil data		
Soil type: ____________		
Property	**Unit**	**Value**
Soil corrosivity	*ohm-m*	

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Table 3.5. Groundwater table		
Groundwater zone: ___________		
Property	**Unit**	**Value**
Average groundwater table depth	*m*	
Average groundwater fluctuation	*m*	

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Table 3.6. Pressure		
Pressure zone: ___________		
Property	**Unit**	**Value**
Pressure	*kg/cm*^{2}	

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Table 3.7. Balance factors for different groups of indicators	
Group	**Balance Factor**
Pipe	
Installation	
Corrosion	
Load/strength	
Intermittency	
Failure	
Physical	
Environmental	
Operational	
Pipe condition assessment	

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Table 3.8. Weights for different indicators					
Indicator	**Weight**	**Indicator**	**Weight**	**Indicator**	**Weight**
Level 3 indicators		***Level 2 Indicators***		***Level 1 Indicators***	
		Group 1		***Group 1***	
Physical		Pipe		Material decay	
Environmental		Installation		Diameter	
Operational		***Group 2***		Length	
		Corrosion		Int. protection	
		Load/strength		Ext. protection	
		Group 3		***Group 2***	
		Intermittency		Bedding condition	
		Failure		Workmanship	
				Joint method	
				No. of joints	
				Group 3	
				Year of install.	
				Soil corrosivity	
				Surface permeability	
				GW condition	
				Group 4	
				Buried depth	
				Traffic load	
				Hydraulic pressure	
				Group 5	
				No. of valves	
				No. of water supply/day	
				Duration of water supply/day	
				Group 6	
				Breakage history	

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3.2 Background

A water supply system consists of:

- Visible surface assets such as treatment plants and pumping stations
- Invisible assets – the buried infrastructure of the water distribution system.

The water distribution system (WDS) is the most important component of water supply system, conveying water from source to consumers' outlets. The distribution system constitutes a substantial proportion of the cost of a water supply system, in some cases as much as half the overall cost of the system.

Over 98 per cent of pipelines are buried. No matter how well these pipelines are designed, constructed and protected, once in place they deteriorate due to their physical condition, environmental abuse, external damage, soil movements/instability etc. Thus one of the problems faced by the water utilities around the world is the ageing and deterioration of the pipe network of the water distribution system. It is estimated that water networks serving the utilities in Western Europe and North America are up to 150 years old (Sægrov et al. 1999). Half of all large diameter water mains in the 50 largest US cities are more than 50 years old (Summers 2001). It is well documented in the literature (Yan and Vairavamoorthy 2003a) that structural and functional deterioration of water mains has the potential to cause health hazards. USEPA emphasizes that water pipes corrosion and ageing is one of the main concerns related to water distribution networks that may pose a threat to public health (AWWSC 2002).

As a result of the ageing and deterioration process taking place over the past few decades, it is estimated that over the next 20 years urban pipeline infrastructure rehabilitation is one of the main activities being undertaken by municipal water and wastewater authorities (McNeill and Edwards 2001). The estimated capital investment needed for the rehabilitation of these water supply pipes and sewers is more than $700 billion (McNeill and Edwards 2001; Summers 2001).

There may not be adequate budgetary provision for the huge investment to be made in the rehabilitation of the water supply pipes of many municipalities in developing and underdeveloped countries. Therefore there are chances that this important activity is overlooked and in that process the water distribution network is damaged completely. Over the years, water utilities have learnt from past experience that pro-active rehabilitation is much more cost-effective than a reactive one, since the reactive approach advocates the rule of 'do nothing until a system component fails', which increases cost and leads to customer dissatisfaction and potential environmental problems (Loganathan et al. 2002). However, pro-active rehabilitation requires the assessment of current pipe condition and predication of future pipe break rates.

As the investment needed for the rehabilitation of the entire water distribution system is huge, it is essential to prioritize the activities of rehabilitation of the water distribution systems in terms of the section of the pipe distribution network which needs to be considered first for the rehabilitation. However, inspection and replacement of underground assets will be time-consuming and costly, and the available funds for such rehabilitation activities are often limited. Therefore there is a need to prioritize investment based on an assessment of pipe condition. In general, while undertaking a pipe rehabilitation programme the following steps are performed:

- Predict condition of pipes using condition assessment model.
- Inspect pipes with the worst condition.
- Undertake pipe rehabilitation based on the above.

Therefore, before undertaking any pipe rehabilitation works, assessment of pipe condition and the identification of the worst pipes are important. The objective of this model is to provide guidelines which enable to assess the condition of pipes of water distribution network and identify the pipes which are subjected to the most risk, if not replaced.

As stated in Chapter 1, IRA-WDS assesses the risk associated with contaminant intrusion into the water distribution system during non-supply hours (especially for intermittent water supplies). The condition of water distribution pipes that determines the potential intrusion pathway is one of the 2 conditions for contaminant intrusion into water distribution systems that are intermittent (the other condition being a pollution source, as described in Chapter 2). The pipe condition, assessed by the PCA model presented below, is combined with the contaminant loading along the pipe estimated by contaminant ingress model (Chapter 2) to know the relative risk of contaminant intrusion due to the pipe (Chapter 4).

3.3 Pipe Condition Assessment

Pipe condition assessment is the process of assessing the status of the underground pipes based on their condition. Water pipe condition is affected by a deterioration process which is complex because of its dependency on many factors that interactively contribute to the process. These factors can be broadly categorized into three groups (AWWSC 2002):

- Physical factors (e.g. pipe age, diameter, length, material, etc.)
- Environmental factors (e.g. soil corrosivity, internal and external loads, pipe location, etc.) and
- Operational factors (e.g. break history, leak records, operation pressure, etc.).

The pipe condition is the cumulative effect of the different factors in these three categories.

The method for assessing pipe condition based on the above factors would obviously involve uncertainties, as in most cases it is not possible to obtain accurate asset information due to a lack of organized record-keeping by the water authorities. However, some of these factors, especially physical factors, may be available in inventory databases, which have deterministic values except for pipe material. Environmental and operational factors are difficult to quantify using deterministic values but are dealt with using the possibility approach to take account of the associated uncertainties.

Existing methods for predicting the conditions of buried pipes can be classified according to three models:

- Deterministic
- Probabilistic
- Cost.

Deterministic models use parameters like pipe age and breakage history, operational environments, pipe material etc. to predict the pipe failure (Shamir and Howard 1979), whereas probabilistic models predict the probabilities of the pipe failure based on survival rates, breakage rate etc. (Kleiner and Rajani 2001). Cost models on the other hand are based on both deterministic and probabilistic models and consider the economical life of the pipes along with the deterioration factors (Loganathan et al. 2002). These approaches appear to have difficulties in dealing with pipe deterioration. In case of deterministic approach, there are many factors that contribute to deterioration and only a few are considered in the development of models. In the probabilistic approach, due to the insufficiency and inaccuracy of breakage data, it is difficult to establish the probability distribution function for breakage. The insufficient knowledge about the complexity of the pipe deterioration process (for deterministic models), the lack of pipe breakage historical data (for probabilistic models) and a lack of pipe deterioration data (for cost models) cause difficulties when applying these models. Furthermore the validity of these methods is highly dependent on the availability of data and they also have the shortcoming of an inability to incorporate inherent uncertainties associated with data.

However, there is enough knowledge regarding the deterioration factors causing pipe breakage and understanding of their influence on pipe deterioration. It is therefore possible to develop a model to assess the condition of a water pipe using the available knowledge and understanding about these deterioration factors. Hence, a pipe condition assessment model which ranks different pipes based on their deterioration due to combined effect of different factors using a ‘fuzzy’ approach (to consider uncertainties associated with data) was developed and used for this study.

By using this model, the pipe condition can be evaluated with basic pipe condition indicators such as pipe age, pipe material, pipe diameter, soil condition, traffic loads, etc (first level indicators). The uncertainties inherent in these pipe condition indicators are described with fuzzy set theory (Zadeh 1965). The first-level indicators are aggregated into groups based on their similarities to form the second-level indicators. Similarly, the second-level pipe condition indicators are grouped to form the final indicator (Figure 3.3). Based on the hierarchical pipe condition structure established from the above aggregation process, fuzzy composite programming is used to compute an ‘indicator distance metric’ for each indicator, and finally an ‘overall distance metric’ for each pipe is obtained. This final distance metric is used to evaluate and rank the conditions of pipes. The fuzzy composite programming used for the PCA model is described in the next section and the methodology used for estimating the final distance metric is described in Figure 3.3.

3.4 Fuzzy Composite Programming

The methodology used in pipe condition assessment is the multiple-criteria decision-making (MCDM) technique which combines the available, often completely different, pipe condition indicators into a final overall pipe condition indicators. The selected MCDM technique is fuzzy composite programming (FCP) which incorporates both fuzzy set theory and its arithmetic corollaries (Dubois and Prade 1988; Kaufmann and Gupta 1991). FCP has been applied in many instances in MCDM to problems related to water resource and environment engineering (Bardossy and Duckstein 1992; Hagemeister et al. 1996; Lee et al. 1991; Lee et al. 1992). Application of FCP methods to pipe condition assessment was more recently introduced by Yan and Vairavamoorthy (2003b). However, they stated that the application of FCP to pipe condition assessment may be sensitive to weights and balance factors used in the process.

Zeleny (1973) developed a mathematical programming technique that employs a single level normalized/non-normalized distance-based methodology to rank a discrete set of solutions according to their distances from an ideal solution. This is called ***compromise programming***.

This technique forms the basis for ***composite programming***, developed by Bardossy et al. (1985). This deals with problems of a hierarchical nature (i.e. when certain criteria contain a number of sub-criteria). Composite programming extends compromise programming to a normalized multi-level methodology. Composite programming generates composite distance metrics of each sub-criterion within the same group, and then combines the distance metrics of each sub-criterion to form a single composite distance metric. The process iterates with the successive levels until a final level composite distance metric is reached (one composite distance metric for each alternative).

The fuzzy set theory (Zadeh 1965) is used to include the inherent uncertainties. The addition of fuzzy set theory to compromise programming to represent uncertainties of indicators forms ***fuzzy compromise programming***.

Similar to this, when fuzzy compromise programming is extended to a normalized multi-level distance-based methodology (composite programming) to account for uncertainties, ***fuzzy composite programming*** (FCP) is formed. Thus the combination of fuzzy set theory with composite programming forms fuzzy composite programming (FCP), which can cope with unavoidable vagueness, imprecision, and uncertainty associated with basic pipe condition indicator data. This FCP technique is used for the pipe condition assessment in the present study.

3.4.1 Method

Compromise programming uses equation (3.1) to rank a discrete set of solutions according to their distance from an ideal solution. Composite programming applies the compromise programming equation (3.1) to each sub-criterion, and then combines the compromise distance metrics of each sub-criterion to form a single composite distance metric (one composite distance metric for each objective or alternative of the problem; in this case different alternatives are pipes).

$$L_j = \left\{ \sum_{i=1}^{n} \left[w_i^p \left(\frac{f_i - f_i^w}{f_i^b - f_i^w} \right)^p \right] \right\}^{\frac{1}{p}} \tag{3.1}$$

where

L_j - distance metric of alternative

w_i - weight of indicator i

p - balance factor

f_i^b - best value for indicator i

f_i^w - worst value for indicator i

f_i - actual value for indicator i

n - number of indicators

The addition of fuzzy set theory (Zadeh 1965) to compromise programming is used to represent uncertainties of indicators and this is called fuzzy compromise programming, and when this is extended to a normalized multi-level distance-based methodology, fuzzy composite programming is formed. The normalization process is performed with the use of best and worst first-level indicator values (Hagemeister et al. 1996).

$$S_i = \frac{f_i - f_i^w}{f_i^b - f_i^w} \tag{3.2}$$

where

f_i - actual value of i^{th} fuzzy indicator

f_i^w - the worst value of i^{th} indicator

f_i^b - the best value of i^{th} indicator

The normalization formula given above can have different forms depending on whether the maximum is the 'best' or 'worst' value.

$$S_i = \begin{cases} \dfrac{f_i - f_i^-}{f_i^+ - f_i^-} & f_i^+ = f_i^b \\ \dfrac{f_i^+ - f_i}{f_i^+ - f_i^-} & f_i^+ = f_i^w \end{cases} \tag{3.3}$$

where

f_i^+ - maximum possible value of i^{th} fuzzy indicator

f_i^- - minimum possible value of i^{th} indicator

It should be noted that this normalization process will result in the coordinate (1, 1) to be the ideal point. Substitution of equation (3.2) into equation (3.1), and ignoring the exponent p on the weight w (Bardossy and Duckstein 1992), yields the following composite distance for j^{th} group of indicators. The composite distance, L_j, is the distance between the actual point of indicator and the ideal one (Woldt and Bogardi 1992):

$$L_j = \left[\sum_{i=1}^{n_j} w_{j,i} S_{j,i}^{p_j} \right]^{1/p_j} \tag{3.4}$$

where

L_j - composite distance metric for B+1 level group j of B level indicators

$S_{j,i}$ - normalized value of the B level indicator i in the B+1 level group j of B level indicators

n_j - number of B level indicators in group j

$w_{j,i}$ - weights expressing the relative importance of B level indicators in group j such that their sum is 1

p_j - balancing factors among indicators for group j

For example, if we consider the composite structure presented in Figure 3.4, and let B=1: at B+1=2 level group, j=1 is pipe indicator which is obtained from combining the three indicators (material decay, diameter, length, internal protection and external protection) at B=1 level. Therefore equation (3.4) combines the normalized first-level indicators to obtain their respective second-level composite distance. The process of computing successive levels of composite distance is repeated with previous level composite distance, L_j, being substituted in place of variable $S_{j,i}$ until the final composite distance is reached for the system. In the case of pipe condition assessment, this final-level indicator illustrates the combination of physical, environment and environmental factors. The procedure is explained in Figure 3.5.

3.4.2 Fuzzy set theory

One of the main features of fuzzy set theory is its ability to deal with uncertain, imprecise and linguistic information, such as busy, very busy, good, excellent, etc. (Zadeh 1965). This theory uses fuzzy numbers to represent parameter uncertainty. In this study, therefore, fuzzy number is used to interpret the linguistic values and represent the uncertainties. The process to determine the fuzzy number to express linguistic value is subjective and could rely a great deal on experts' knowledge.

A fuzzy number is a quantity whose value is imprecise and is described by the possibility that the uncertain parameter, *X,* may take on a certain value *x* with the help of a membership function. A membership function, $\mu(X)$, is a curve or relationship that defines how each point in the input space or range of parameter, *X*, is mapped to a membership value (or degree of membership) between 0 and 1. Thus the degree to which a parameter belongs to a fuzzy set is denoted by a membership value between 0 and 1. The two common representations of fuzzy numbers are triangular and trapezoidal (see Figure 3.2).

A popular way to carry out fuzzy arithmetic operations is by way of interval arithmetic (Kaufmann and Gupta 1991). This is done by introducing an α-cut of the membership function $\mu(X)$, (denoted as α). α is the set of all X such that $\mu(X)$ is greater than or equal to α. Thus a set of α-cut of a fuzzy number (X_α) is always represented by an interval and hence fuzzy arithmetic operations are possible. For a fuzzy set, X, shown in Figure 3.2, the α-cut set of X is the set of all x such that membership value of X, ($\mu(X)$), is greater than or equal to α and is defined by equation (3.5).

$$X_\alpha = \{\alpha | \mu[\,X\,] \geq \alpha\} \qquad (3.5)$$

Note that by virtue of the condition on $\mu(X)$ in equation (3.5), the set X_α is now a crisp set. In this way, a fuzzy set can be converted to an infinite number of cut-sets. For example, for a trapezoidal membership function of Figure 3.2 (b), when $\alpha = 0.5$, $X_{0.5}$ =[a_1, a_2] or when $\alpha = 1.0$, $X_{1.0}$ = [b_1, b_2]. Therefore, any fuzzy number may be represented as a series of intervals (one interval for every α-cut). Thus the fuzzy number operation is converted into an intervals operation, the details of which can be found in Kaufmann and Gupta (1991).

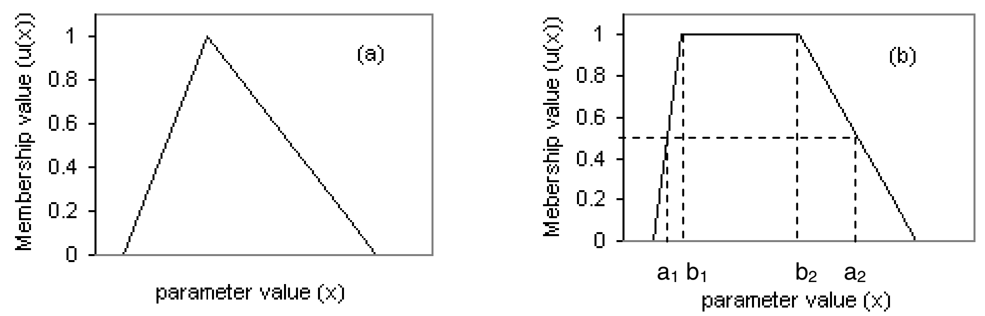

Figure 3.2. Two representations of fuzzy number (a) Triangular (b) Trapezoidal

3.4.3 Balance factors

The decision-maker is also required to determine balance factors when applying the pipe condition assessment model. Balance factor determines the degree of compromise between indicators of the same group. Low balance factors are used for a high level of compromise among indicators of the same group (Jones and Barnes 2000).

- A balance factor of 1 suggests that there is a perfect compromise between indicators of that group.
- A balance factor of 2 suggests that the level of compromise is moderate.
- A balance factor greater than 3 indicates that there is minimal compromise.

3.4.4 Weights

Prior to examining alternatives, decision-makers must assign weights to indicate their preferences to the relative importance of the various pipe indicators in a particular group. Most of the applications of the FCP method mentioned above use crisp numbers to express weights according to the judgement of decision-maker. However, Lee et al. (1991; 1992) proposed the use of the ***analytic hierarchy process*** (AHP).

In this study the following three methods are used:

- 'Equal weights' method assigns an equal weight to all the indicators of a particular group. The weights are assigned such that their sum equals 1.
- 'Variable weights' method gives the user flexibility to assign different weights to different indicators of a particular group. The different weights will be based on the user's perception of the relative importance of one indicator over another. Again the sum of the weights assigned must be equal to one.
- The AHP method can also be used to calculate and assign weights. Details of this method are given in Appendix B (Appendix D provides a questionnaire that can be completed by several respondents to aid in the AHP process.).

3.5 Application to Pipe Condition Assessment

The procedure for assessment of pipe condition used in the model involves the following steps.

1. Identify the indicators influencing the pipe condition and their types (fuzzy or crisp).
2. Prepare the composite structure of the pipe condition indicators.
3. Obtain the weightings for each indicator in each group and decide balance factor for the group.
4. Normalize all the indicators into a scale of [0, 1].
5. Obtain a fuzzy number by using the FCP-based hierarchical aggregation process for each pipe (i.e. for a pipe network with *n* pipes, *n* fuzzy numbers are obtained)
6. Rank the fuzzy numbers.

The procedure is illustrated by the flowchart in Figure 3.3.

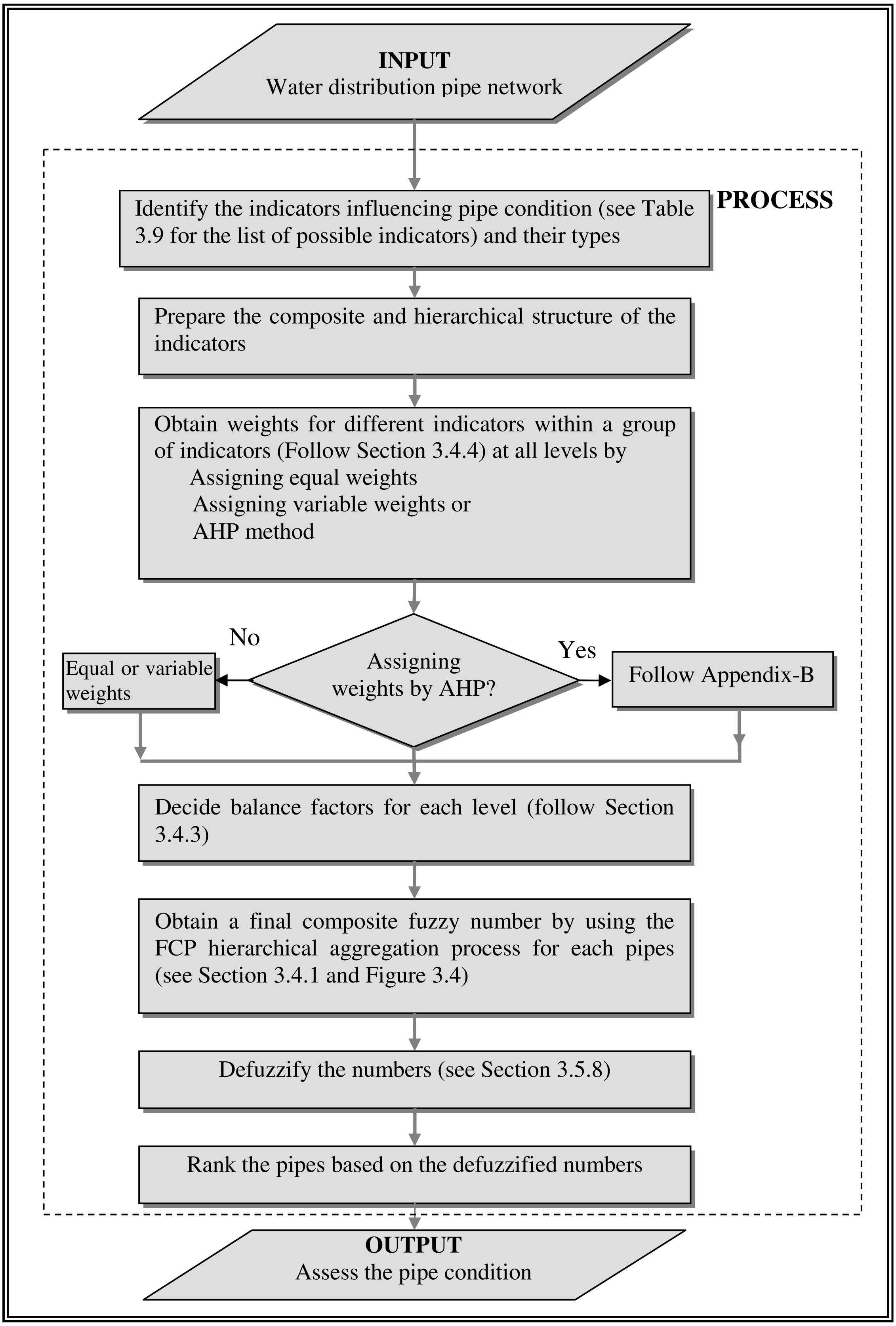

Figure 3.3. The flowchart for pipe condition assessment

3.5.1 Basic pipe deterioration indicators

A number of indicators (Table 3.9) of water pipe susceptibity to deterioration have been identified. More detailed explanations are given in Appendix C.

Table 3.9. Pipe Condition Assessment Indicators

Level 1 Indicators	Description
Material decay	Hazen-William coefficient of friction (C) is considered to characterize this influence
Diameter	Larger diameter pipes are less prone to failure than smaller diameter pipes
Length	Larger length pipes are more prone to failure than smaller length pipes
Int. protection	The pipes having internal protection by lining and/or coating are less susceptible to corrosion
Ext. protection	The pipes having external protection by lining and/or coating are less susceptible to deterioration
Bedding condition	Improper bedding may result in premature pipe failure
Workmanship	Poor workmanship may deteriorate the pipes and cause more risk regardless of pipe age and other factors
Joint method	Some types of joints experience premature failure (e.g. leadite joints)
No. of joints	The more joints a pipe has, the greater the risk of the pipe getting structurally worse
Year of installation	The effects of pipe degradation become more apparent over time
Soil corrosivity	Pipe deteriorates quicker in more corrosive soil and the degree of deterioration depends on the pipe material
Surface permeability	The more permeable surface allows more moisture to percolate to the pipe. Surface salts will be carried to the pipe with the moisture
GW condition	The water pipes are deteriorated by the groundwater table
Buried depth	Pipes buried at greater depths have more possibility of failure than those buried at shallower depths
Traffic load	Pipe failure rate increases with traffic loads on the surface
Maximum pressure	Changes to internal water pressure will change stresses acting on the pipe
No. of valves	The greater the number of valves, the greater the deterioration of the pipe
No. of water supply/day	The greater the number of water supplies the more the pipes will deteriorate
Duration of water supply/day	The longer the duration of water supply, the smaller the chances of pipe failure
Breakage history	The number of pipe breakages per year

3.5.2 Types of indicators

Among the twenty selected pipe condition indicators at the first level, many of them are difficult to express in crisp form; for example, soil corrosivity, pipe material, pipe bedding condition, and pipe joint method are a few which involve vague and imprecise information. In addition to the existing vagueness, some information such as traffic loads and pipe location are expressed linguistically. Such vague or imprecise and linguistic information can be dealt with fuzzy set theory (Zadeh 1965) (see Section 3.4.2) and hence used in this study to interpret the linguistic values and represent the uncertainties. Triangular or trapezoidal fuzzy membership functions are used to map the parameter to membership values between the interval (0,1). Interval operations are used as fuzzy number arithmetic in this research. Five intervals, i.e. 0, 0.25, 0.5, 0.75, 1.0 are used for fuzzy arithmetic operations.

3.5.3 Composite structure

The hierarchical structure of composite programming provides a process for integrating different types of information into a single indicator that can provide deeper understanding of the interrelationships between numerous pipe condition indicators. Figure 3.4 gives the composite hierarchical structure used in pipe condition ranking in this study. This structure is developed in a way that enables known or relatively easily obtained information to be used to produce the first level indicators. The composite programming hierarchical structure is used to combine first-level indicators based on their similarities into second-level indicators. The aggregation process continues until the final-level indicator is achieved.

The pipe condition can be evaluated with basic pipe condition indicators (first level indicators) that contribute to the deterioration. To illustrate the relationships between the pipe condition assessment indicator and deterioration, twenty first-level indicators (Figure 3.4) are proposed in this study. These are broadly divided into six groups (pipe indicators, installation indicators, corrosion indicators, load/strength indicators, intermittency and failure indicators) at second level. These are grouped into three third level indicators (physical, environmental and operational). These are further combined to obtain final indicator, pipe condition assessment.

It should be noted that more indicators could be added into this composite structure if more information were available (e.g. water quality) or indicators for which information/data are not available can be omitted (for example, hydraulic pressure).

Depending on the importance of each indicator and the availability of data, the user should select the indicators for pipe condition assessment and mark those in Table 3.1. The input dialog window of IRA-WDS (Chapter 4 of Book 4 (IRA-WDS user manual)) allows the user to select the specified indicators. When some indicators at the first level are treated as fuzzy numbers, the second level, third level and final level indicators are also fuzzy numbers. The different indicators with their type are presented in Table 3.4.

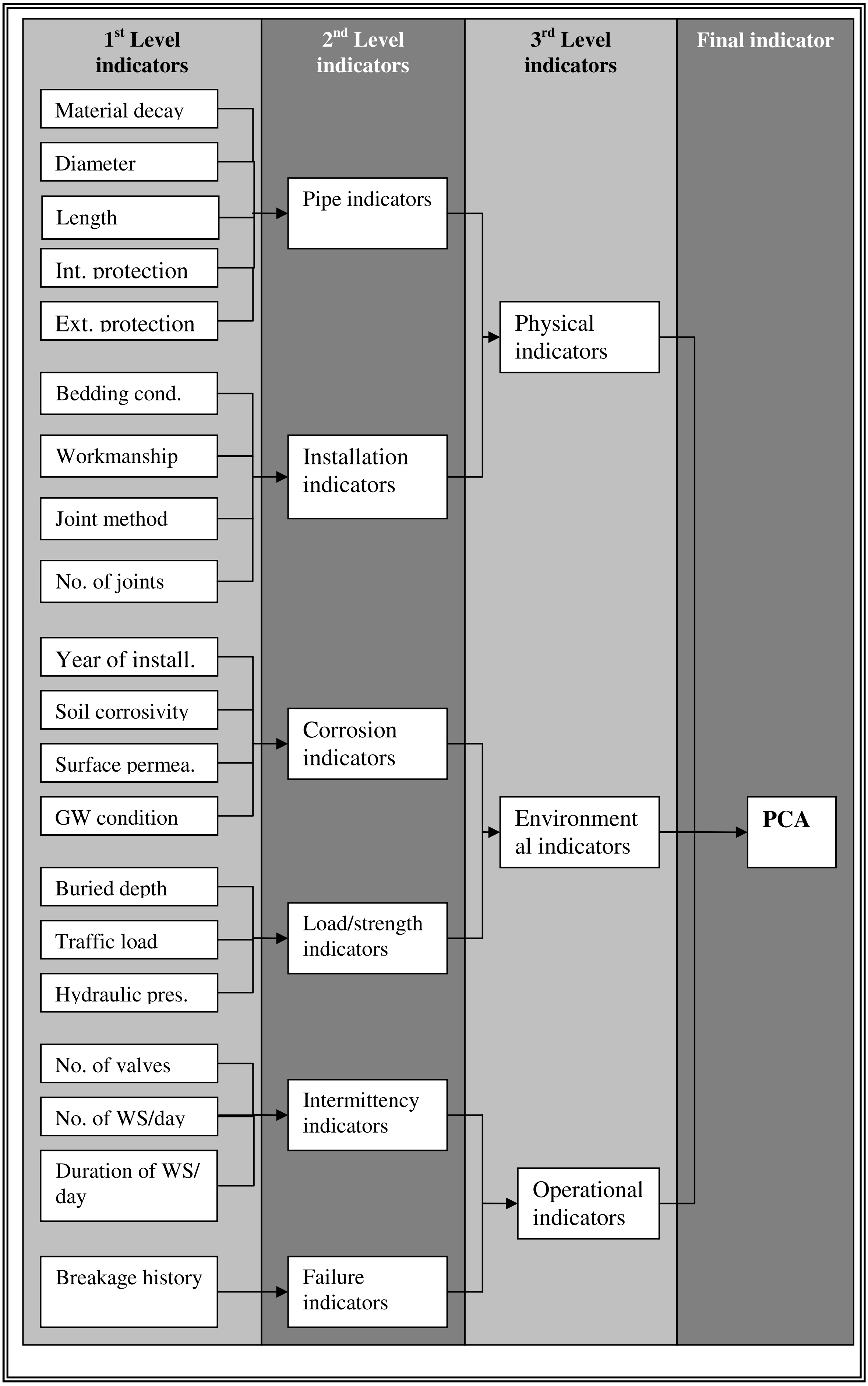

Figure 3.4. Composite structure of different pipe condition assessment indicators

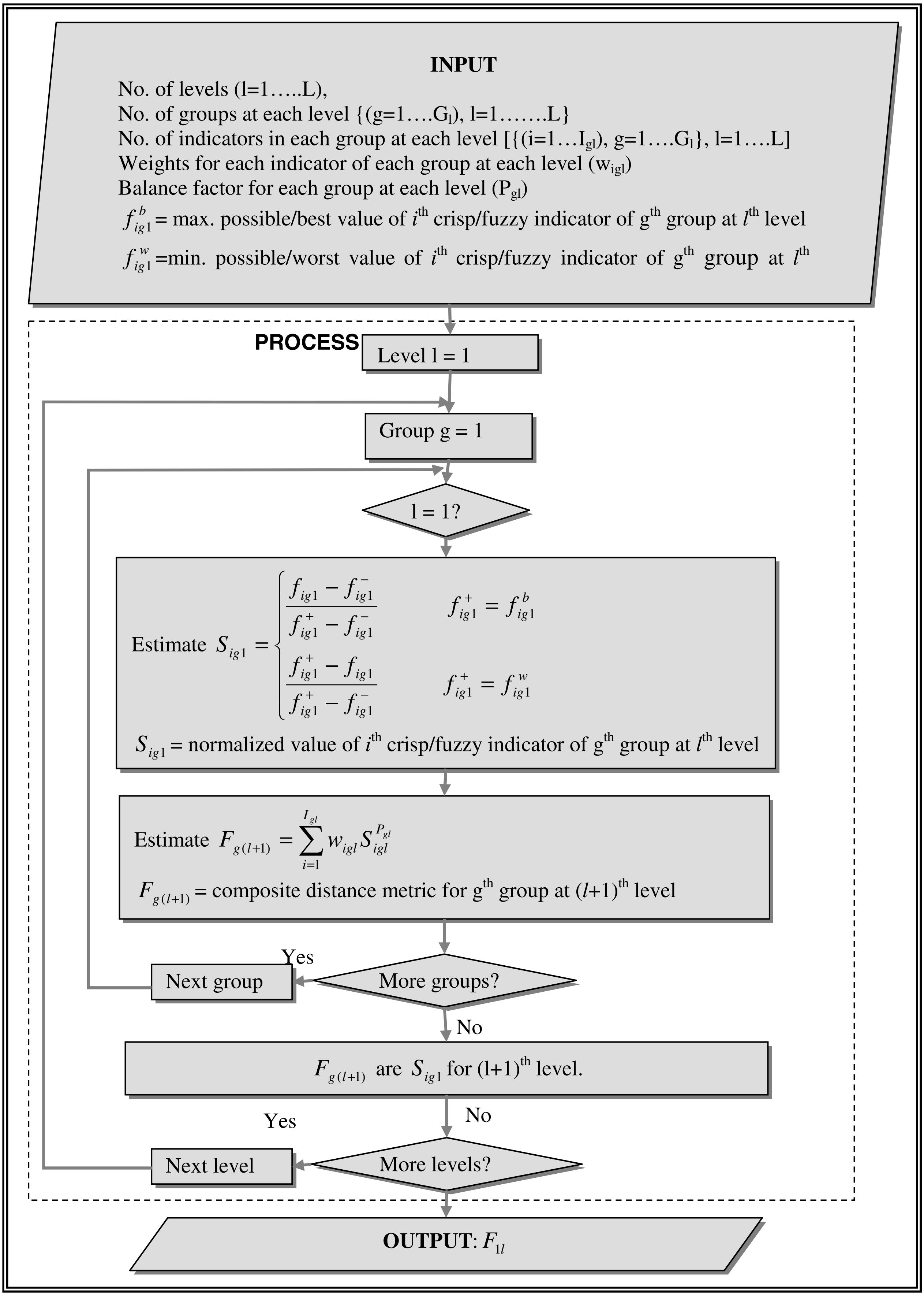

Figure 3.5. The flowchart for obtaining the final composite distance metric

3.5.4 Weights and balance factors

Prior to examining alternatives, the decision-maker is required to assign weights for indicators of each group at different levels. Assigning weights for different level indicators allows the incorporation of individual perceptions into the assessment system. This has the advantage of allowing users to recognize the importance of indicators in different analyses. There are several ways to assign weights for deterioration indicators (see Section 3.4.4). In this study the weights can be assigned by 'equal weight' and 'variable weights' or generated by AHP.

IRA-WDS provides an input dialog box to enable the user to perform the pair-wise comparison required for AHP (i.e. to indicate the preference of one indicator over another and the degree of preference). IRA-WDS then computes the weights for each indicator and these weights are stored in a file and displayed.

After assigning the weights using one of the methods described above, the user should be able to complete Table 3.8. The data from this table can then be directly inputted into IRA-WDS (see Chapter 4 of Book 4 to see input dialog window for IRA-WDS).

The decision-maker is required to determine balance factors in order to evaluate alternatives using fuzzy composite programming. Balance factors determine the degree of compromise between indicators of the same group. Low balance factors are used for a high level of allowable compromise between indicators of the same group and vice versa.

Balance factors are entered into IRA-WDS by means of an input dialog box (see Chapter 4 of Book 4 to see input dialog window for IRA-WDS). Using this information, the user is able to complete the Table 3.7.

3.5.5 The effect of pipe material

The above described indicators are interdependent: for example, the effect of pipe diameter on the pipe failure may be different for different pipe material; the effect of traffic load on pipe failure may be a function of pipe material and the buried depth. However, in this study the pipe material is considered the most important parameter and corrosion and load/strength indicators are considered to be influenced by the pipe material.

To represent the importance of pipe material, three surrogate measures are used, namely, corrosion resistance, maximum pressure and impact strength to indicate the influence of pipe material on pipe condition. The maximum pressure reflects the strength of pipe material and expressed in crisp form. The impact strength represents the ability of a material to withstand impact without damage and is expressed in crisp form. The corrosion resistance implies the intrinsic ability of pipe material to resist degradation by corrosion (internal and external) and is given in linguistic form with fuzzy description.

The weight based on the value of the appropriate measure is assigned to the indicator. The indicators that are influenced by pipe material and the corresponding measure are listed in Table 3.10.

Table 3.10. Indicators that are influenced by the pipe material and the corresponding measure

Indicator	Measure
Soil corrosivity	Pipe material corrosion resistance
Surface permeability	Pipe material corrosion resistance
GW condition	Pipe material corrosion resistance
Buried depth	Impact load
Traffic load	Impact load
Hydraulic pressure	Maximum pressure

The typical values of pipe material corrosion resistance, impact strength and maximum pressure are presented in Table 3.11.

Table 3.11. Typical values of pipe material corrosion resistance, impact strength and maximum pressure

Pipe material	Pipe material corrosion resistance		Impact strength *m-kg/m*	Maximum pressure *kg/cm*^{2}
	Internal	External		
DI	Highly corrodible	Corrodible	102.5	31.62-78.54
PVC	Non-corrodible	Non-corrodible	4.40	8.16-15.3
HDPE	Non-corrodible	Non-corrodible	20.5	10-20
AC	Mildly corrodible	corrodible	23.5	5.1-35.7
PE	Non corrodible	Corrodible	58.5	15-25
PC/RCC	Mildly corrodible	Corrodible	30	20.4-30
Steel/GI	Corrodible	Corrodible	150	14.28-97.92
CI	Highly corrodible	Extremely corrodible	150	14.28-97.92

3.5.6 Normalization

Pipe condition indicators are normalized using equation (3.2). The maximum and minimum values (or best and worst values) for normalization can be obtained from:

- ***Criterion A:*** Design values. For example, the crisp indicator, diameter, is normalized with the designed maximum and minimum values of the diameter for each pipe material. These designed maximum and minimum values can be obtained from the manufacturer for each pipe material.

- ***Criterion B:*** Global maximum and minimum. For example, the crisp indicator, soil corrosivity, is normalized with global maximum soil corrosivity (for clay soil) and global minimum soil corrosivity (for sandy soil).
- ***Criterion C:*** Normalized value. This criterion is used for the fuzzy variable in linguistic form. For example, for the fuzzy indicator, surface permeability, the global normalized membership function is used.
- ***Criterion D:*** Obtaining the maximum and minimum values by comparing the values of all alternatives (i.e. pipes in this case) for each indicator from the dataset. For example, the indicator, length, is normalized with the maximum and minimum lengths of the pipe from the data set.

The procedure is described in Figure 3.6. Table 3.12 narrates the different criteria used for the normalization of the indicators. Table 3.13 narrates the different criteria used for the normalization of the measures or attributes used for incorporating the effect of pipe material on different indicators.

Note: If two data sets (or water distribution systems) are to be compared, the maximum and minimum values in Criterion D should be obtained by comparing the values of all alternatives (i.e. pipes in this case) for each indicator from all the data sets.

3.5.7 Final composite fuzzy number using FCP

The final composite fuzzy number for each pipe is obtained by using fuzzy composite programming as described in Sections 3.4.1 and 3.4.2 and shown in Figure 3.6.

Table 3.12. Different criteria used for the normalization of the indicators	
Indicator	**Criterion**
Material decay	A
Diameter	A
Length	D
Int. protection	C
Ext. protection	C
Bedding condition	C
Workmanship	C
Joint method	C
No. of joints	D
Year of installation	A
Soil corrosivity	B
Surface permeability	C
GW condition	C
Buried depth	D
Traffic load	B
Maximum pressure	B
No. of valves	D
No. of water supply/day	D
Duration of water supply/day	D
Breakage history	D

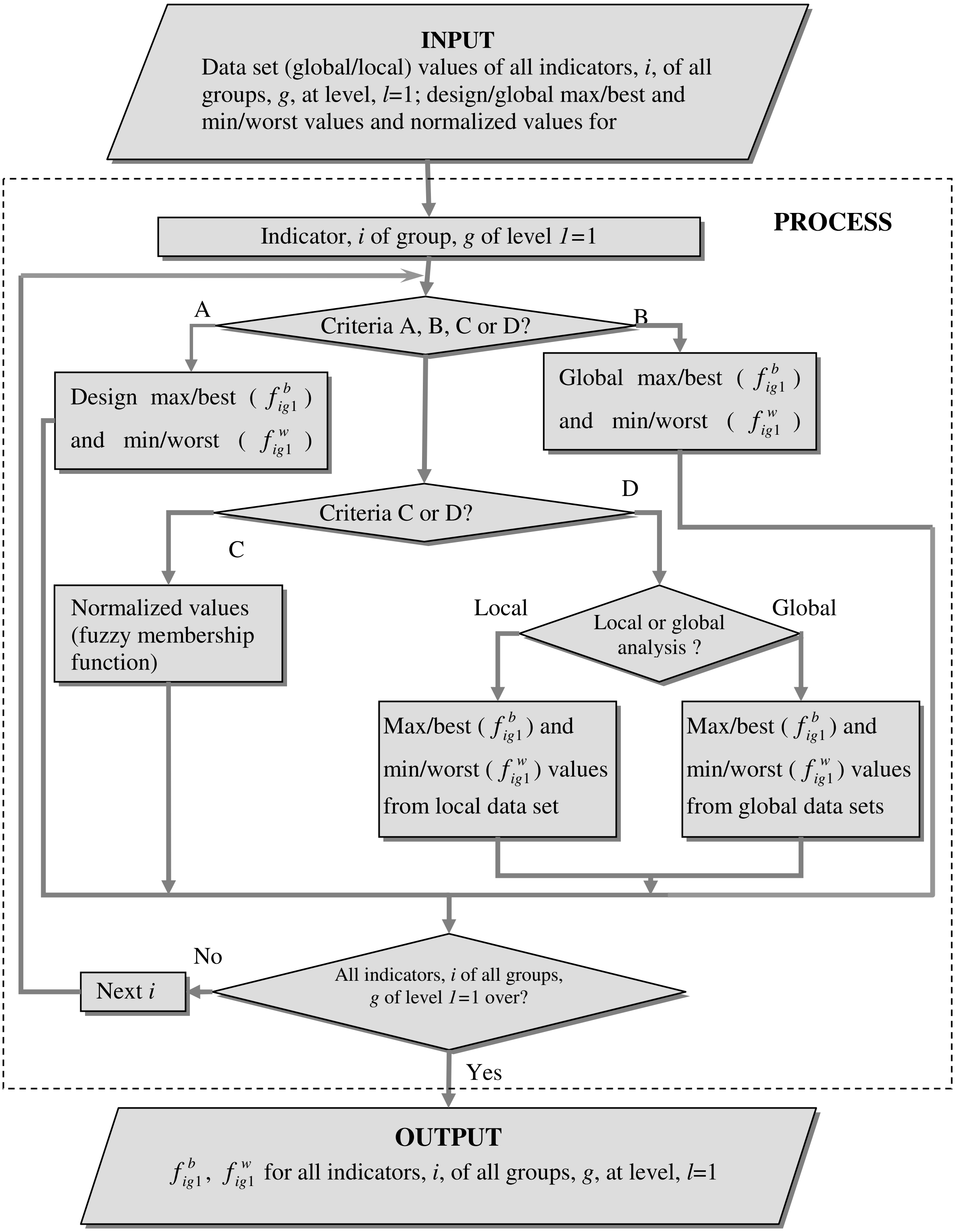

Figure 3.6. Obtaining maximum/best and minimum/worst values for indicators of different groups at Level 1

Table 3.13. Different criteria used for the normalization of the pipe material attributes/measures	
Measure	**Criterion**
Pipe material corrosion resistance	C
Impact load	B
Maximum pressure	B

3.5.8 Ranking

By using the FCP hierarchical aggregation process, a final composite number was obtained to assess pipe condition for each pipe. The final composite number is fuzzy. Thus for a pipe network with *n* pipes, *n* fuzzy numbers *(L (j), j=1, 2… n)* associated with the *n* pipes were obtained. These pipes need to be ranked according to the composite number. The following procedure is used to rank these fuzzy numbers.

The fuzzy number obtained from FCP process contains vague and imprecise information inherent from first-level indicators. Using fuzzy indicators instead of crisp ones is more realistic to reflect real systems, but it is not instinctive for people who are not familiar with fuzzy sets theory to understand the information included in the final fuzzy result. Thus some methods, such as defuzzification or fuzzy ranking method, should be applied to convert fuzzy results into crisp numbers or give a ranking order of fuzzy results respectively, which is more instinctive to practising engineers.

In the present research, we use the fuzzy ranking method to rank these *n* fuzzy numbers, which corresponds to the ranking of *n* pipes' condition. There are many fuzzy number ranking methods available from literature. Different fuzzy number ranking methods extract various features from fuzzy sets. These features may be a centre of gravity, and area under the membership function, or various intersection points between fuzzy sets. A particular ranking method extracts a specific feature, and then ranks fuzzy quantities according to the feature (Prodanovic and Simonovic 2002). In this study the fuzzy ranking method developed by Chen (1985), which determines the ranking of *n* fuzzy numbers by using the maximizing set and minimizing set, was used as it does not require subjective weightings for different parts of membership function to rank fuzzy quantities (Prodanovic and Simonovic 2002).

The maximizing set *Max* is a fuzzy subset with membership function $u_{Max}(x)$ given as:

$$u_{Max}(x) = \begin{cases} (x - x_{\min})/(x_{\max} - x_{\min}), & x_{\min} \le x \le x_{\max} \\ 0 & , \quad \text{Otherwise} \end{cases} \tag{3.6}$$

where $x_{\min} = \inf S$, $x_{\max} = \sup S$, $S = \bigcup_{j=1}^{n} S_j$, $S_j = \{x \mid u_{L_j}(x) > 0\}$.

Then the right utility value, U_{Max}, for pipe j is defined as:

$$U_{Max}(j) = \sup\{\min[u_{Max}(x), u_{L_j}(x)]\} \tag{3.7}$$

The minimizing set *Min* is a fuzzy subset with membership function $u_{Min(x)}$ given as:

$$u_{Min}(x) = \begin{cases} (x - x_{\max})/(x_{\min} - x_{\max}), & x_{\min} \le x \le x_{\max} \\ 0 & , \quad \text{Otherwise} \end{cases} \tag{3.8}$$

Then the left utility value, U_{Min}, for pipe j is defined as:

$$U_{Min}(j) = \sup\{\min[u_{Min}(x), u_{L_j}(x)]\} \tag{3.9}$$

The total utility or ranking value for pipe *j* is:

$$U_T = \frac{U_{Max}(x) - U_{Min}(x) + 1}{2} \tag{3.10}$$

$U_T(j)$, *j=1, 2…n* can be used to rank *n* fuzzy numbers associated with *n* pipes.

3.6 Implementation of the Pipe Condition Assessment Model in IRA-WDS

Using the information provided in this section, users should be able to complete Tables 3.1 to 3.6. These tables are required to use IRA-WDS for pipe condition assessment. The information required to complete Table 3.1 should be obtained from the records of organizations such as the Municipal Corporation or Water Authority, and from surveys and observations. The IRA-WDS has the default database for the properties of different pipe materials (Table 3.2). These properties are presented in tables in Appendix C. The user can add new pipe materials and their properties, and change the properties of the pipe materials in the default database with the help of an input dialog window provided in IRA-WDS (Chapter 4 of Book 4).

The IRA-WDS has the default membership for different linguistics and fuzzy indicators. However, users can construct the membership function for specified indicators by completing Table 3.3. The information provided in this section enables the user to construct the membership function for different indicators.

The IRA-WDS has the default database for the soil corrosivity for different soils (Table 3.4). These soil corrosivity values are presented in tables in Appendix C. However, users can modify these values. The information required to complete Tables 3.5 and 3.6 should be obtained from the Municipal Corporation or the appropriate Water Authority. These data are spatial; IRA-WDS needs the data in the form of shape files (Chapter 4 of Book 4).

3.7 Application

An example is presented to illustrate the applicability of the developed pipe condition assessment model. The example consists of five pipes and 10 pipe indicators at the first level. The example follows the procedures for pipe condition assessment described in Section 3.5 and obtains the final pipe condition distance metrics (a fuzzy number) for each pipe and their condition rankings.

3.7.1 Hierarchical composite structure

Two groups of water pipe deterioration indicators, i.e. physical and environmental indicators, have been selected in this example. Some of these indicators are expressed in crisp numbers whilst others are described in a linguistic way that could be interpreted with fuzzy numbers. The hierarchical composite structure of water pipe deterioration indicators is given in Figure 3.7.

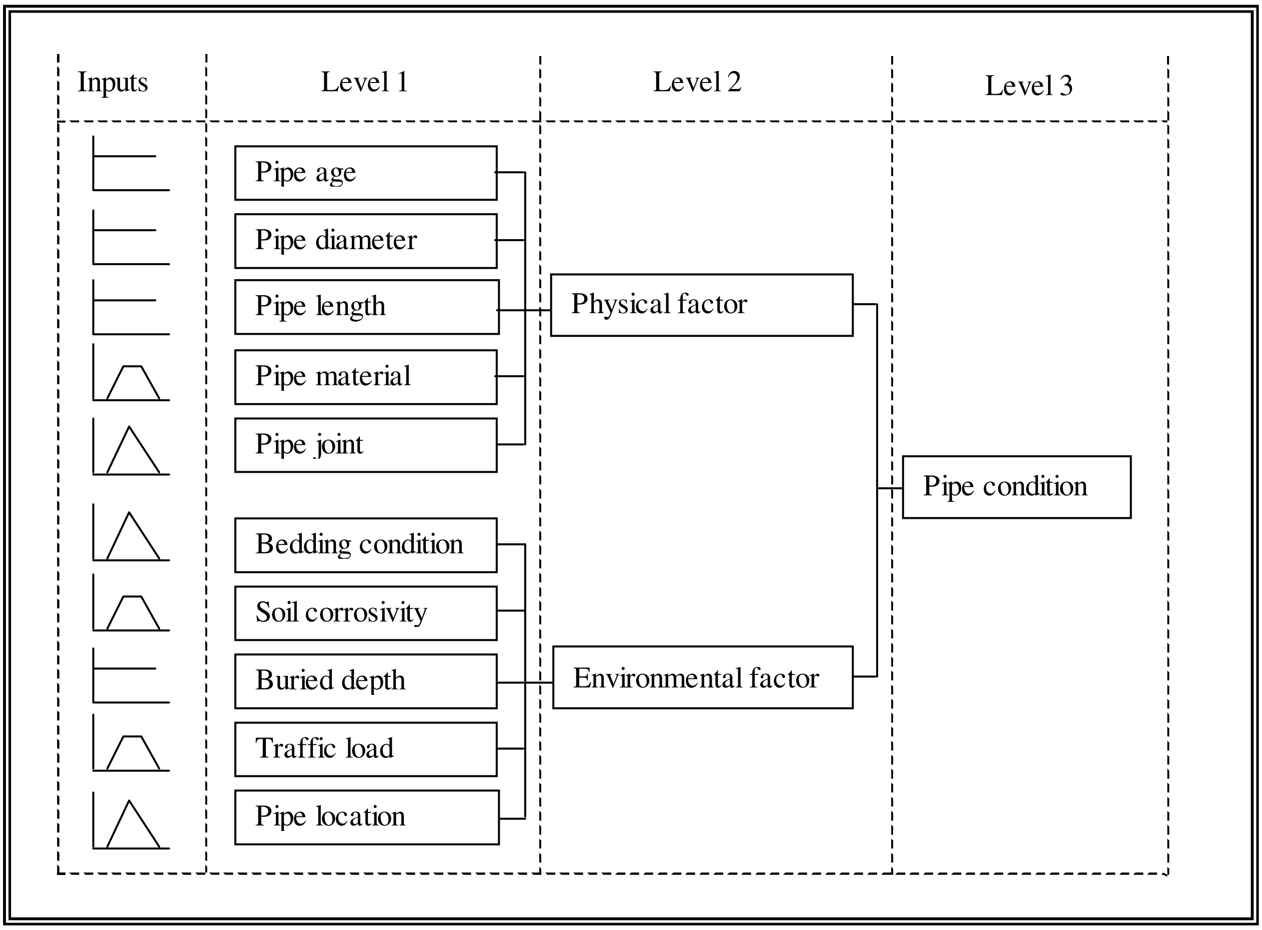

Figure 3.7. Pipe condition assessment composite structure

3.7.2 Values of basic indicators

The values of 10 indicators for all five pipes are shown in Table 3.14. Among these 10 first-level indicators, pipe material, pipe joint, pipe bedding, soil condition (corrosivity), traffic loads, and pipe location are expressed as fuzzy numbers. The fuzzy membership functions for these fuzzy indicators are shown in Figures 3.8 and 3.9.

Table 3.14. Values of first-level indicators for application example

Pipe condition indicators	Values of pipe condition indicator				
	Pipe 1	**Pipe 2**	**Pipe 3**	**Pipe 4**	**Pipe 5**
Pipe age	1953	1964	1978	1988	1992
Pipe diameter (mm)	400	300	300	600	500
Pipe length (m)	600	400	800	400	300
Pipe material	CI	CI	DI	ST	PVC
Pipe joint	lead	leadite	rubber	rubber	rubber
Traffic loads	very quiet	very busy	busy	normal	very busy
Soil condition	high	low	high	low	medium
Location	poor	medium	excellent	excellent	good
Pipe bedding	clay	gravel	clay	sand	sand
Buried depth (m)	2.5	2.0	1.8	1.2	1.5

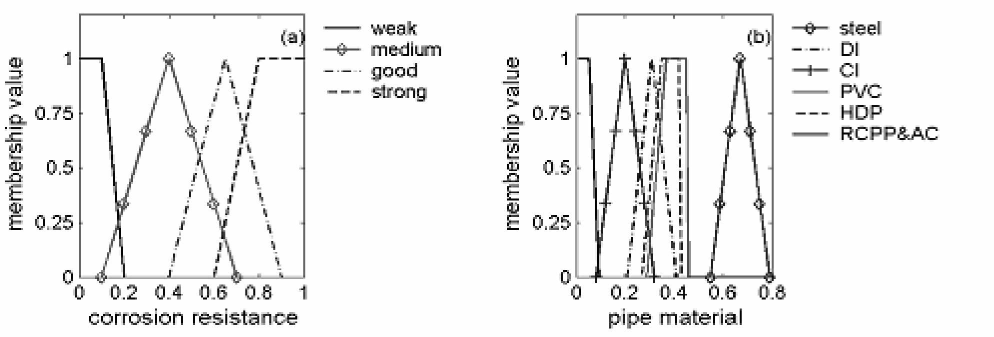

Figure 3.8. Fuzzy membership functions for corrosion resistance and pipe material

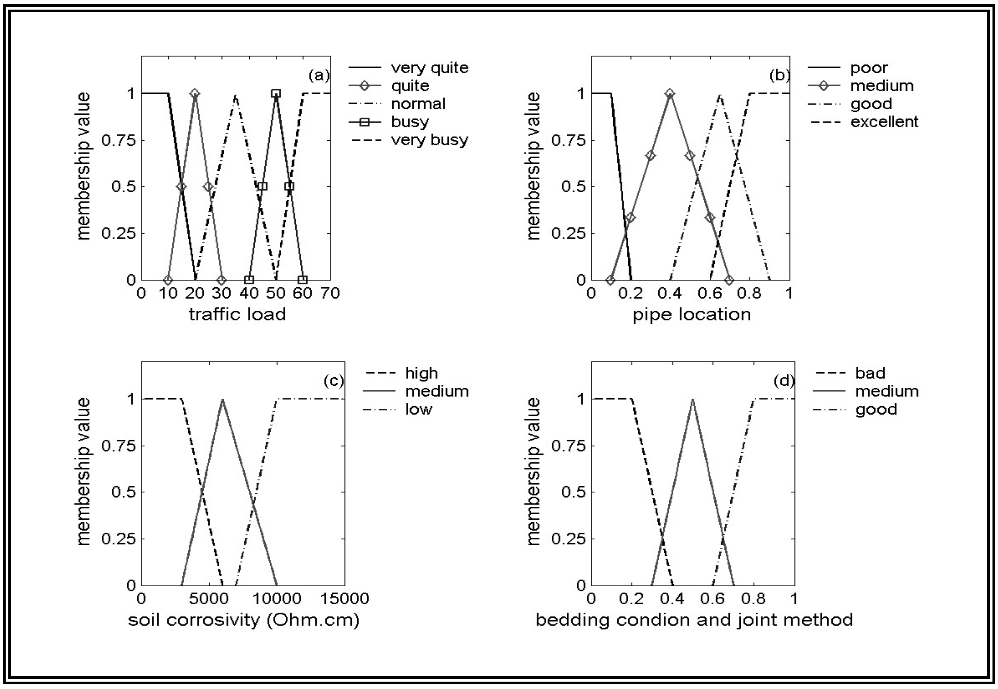

Figure 3.9. Fuzzy membership function of uncertain pipe indicators (traffic load, pipe location, soil corrosivity, and bedding condition and joint method)

3.7.3 Membership functions

To represent the importance of pipe material, two surrogate measures are used in this example, namely, maximum pressure and corrosion resistance. The comparisons of pipe material in terms of these two properties are given in Table 3.11. The maximum pressure reflecting the strength of the pipe material is expressed in crisp form, while the corrosion resistance that implies the capacity of pipe material to resist internal and external loads is given in linguistic form whose fuzzy description is as shown in Figure 3.8.

These two pipe material indicators are combined using appropriate weights (0.6 for maximum pressure of 0.6 and 0.4 for corrosion resistance are used in this example) to derive a single pipe material indicator, as given in Figure 3.5.

3.7.4 Weights and balance factors

Triangular fuzzy numbers were chosen to express the relative importance of different level indicators (column 4 of Table 3.15). The balance factor of 1 is used for first level indicators and a triangular fuzzy number is selected for the balance factor of second level indicators (column 5 of Table 3.15).

3.7.5 Normalization

Equation (3.2) is used to normalize the pipe condition indicators. The maximum and minimum values for normalization can be obtained from the design standard (criteria A) or can simply be obtained by comparing the values of all alternatives (pipes) for each indicator (criteria D) (see Section 3.5.6). Criteria D is used, based on the values given in Table 3.15.

Table 3.15. Best and worst indicators value, weights and balance factors				
Indicators	**Best value**	**Worst value**	**Weights**	**Balance factors**
(a) Level 1				
Pipe age	2000	1900	(0.2, 0.3, 0.4)	1
Pipe diameter (mm)	2000	50	(0.1,0.2, 0.3)	1
Pipe length (m)	50	2000	(0.1, 0.15, 0.4)	1
Pipe material	1	0	(0.2, 0.25, 0.3)	1
Pipe joint	1	0	(0.05,0.1, 0.2)	1
Traffic loads (vehicles/min)	0	100	(0.05, 0.15, 0.2)	1
Soil condition	50000	0	(0.1, 0.3, 0.4)	1
Location	1	0	(0.1, 0.2, 0.4)	1
Pipe bedding	1	0	(0.1, 0.25, 0.3)	1
Buried depth (m)	1	10	(0.05, 0.1, 0.2)	1
Maximum pressure (kPa)	20000	1000	0.6	1
Corrosion resistance	1	0	0.4	1
(b) Level 2				
Physical	*		(0.6, 0.7, 0.9)	(2.0, 2.5, 3.0)
Environmental	*		(0.2, 0.3, 0.4)	(2.0, 2.5, 3.0)

*Second level indicators are normalized, thus do not need best and worst values for normalization.

3.7.6 Results

The normalized indicator values are aggregated successively by using equation (3.4) until a final condition indicator is reached for each pipe as shown in Figure 3.5. The final indicator is used as criterion to rank the condition of pipes. The pipe condition indicators obtained from the FCP process are fuzzy numbers, which are shown in Figure 3.10. The fuzzy numbers were ranked using the method of Chen (1985) and the results are given in Table 3.16.

The results from Figure 3.10 show that the fuzzy number of pipe 1 is smaller than that of pipe 4. This indicates that pipe 1 has the worst condition whilst pipe 4 has the best condition, as shown in Table 3.16. It is noticed that the condition of pipe 4 is better than that of pipe 5, even though pipe 5 is new compared to pipe 4. This is probably due to the other contributing factors such as traffic. This illustrates that pipe condition assessment is a complex process resulting from many contributing factors and can hardly be decided from a single pipe condition indicator.

The pipe condition ranks given in Table 3.16 can be used when assigning priority for pipeline inspection and rehabilitation. It provides a quick and economical method of determining the relative quality of a large number of pipes.

Table 3.16. Final pipe condition indicator values

Ascending order	Values of membership function				
	0.00	0.25	0.50	0.75	1.00
1 (very bad)	[0.047, 0.78]	[0.084, 0.66]	[0.014, 0.54]	[0.21, 0.41]	[0.028, 0.30]
2	[0.056, 0.82]	[0.096, 0.70]	[0.15, 0.57]	[0.22, 0.44]	[0.30, 0.31]
3	[0.077, 0.89]	[0.013, 0.78]	[0.20, 0.66]	[0.28, 0.53]	[0.37, 0.40]
5	[0.11, 0.96]	[0.17, 0.85]	[0.25, 0.73]	[0.34, 0.60]	[0.43, 0.46]
4 (very good)	[0.13, 1.00]	[0.20, 0.91]	[0.28, 0.78]	[0.38, 0.65]	[0.48, 0.50]

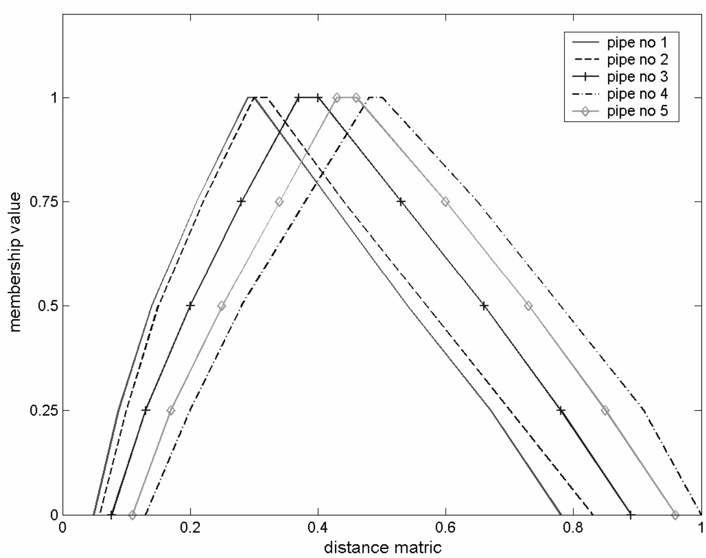

Figure 3.10. Fuzzy numbers representing water pipe condition

3.8 Conclusions

At this stage of the chapter readers should be able to complete Tables 3.1 to 3.9 for their particular area of study. These tables form the basis of the input data for the pipe condition assessment model part of IRA-WDS. The data contained in Tables 3.1 to

3.9 are entered into IRA-WDS by means of the several input dialog windows within the software. Figure 3.11 shows an example of these input dialog windows and more details of this can be found in Chapter 4 of Book 4 (IRA-WDS user manual).

An example of the output from a successful run of the pipe condition assessment model part of IRA-WDS are shown in Figure 3.12 and Table 3.17. These outputs are combined with the outputs from the contaminant ingress model part of IRA-WDS (discussed in Chapter 2), to give potential contaminant loads from pollution sources into the water distribution pipes.

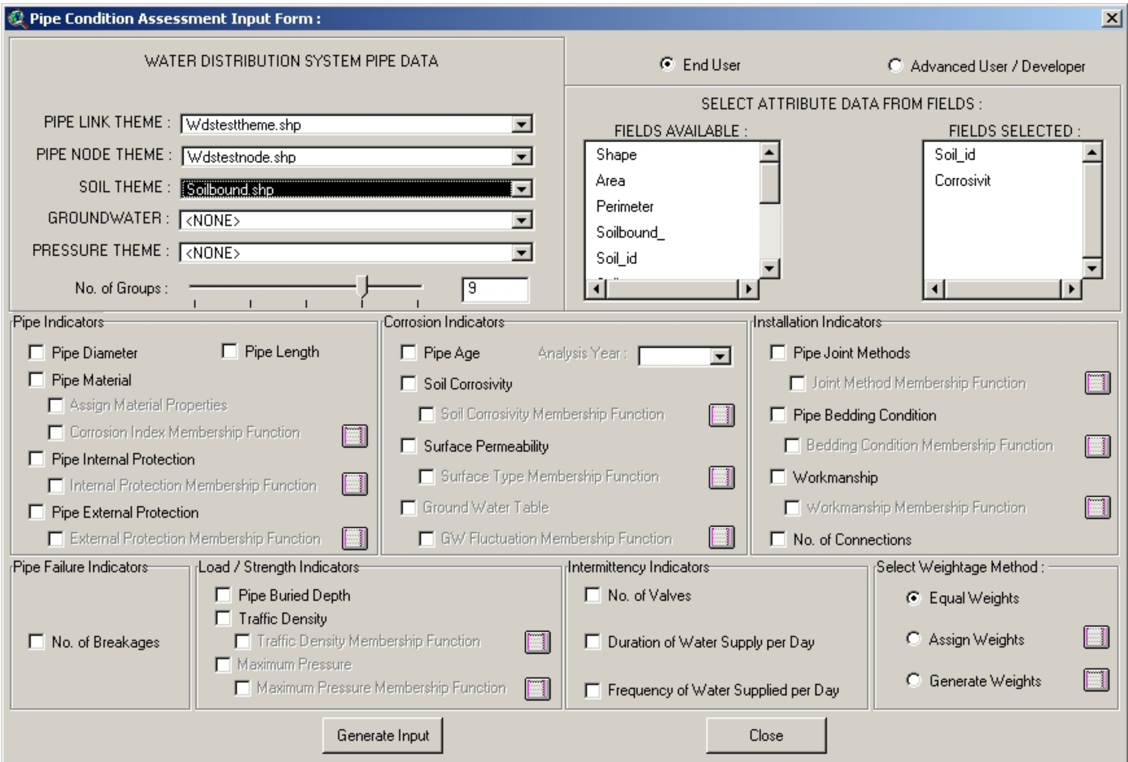

Figure 3.11. Example of input dialog window for PCA in IRA-WDS

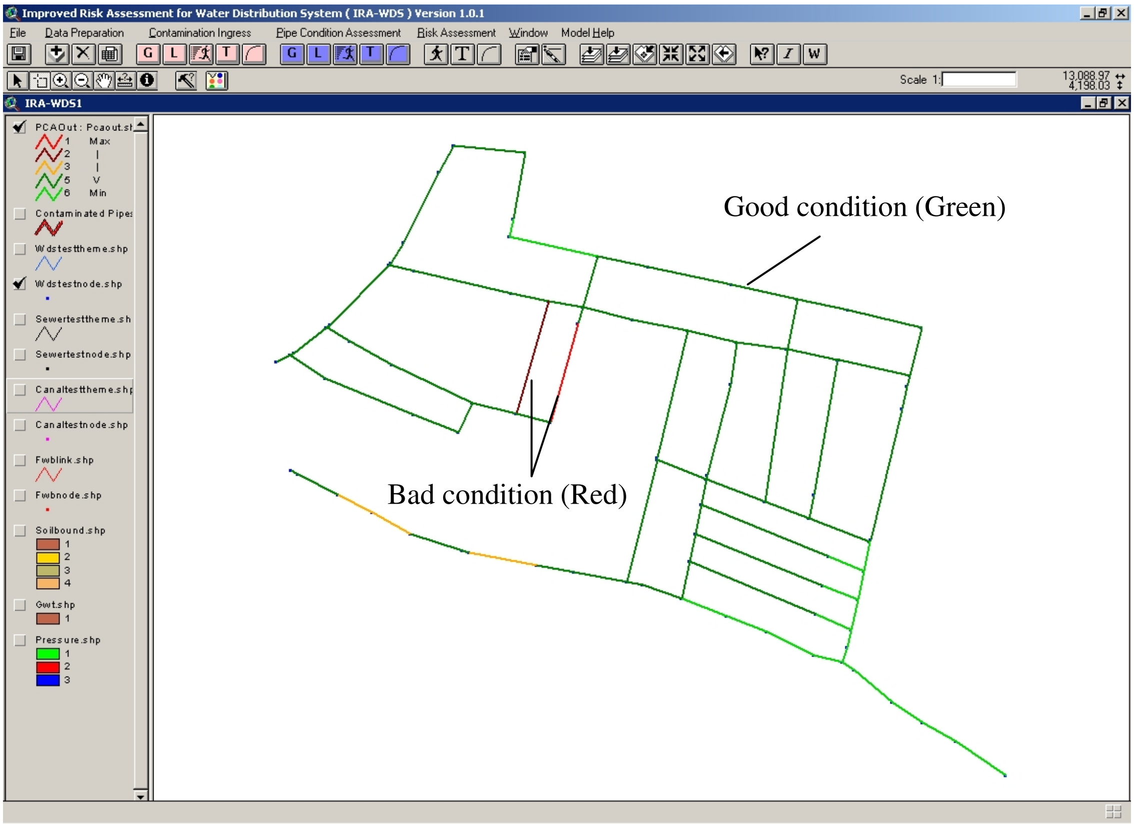

Figure 3.12. An example of the output from a successful run of the pipe condition assessment model part of IRA-WDS

Table 3.17. An example of the output from a successful run of the pipe condition assessment model part of IRA-WDS					
Pipe ID	**Defuzzy**	**Rank**	**Pipe ID**	**Defuzzy**	**Rank**
950	0.000	1	883	0.805	8
944	0.283	3	994	0.805	8
1043	0.430	4	945	0.806	8
1074	0.448	4	956	0.806	8
1025	0.491	5	915	0.808	8
831	0.776	7	786	0.809	8
975	0.777	7	885	0.811	8
824	0.778	7	1017	0.814	8
880	0.781	7	949	0.814	8
852	0.793	7	855	0.815	8
866	0.797	7	976	0.817	8
837	0.797	7	856	0.817	8
951	0.797	7	993	0.817	8
936	0.799	7	1016	0.818	8
1083	0.799	7	995	0.818	8
957	0.800	8	1045	0.820	8
809	0.802	8	1012	0.821	8
989	0.804	8	800	0.823	8