DECISION TOOLS FOR DEMOLITION TECHNIQUES SELECTION

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ABSTRACT

Demolition is an activity in which the construction process is reversed; that is, the structure, or parts of the structure, are disassembled and removed. Sometimes it is misleading to use the word demolition to describe the industry today, since some structures are no longer demolished, but carefully dismantled or deconstructed so that more materials can be reused and recycled. The demolition of any type of structure is unique, due to the shear number of parameters that govern the demolition process. Before selecting any type of demolition technique, the demolition contractor needs to consider a set of criteria and assess their relevance to the demolition work to be undertaken, in order to arrive at the most appropriate demolition technique. Criteria that may be important on one particular demolition project may not necessarily be so on another project. Many factors have to be considered in selecting the best techniques for the demolition work, and require the demolition engineers to have multicriteria decision-making (MCDM) ability. This paper, therefore, discusses the use of the Analytic Hierarchy Process (AHP) as one of the MCDM approaches to develop a tool for demolition techniques selection. The tool was developed to assist demolition engineers to select the most appropriate demolition techniques for any given project. It concludes that, by using this tool, demolition engineers can make more informed decisions on demolition techniques, based on a sound technical framework.

KEYWORDS: Demolition; Deconstruction; Decision Tools; Demolition Techniques Selection Model; Analytic Hierarchy Process (AHP); Multicriteria Decision Making (MCDM)

INTRODUCTION

Demolition engineers are faced with decision problems in the selection of demolition techniques. In practice, the decision is based on the experience, skill, and knowledge of the demolition engineer. Furthermore, there are many elements of the problems, and the interrelationships among the elements are very complicated. According to Abdullah [1], there are six main criteria and several sub-criteria that affect the choice of demolition techniques. The main criteria are: structural characteristics, site conditions, demolition cost, past experience, time, and reuse and recycling. In addition, research done by Kasai [2] suggested that there are eight criteria: structural form of the building, location of the building, permitted level of nuisance, scope of demolition, use of building, safety and demolition period. Both researchers agreed that the decision makers have to keep in mind that health and safety is the main concern in the selection process. The selection of the most appropriate demolition technique will be subject to a unique combination of these criteria.

The characteristics of the problem mentioned involve a multi-criteria, decision-making (MCDM) approach. MCDM is a critical decision tool for many scientific and engineering challenges [3]. It aims to help decision-makers learn the problems and to guide them in identifying a preferred course of action [4]. Decision analysis is used when a decision maker needs to evaluate the advantages and disadvantages of a number of alternative solutions for a given problem. Then, the alternatives can be evaluated in terms of a number of decision criteria.

The Analytic Hierarchy Process (AHP) is a MCDM approach and was developed by Saaty (1977 and 1994). AHP aims at quantifying relative priorities for a given set of alternatives on a ration scale, based on the judgment of the decision maker, and it stresses the importance of the intuitive judgments of a decision maker, as well as the consistency of the comparison of alternatives in the decision-making process [5]. Since its introduction, AHP has been applied to many types of decision problems. Some of the construction engineering applications of the AHP include: its use in project procurement system selection models [6], application of AHP in project management [7], a multi-criteria approach to contractor selection [8], and other engineering problems [9]. The majority of these applications have introduced analytical solutions for problems involving both quantitative and qualitative criteria, similar to the selection process that is the objective of this paper.

The AHP model provides a framework to aid in evaluating complex decision scenarios. Therefore, this paper presents the development of a decision tool for the selection of demolition techniques, using AHP as a theoretical framework. The framework will ensure a better understanding of the problems and criteria, and will ultimately assist the demolition engineer in determining the final selection of the demolition technique. Furthermore, the proposed method provides a systematic methodology to incorporate all relevant criteria simultaneously for the selection of the most appropriate demolition technique in any demolition project.

THE DEMOLITION PROCESS

The demolition process can be divided into four main stages: Tendering stage, Pre-demolition stage, Actual demolition stage, and Post-demolition stage (Figure 1). Although the selection of demolition techniques, the main concern of this paper, is carried out at the tender stage, this section discusses all four main stages to enable a better understanding of the demolition project.

Tendering Stage

The demolition process starts when the client makes a decision to demolish a structure. The demolition contractors are then invited to bid for the job. The contractor has to find out about the site before he or she can prepare a risk assessment. In the UK code of practice for demolition, section 7.1 BS 6187:2000 [10] states that knowledge of the site should be elicited by an initial desk study and followed by an on-site survey to augment the desk study. Off-site features that can affect work on site should also be determined. The next step is to carry out the risk assessment, which identifies the risks associated with the work and planning the removal or reduction of the risks before the work commences. The main part of the demolition process is the selection of the most appropriate demolition techniques.

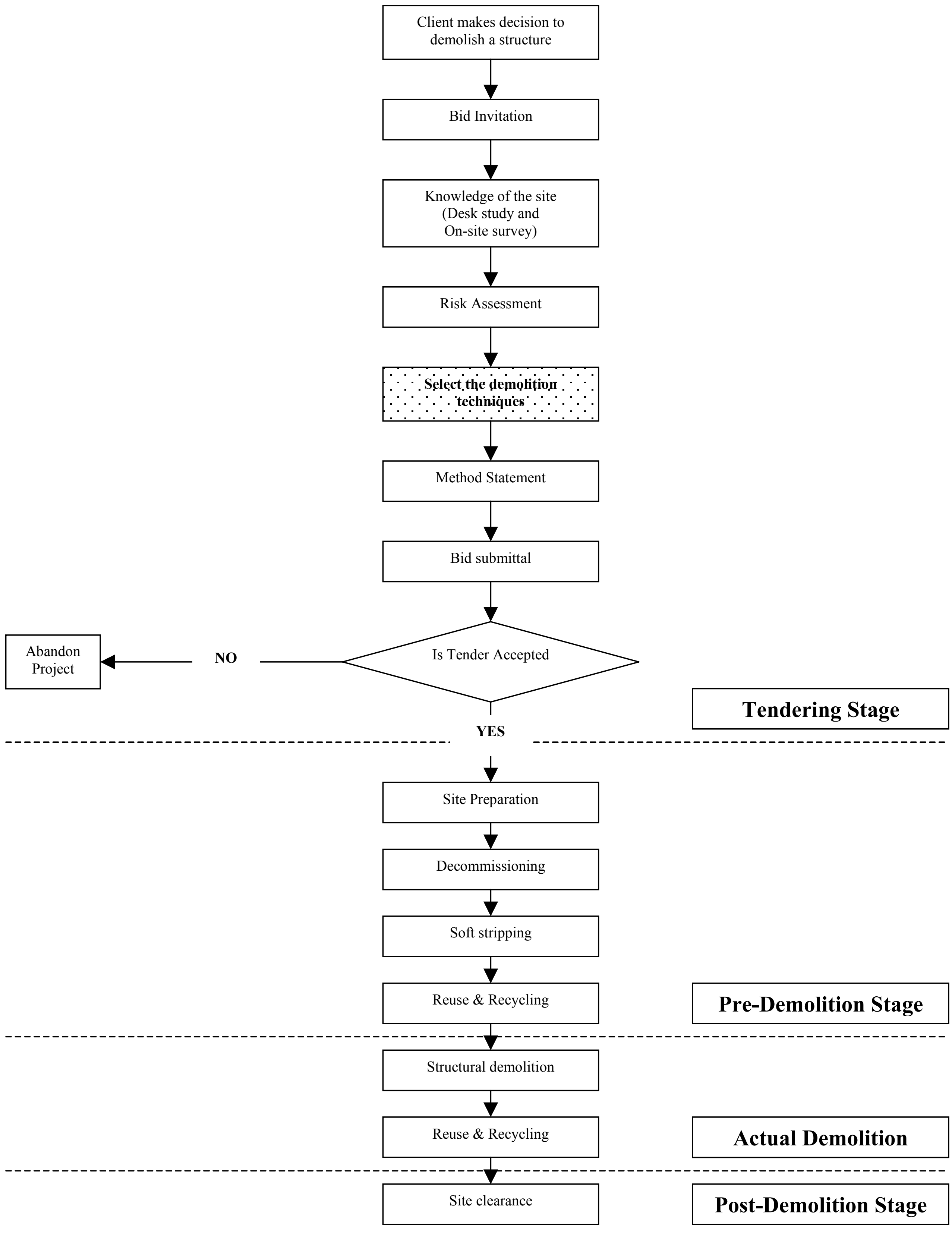

Figure 1: Flowchart for the demolition process

In practice, demolition contractors do not have a structured framework for selecting the demolition technique. They make judgements based on their skills, relevant knowledge on the techniques, and past experience. This has resulted in the need to conduct a selection process for any specific project in a structured and systematic manner. The next process is to produce a method statement. The method statement addresses the site's particular needs (i.e., site preparation), and details the planned sequences and techniques of demolition selected in the previous process. The tender document with the method statement will then be submitted to the client for the contractor evaluation purpose. If the contractor is selected by the client to do the job, they will continue with the next stage, the Pre-demolition stage. If the contractor does not get selected by the client, they have to abandon the project and bid for another job.

Pre-demolition Stage

Site preparation is the first process in the pre demolition stage. The process may include the erection of security fencing, and the setting-up of welfare facilities (e.g., site office, washing facilities and toilet). The next process is the decommissioning process. Decommissioning can be defined as a "process whereby an area is brought from its fully operational status to one where all live or charged systems are rendered dead or inert and reduced to the lowest possible hazard level" [10]. The decommissioning activities include, for example, removal of all asbestos and chemicals (e.g., battery acids and oils), and controlled release of stored energy in strong springs or suspended counterweights.

The process followed after decommissioning is soft stripping. The soft stripping is the removal of non-structural items such as fixtures and fittings, windows, doors, frames, suspended ceilings, and partitions. Some of the product from the soft stripping process can be reused and recycled. Materials, such as wood from windows or door panels, can be reused as building lumber, landscape mulch, pulp chip, and fuel [11]. The bricks can be cleaned and reused, but this is rarely done. Aluminium, stainless steel panels, and copper are the typical recycled metals. Architectural artefacts, such as sinks, doors, bathtubs, and used building materials, are almost always resold. Even the industrial process equipment can be marketed both domestically and internationally.

Actual Demolition Stage

The actual demolition starts when the structural elements are demolished. There are three main types of structural demolitions: Progressive demolition, Deliberate collapse mechanisms, and Deconstruction. These are the alternative techniques that can be selected by the contractor in the selection process, conducted in the tendering stage.

Progressive Demolition

Progressive demolition is the controlled removal of sections of the structure while retaining the stability of the remainder, and avoiding collapse of all or part of the structure to be demolished. Progressive demolition is particularly practical in confined and restricted areas, and may be considered for the majority of sites. The progressive demolition includes: Progressive demolition by hand (hand tools such as an impact hammer, diamond disc cutter, and wire saw); Progressive demolition by machine (Excavator attached with boom and hydraulic attachments, such as pulverisers, crushers, and shears); and Progressive demolition by balling, which involves the progressive demolition of a structure by the use of an iron ball that is suspended from a lifting appliance and then released to impact the structure repeatedly in the same or different locations.

Deliberate Collapse Mechanisms
Demolition by deliberate collapse is the removal of key structural members to cause complete collapse of all or part of a building or structure. This method is usually employed on detached, isolated, fairly level sites, where the whole structure is to be demolished. A sufficient space must be allocated to enable removal of equipment, and to keep personnel at a safe distance. The demolition by deliberate collapse includes deliberate collapse by explosive and deliberate collapse by wire rope pulling.

Deconstruction
The deconstruction technique in this research is defined as the dismantling of a structure, which is usually carried out in the reverse order of construction. It is also known as a top-down technique or, in general terms, the demolition proceeds from the roof to the ground. The demolition contractors should consider reuse of materials such as bricks, roof tiles, timber, and fixtures and fittings, when using this technique. This technique can be used, for example, as part of renovation or modification work and to prepare the way for deliberate collapse. The elements to be removed should be identified, and the effects of removal on the remaining structure should be fully understood and included in the method statement, with the elements to be removed marked on-site. If instability of any of the remainder might result in a risk to personnel on the site or to other people nearby, sections of the structure should not be removed. The deconstruction can be done by hand, machines, bursting, or hot cutting.

The reuse and recycling process can be done after or concurrently with the structural demolition process. With current technologies such as hydraulic excavators attached with pulverisers, concrete crushing, and screening machines, contractors are able to separate demolition debris. This process can maximise the use of resalable materials and subsequently reduce waste disposal costs. Typical recycled materials are metals and concrete debris. The recycled metals are: scrap iron, rebar (reinforced rods in concrete), aluminium, stainless steel, and copper. Concrete debris is pulverised, and can be used as fill material and sub-base.

Post-demolition Stage
The final process is the site clearance, in which the site should be left in a safe and secure condition. Any pits, sump, trenches, or voids must be left filled and securely covered, and the site drainage system must be thoroughly cleaned and tested to ensure that it continues to operate. All contaminants must be left or removed in a manner such that they demonstrate no hazard to health or to the environment. Finally, the planning supervisor should ensure that the Health and Safety File has been compiled and handed to the client upon completion of the work.

METHODOLOGY

To identify the most important decision criteria in the demolition techniques selection process, a postal questionnaire was sent to a sample of demolition engineers across the United Kingdom (UK). The National Federation of Demolition Contractors (NFDC) and the Institute of Demolition Engineers (IDE) provided the sampling frame for this survey. A questionnaire with a cover letter explaining the purpose of the study was mailed to 100 demolition engineers. A total of 67 surveys were returned, of which, 61 contained usable replies. Statistical analysis was carried out to refine these criteria, with the purpose of identifying the relative degree of importance of each criterion [12].

Once the most important criteria in the decision process were identified, structured interviews with six key experts were conducted to reassess and ensure the relevance of the identified criteria. Based on the findings from both surveys, an AHP decision model was built to evaluate the decision-making process for selecting demolition techniques.

THE ANALYTIC HIERARCHY PROCESS

AHP is a decision-aiding method developed by Saaty in the 1970s and published in his 1980 book, *The Analytic Hierarchy Process*. AHP uses a multi-level hierarchical structure of goals, criteria, sub criteria, and alternatives. A set of pairwise comparisons are used to obtain the weights of importance of the decision criteria, and the relative importance measures of the alternatives in terms of each individual decision criterion, and towards the overall goal of the problem. It also provides a mechanism for improving consistency if the comparisons are not perfectly consistent. The strength of AHP is its ability to structure a complex, multi-criteria problem hierarchically, and then to investigate each level separately, combining the results as the analysis progresses [8].

Since its introduction, a number of criticisms have been launched at AHP. Belton and Gear [13] observed that AHP could be subject to rank reversal, when an alternative identical to one of the existed alternatives is introduced. To overcome this problem, they introduced *revised-AHP*, which proposed that each column of the AHP decision matrix be divided by the maximum entry of that column. In 1994, Saaty [14] accepted the variants of the original AHP, and it is now called the *Ideal Mode AHP*. In addition, Dyer and Wendell [15] critiqued the AHP on the grounds that it lacked a firm theoretical basis. Nevertheless, the original AHP, or the ideal mode, is the most broadly accepted method and is considered by many as the most reliable MCDM method [3].

The overall selection process will primarily depend upon the results generated through the use of the AHP model using Expert Choice. Expert Choice is professional commercial software developed by Expert Choice, Inc. [16]. It helps simplify the implementation of the AHP's steps and automates many of its computations such as matrix calculation in pairwise comparisons. It can also perform sensitivity analysis, which is used to investigate the sensitivity of the alternatives to changes in the priorities of the criteria.

MODEL DEVELOPMENT

A demolition project example will be demonstrated here for illustration purposes. Table 1 presents the demolition project's characteristics based on which one of three demolition techniques (Progressive Demolition, Deliberate Collapse Mechanism, and Deconstruction) is selected.

Harker and Vargas [17] point out that there are three principles used in AHP for problem solving: (1) *decomposition* - structures the elements of the problem into a hierarchy, (2) *comparative judgments* - generates a matrix of pair wise comparisons of all elements in a level with respect to each related element in the level immediately above it, where the principal right eigenvector of the matrix provides ratio-scaled priority ratings for the set of elements compared. AHP uses a mathematical technique, eigenvector scaling, for translating pair wise rating into numerical scores representing the importance of each individual criterion and (3) *Synthesis of priorities* - generates the global or composite priority of the elements at the lowest level of the hierarchy, i.e., the alternatives.

TABLE 1: THE PROJECT CHARACTERISTICS

Project Characteristics	Explanations			
Structure Characteristics	1. Height of structure: 12 Storey 2. Type of structure: Building mainly made of Pre-cast panel 3. Stability of structure: Stable 4. Extent of demolition: Full Demolition 5. Previous used of structure: Housing			
Site Condition	1. Health and Safety of persons on and off site:	PD	DCM	DC
	Risk of danger to demolition workers Risk of danger to members of the public	Medium Low	Low Medium	High Low
	2. Environmental: Acceptable Level of Nuisance			
	Accepted level of noise Accepted level of dust Accepted level of vibration	70-74db(A) Significant amount of dust Significant effect of human body		
	3. Proximity of adjacent structure	50 meters		
	4. Accessibility of the plant	Accessible		
Demolition Cost	Demolition Cost (Lump Sum)	PD	DCM	DC
	1. Manpower	£ 50 000	£ 30 000	£ 50 000
	2. Machineries	£ 65 000	£ 70 000	£ 75 000
	Total Cost	£115 000	£100 000	£125 000
	Accepted level of noise Accepted level of dust Accepted level of vibration	70-74db(A) Significant amount of dust Significant effect of human body		
	Proximity of adjacent structure	50 meters		
	Accessibility of the plant	Accessible		
Past Experience		PD	DCM	DC
	1. Familiarity with specified technique	Familiar	Familiar	Not Familiar
	2. Availability of plant and equipment	Available	Available	Available
	3. Availability of expertise	Available	Available	Available
Reuse and Recycling	Level of concern over reuse and recycling	Moderate level of concern		
Time	Proposed project completion date is three months.			
Note: PD – Progressive Demolition DCM – Deliberate Collapse Mechanism DC – Deconstruction				

Decomposition

Saaty [14] pointed out that the hierarchic structure is beneficial to a decision-maker by providing an overall view of the complex relationships inherent in the situation and in the judgment process. It also allows the decision-maker to assess whether he or she is comparing issues of the same order of magnitude. By following the AHP principles, the hierarchy of the problem can be developed as shown in Figure 2. A hierarchy is a tree-like structure that is used to decompose a decision problem. It has a top-down flow, moving from general categories (criteria) to more specific ones (sub-criteria), and finally to the alternatives [16].

The selection of the most appropriate demolition techniques is the goal of the decision makers, and this is located at level 0 of the model to serve as a goal node. Factors affecting the demolition technique selection, which had been classified into six categories, were inserted in level 1 of the model to serve as the main criteria. Level 2 of the model define sub-criteria nodes for categories in level 1. Levels 1 and 2 of the hierarchy consisted of a total of 6 and 17 nodes, respectively. Finally the alternative solution (demolition techniques) occupied level 3 to serve as the choice available to the decision makers.

Comparative Judgments

The second step is to define the priority (or weight) of each criterion by comparative judgment. Muralidhar *et al*. [18] emphasized that the advantage of using a pairwise method is that it allows the decision-maker to focus on a comparison of two objects, and the observation can be made free of extraneous influences. At each level, comparative judgments or pairwise comparisons are conducted for each category with the ones in the adjacent upper level, and the ratings are entered into a comparison matrix. Based on the decision maker's perception, the priorities among the criterion items in the hierarchy are established, using pairwise comparisons. The judgments are entered using the fundamental scale for pairwise comparisons (see Table 2). The elements on the second level (Structure characteristics, site conditions, cost, past experience, reuse and recycling, and time) are arranged into a matrix, and the decision makers make judgments about the relative importance of the elements, with respect to the overall goal of selecting the most appropriate demolition technique.

TABLE 2: SCALE OF RELATIVE IMPORTANCE USED BY SAATY [14]

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgement slightly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Demonstrated importance	An activity is strongly favoured and its dominance demonstrate in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgements	When compromise is needed
Reciprocals of above nonzero	If activity i has one of the above nonzero numbers assign to it when compared with activity j, then activity j has the reciprocal value when compared with i.	

- **Goal: to select the most appropriate demolition techniques**
  - **Structure Characteristic**
    - **Height**
    - **Type**
    - **Stability**
    - **Degree of demolition**
    - **Use of the structure**
  - **Site conditions**
    - **Health & safety for the person on and off site**
    - **Acceptable level of nuisance**
    - **Proximity of the adjacent structure**
    - **Site accessibility**
  - **Cost**
    - **Machinery**
    - **Manpower**
  - **Past experience**
    - **Familiarity with a specified technique**
    - **Availability of plant and equipment**
    - **Availability of expertise**
  - **Reuse & recycling**
    - **Level of reuse and recycling**
  - **Time**
    - **Site preparation**
    - **Actual demolition**

Alternatives

Progressive Demolition Deliberate Collapse Mechanism Deconstruction

FIGURE 2: HIERARCHICAL STRUCTURE FOR THE SELECTION OF DEMOLITION TECHNIQUES

For example, when judging the relative preference of factors located in level 1, with respect to the goal (level 0), a rating of 1 is assigned in the comparison of structure characteristics and site conditions. This indicates equal importance of structure characteristics and site conditions. In comparing cost with past experience, with respect to the goal, the rating of 3 is assigned. This means that cost is of weak importance of one over past experience. The same procedure is repeated when the rating of 7 is assigned in comparing site conditions with time, with respect to the goal. Intensity of importance (7) assigned for this matrix can be explained, as a site condition is strongly favored if compared with time. All the remaining pairwise comparison matrices among the nodes in the hierarchy can be established by following the same procedure. Table 3 presents the start of pairwise comparison of level 0 with level 1. Similar pairwise comparison tables exist for level 1 with level 2 and for level 2 with level 3.

TABLE 3: START OF PAIRWISE COMPARISON OF LEVEL 0 WITH LEVEL 1

Demolition technique selection criteria (1)	Structure characteristics (2)	Site conditions (3)	Cost (4)	Past experience (5)	Reuse & recycling (6)	Time (7)
Structure characteristics	1	1	3	5	4	6
Site conditions	1	1	5	5	7	7
Cost	1/3	1/5	1	3	2	1
Past experience	1/5	1/5	1/3	1	5	2
Reuse & recycling	1/4	1/7	1/2	1/5	1	1/3
Time	1/6	1/7	1	1/2	3	1
Σ	2.950	2.686	10.833	14.700	22.000	17.333

Synthesis of Priorities

The next step is to undertake a synthesis from the model global goal, which converts all of the local priorities into the global weights of alternatives. Local priority is the priority relative to its parent, or upper, level, while global priority, also called final priority, is the priority with respect to the goal [12]. To check the consistency of the pairwise comparison matrix, the following calculation can be done automatically by the AHP software, Expert Choice, or can be done manually. The calculation of the consistency ratio (CR) will be explained next for illustration purposes.

1. Synthesizing the Pairwise comparison matrix:
   The value 0.339 in Table 4 is obtained by dividing (1 from Table 3) by 2.95, the sum of the column items in Table 4 (1+1+1/3+1/5+1/4+1/6).

TABLE 4: SYNTHESIZED MATRIX OF LEVEL 0 WITH LEVEL 1

Demolition technique selection criteria (1)	Structure characteristics (2)	Site conditions (3)	Cost (4)	Past experience (5)	Reuse & recycling (6)	Time (7)	Priority Vector
Structure characteristics	0.339	0.372	0.277	0.340	0.182	0.346	0.309
Site conditions	0.339	0.372	0.462	0.340	0.318	0.404	0.373
Cost	0.113	0.074	0.092	0.204	0.091	0.058	0.105
Past experience	0.068	0.074	0.031	0.068	0.227	0.115	0.097
Reuse & recycling	0.085	0.053	0.046	0.014	0.045	0.019	0.044
Time	0.056	0.053	0.092	0.034	0.136	0.058	0.072
						Σ	1.000

2. Calculating the priority vector:
   The priority vector in Table 4 can be obtained by finding the row averages. For example, the priority of structure characteristic with respect to the goal (level 0) in Table 4 is calculated by dividing the sum of the rows (0.339 + 0.372 + 0.277 + 0.340 + 0.182 + 0.346) by the number of criteria (column), i.e., 6, in order to obtain the value 0.309.

3. Calculating Weighted Sum Matrix:
   The calculation of weighted sum matrix shown below:

$$0.309\begin{bmatrix}1\\1\\1/3\\1/5\\1/4\\1/6\end{bmatrix} + 0.373\begin{bmatrix}1\\1\\1/5\\1/5\\1/7\\1/7\end{bmatrix} + 0.105\begin{bmatrix}3\\5\\1\\1/3\\1/2\\1\end{bmatrix}$$

$$+\ 0.097\begin{bmatrix}5\\5\\3\\1\\1/5\\1/2\end{bmatrix} + 0.044\begin{bmatrix}4\\7\\2\\5\\1\\3\end{bmatrix} + 0.072\begin{bmatrix}6\\7\\1\\2\\1/3\\1\end{bmatrix} = \begin{bmatrix}2.090\\2.503\\0.734\\0.631\\0.270\\0.462\end{bmatrix} \text{(Weighted Sum Matrix)}$$

4. Calculating λ_{max}:
   This involves dividing all the elements of the weighted sum matrices by their respective priority vector element, then computing the average of these values to obtain λ_{max}.

$$\frac{2.090}{0.309} = 6.764 \qquad \frac{2.503}{0.373} = 6.710 \qquad \frac{0.734}{0.105} = 6.990$$

$$\frac{0.631}{0.097} = 6.505 \qquad \frac{0.270}{0.044} = 6.136 \qquad \frac{0.462}{0.072} = 6.417$$

$$\lambda_{max} = \frac{(6.764 + 6.710 + 6.990 + 6.505 + 6.136 + 6.417)}{6} = 6.587$$

5. Calculating the Consistency Index, CI:

$$\text{CI} = \frac{\lambda_{max} - n}{n-1} = \frac{6.587 - 6}{6 - 1} = 0.11$$

6. Calculating the Consistency Ratio, CR:
   Using appropriate value of random consistency ratio, RI, for a matrix size of six using Table 5, RI = 1.24.

TABLE 5: AVERAGE RANDOM CONSISTENCY (RI) [14, 19]

Size of matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

$$CR = \frac{CI}{RI} = \frac{0.11}{1.24} = 0.09$$

7. Checking the consistency of the Pairwise comparison matrix to check whether the decision maker's comparisons were consistent or not. As the CR (0.09) is less than 0.1, the judgments are acceptable.

Similarly, the pairwise comparison for the remaining sub-criteria and decision alternatives can be calculated to set priorities, in terms of the importance of each in contributing to the overall goal. Table 6 shows the local and global priority of each criterion in the final selection of the demolition technique. As a result, from the pairwise comparison matrices, the overall priorities of the model's main criteria were determined (see Table 7).

TABLE 6: THE PRIORITY OF EACH CRITERION IN THE SELECTION OF DEMOLITION TECHNIQUES

Criterion	Local priority [a]	Global priority [b]	Subcriterion	Local priority [a]	Global priority [b]
Structural characteristic	0.313	0.313	Height	0.395	0.124[c]
			Type	0.288	0.090
			Stability	0.162	0.051
			Degree of demolition	0.092	0.029
			Use of structure	0.063	0.020
Site conditions	0.375	0.375	Health and safety for the person on and off site	0.571	0.214
			Acceptable level of nuisance	0.065	0.024
			Proximity of the adjacent structure	0.241	0.090
			Site accessibility	0.124	0.046
Cost	0.109	0.109	Machinery	0.500	0.055
			Manpower	0.500	0.055
Past experience	0.093	0.093	Familiarity with a specified techniques	0.481	0.045
			Availability of plant and equipment	0.114	0.011
			Availability of expertise	0.405	0.038
Time	0.069	0.069	Site Preparation	0.500	0.034
			Actual demolition	0.500	0.034
Reuse & recycling	0.041	0.041	Level of reuse and recycling	1.000	0.041

[a] Local priority is derived from judgment with respect to a single criterion
[b] Global priority is derived from multiplication by the priority of the criterion
[c] The result is obtained as follows: 0.313 X 0.395 = 0.124

TABLE 7: RELATIVE PRIORITIES OF CRITERIA

Criterion	Relative priority
Site conditions	0.375
Structure characteristic	0.313
Cost	0.109
Past experience	0.093
Time	0.069
Reuse & recycling	0.041

Consistency ratio = 0.09

Table 8 shows that the demolition techniques are now ranked according to their overall priorities, as follows: Deliberate collapse mechanisms, Progressive demolition, and deconstruction. This indicates that the deliberate collapse mechanism is the most appropriate demolition technique for the specified demolition project.

TABLE 8: OVERALL PRIORITIZATION OF THE THREE ALTERNATIVES

Criterion	Relative priority
Deliberate collapse mechanisms	0.490
Progressive demolition	0.318
Deconstruction	0.192

Consistency ratio = 0.04

Sensitivity Analysis

Expert Choice software provides tools for performing sensitivity analysis. The general purpose of the sensitivity analysis is to graphically see how the alternatives change with respect to the importance of the criteria or sub-criteria. There are five types of analyses: Performance Sensitivity, Dynamic Sensitivity, Gradient Sensitivity, Head-to-Head Sensitivity, and Two Dimensional Sensitivity.

Performance Sensitivity

Figure 3 shows the screen-shot of the performance sensitivity graph. It displays how the alternatives (progressive demolition, deliberate collapse mechanism, and deconstruction) perform with respect to all six main criteria. Dragging the criteria bars up or down can temporarily alter the relationship between the alternatives and their criteria.

Dynamic Sensitivity

Figure 4 shows the screen-shot of the dynamic sensitivity graph. It is used to dynamically change the priorities of the criteria to determine how these changes affect the priorities of the alternative choices. By dragging the criterion priorities back and forth in the left column, the priorities of the alternatives will change in the right column. If the decision makers think a criterion might be more or less important than originally indicated, the criteria bar can be dragged to the right or left to increase or decrease the criterion priority, and the impact can be seen on the alternatives. For example, as the priority of one criterion decreases (by dragging the bar to the left), the priorities of the remaining criteria increase in proportion to their original priorities, and the priorities of the alternatives are recalculated.

Gradient Sensitivity

Figure 5 shows the screen-shot of the gradient sensitivity graph. This graph shows the alternatives' priorities one criterion at a time. The vertical solid line represents the priority of the selected criterion (structure characteristics) and is read from the X-Axis intersection. The priorities for the alternatives are read from the Y-Axis. To change an objective's priority, drag the vertical solid bar to either the left or right. Then, a vertical doted bar showing the new objective's priority will be displayed.

Head-to-Head Sensitivity

Figure 6 shows the screen-shot of the head-to-head sensitivity graph. The graph shows how two alternatives compare to one another against the criteria in a decision. The middle of the graph lists the criteria used in the decision. In this example, the two alternatives are progressive demolition and deliberate collapse mechanism. The overall result is displayed at the bottom of the graph by a horizontal bar, and shows the overall percentage. In this case, the deliberate collapse mechanism is better than the progressive demolition techniques.

Two-Dimensional Sensitivity

Table 7 shows the screen-shot of the two-dimensional sensitivity graph. This graph shows how well the alternatives perform with respect to any two criteria. In this example, the structure characteristic is represented on the X-Axis and the site condition is on the Y-Axis. The alternatives are represented by the circle. The area of the 2D plot is divided into quadrants. The most favorable alternatives, as defined by the criteria and judgments in the model, will be shown in the upper right quadrant (the closer to the upper right hand corner, the better). In this case, it is the deliberate collapse mechanism. While in opposition, the least favorable alternatives will be shown in the lower left quadrant (progressive demolition and deconstruction). Alternatives located in the upper left and lower right quadrants indicate key tradeoffs where there is conflict between the two criteria.

SUMMARY AND CONCLUSION

The selection of demolition techniques by the demolition engineer requires multi-criteria decision-making ability. The nature of the problem requires a systematic approach to evaluate the available demolition techniques against a number of influential criteria. Therefore, this paper has presented the development of a decision tool to select the most appropriate demolition techniques, based on the AHP approach. A software package called *Expert Choice* was used, as it provides a convenient approach to organizing the selection process, and helps to make the decision less complex, more structured, less time consuming, and therefore, easy to use. An example demolition project was used to demonstrate AHP application in the selection process. The tool presented in this paper proved highly effective, and meets its objectives as a decision-making aid for demolition engineers in selecting the most appropriate demolition techniques.

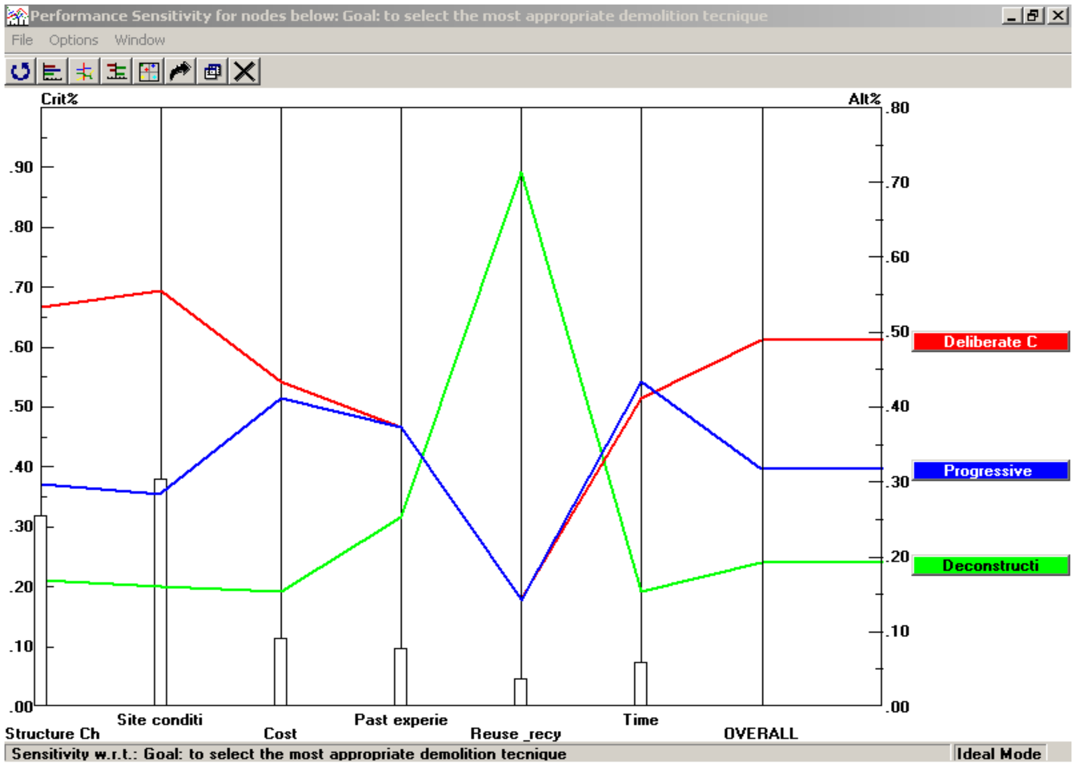

FIGURE 3: PERFORMANCE SENSITIVITY GRAPH

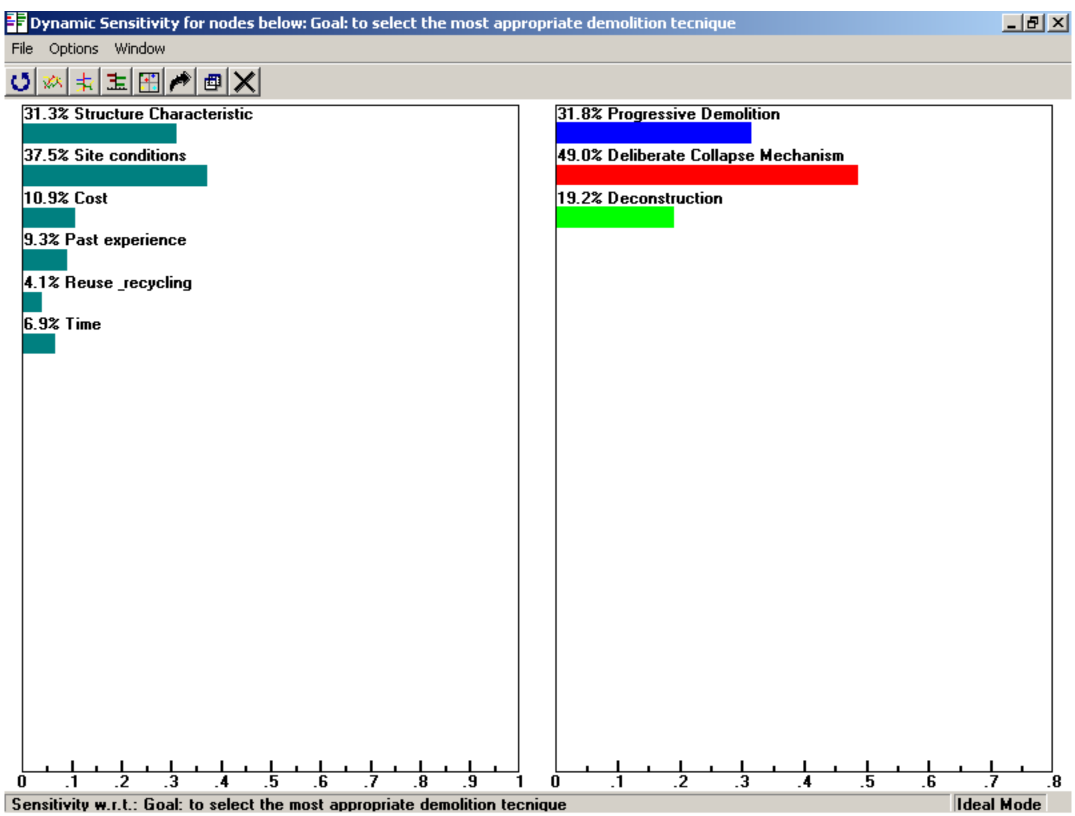

FIGURE 4: DYNAMIC SENSITIVITY GRAPH

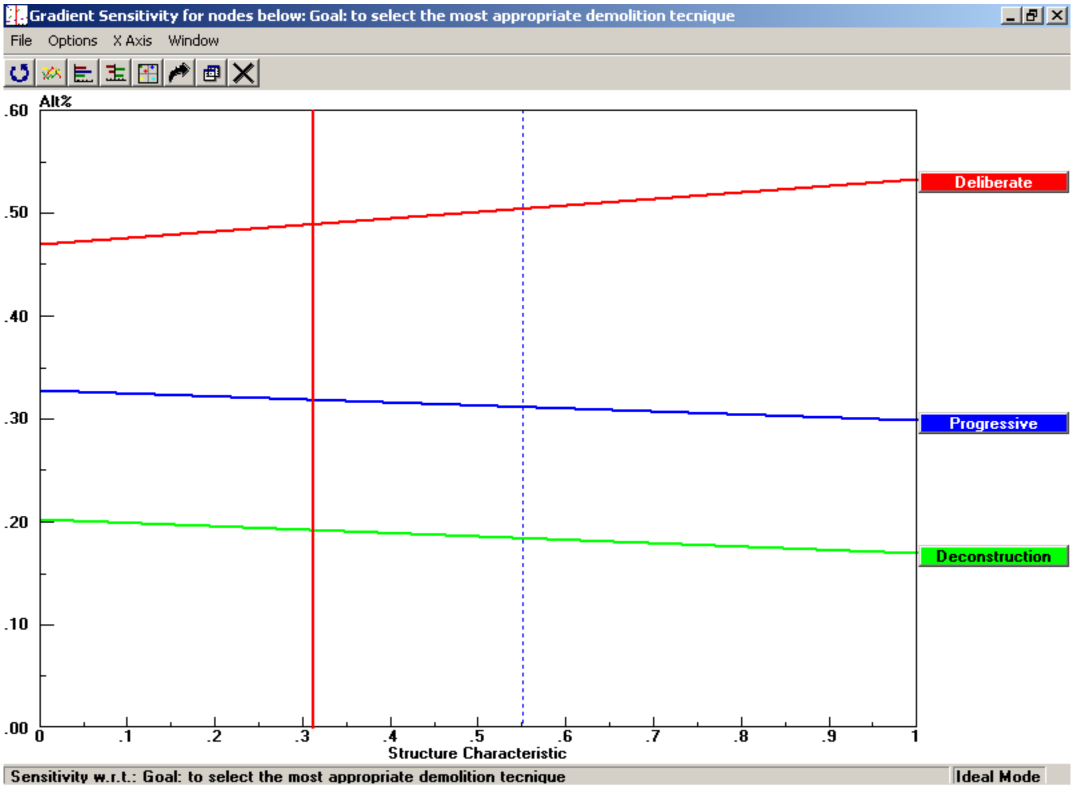

FIGURE 5: GRADIENT SENSITIVITY GRAPH

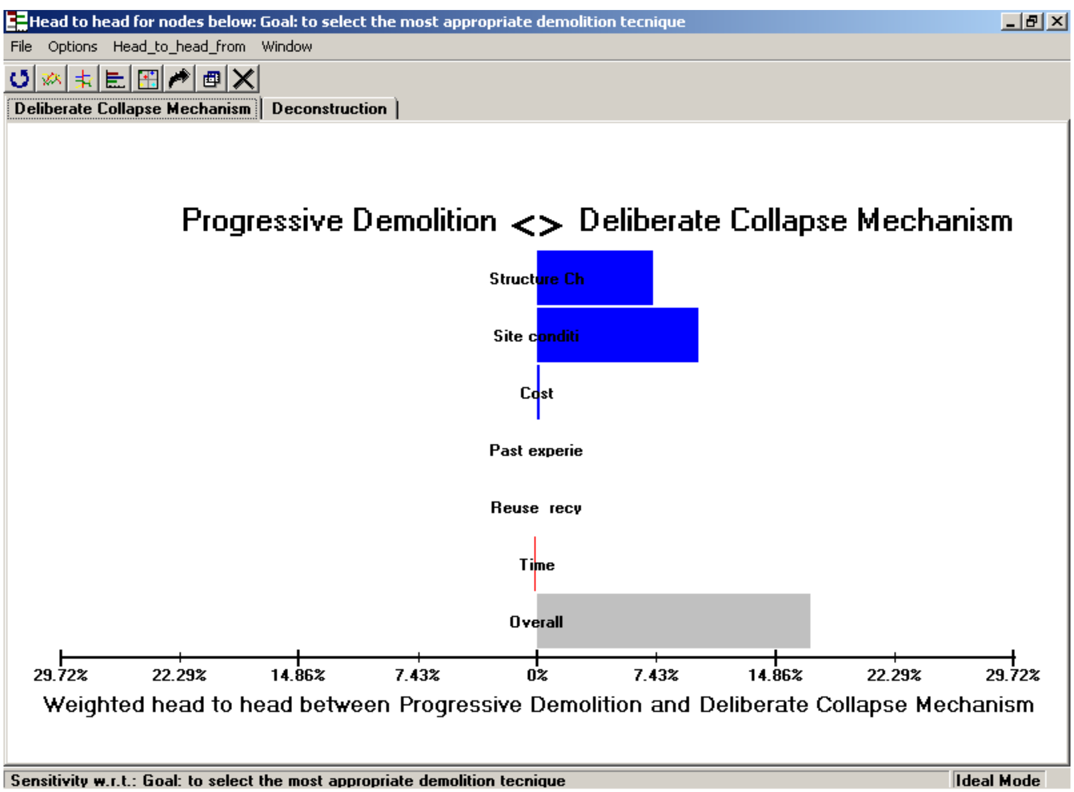

FIGURE 6: HEAD TO HEAD SENSITIVITY GRAPH

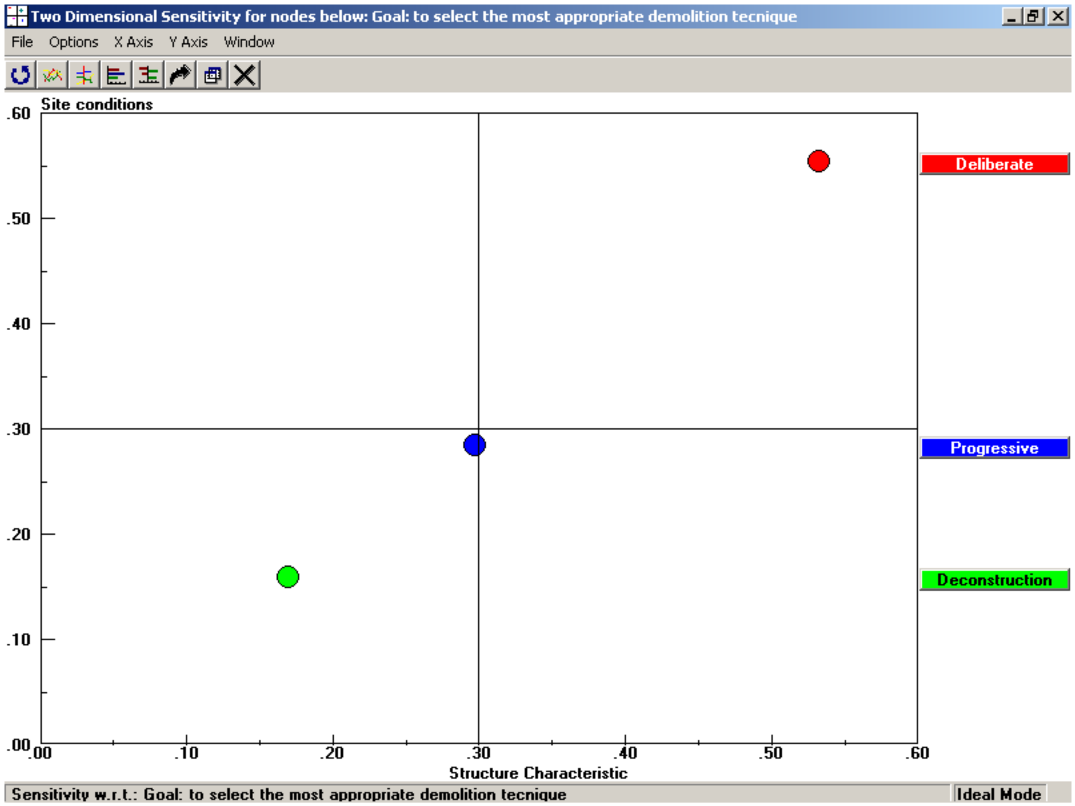

FIGURE 7: TWO DIMENSIONAL SENSITIVITY GRAPH

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