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RISK EXPOSURE AND RISK ATTITUDE OF HOMEOWNERS IN FIRE PROTECTION INVESTMENT DECISIONS

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ABSTRACT

The report demonstrates that the Analytic Hierarchy Process (AHP) is a promising decision tool for evaluating fire protection systems for homeowners. It lays the ground for development of specialized computer software for applying the AHP to decisions of individual homeowners. Unlike conventional methods of economic analysis, the AHP integrates quantifiable and qualitative variables. The study explores how to include in the decision-making process information on an individual's risk exposure and risk attitude, information which is generally difficult or impossible to quantify. By differentiating between risk exposure and risk attitude, this application goes beyond the AHP's conventional treatment of risk. The AHP is applied to the choice of purchasing smoke detectors, a sprinkler system, or a combination of the two. Two hypothetical cases are assumed, one in which the homeowner is risk-taking and has lower-than-average risk exposure, and one in which the homeowner is risk-averse and has higher-than-average risk exposure. Subjective probabilities of fire, death, injury, and property loss are merged with more easily quantifiable benefit and cost criteria. A method of pairwise comparisons provides the data to calculate priority vectors for the fire protection alternatives.

Key Words: Analytic hierarchy process; building economics; decision support software; economic analysis; qualitative data; residential fire protection; risk analysis; risk attitude; risk exposure; sprinkler systems.

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EXECUTIVE SUMMARY

In an effort to reduce residential fire deaths and property losses in the United States, new strategies for fire suppression and fire protection have been explored. One promising strategy is to install fast-response sprinkler systems in houses.

A previous benefit-cost analysis performed at the National Institute of Standards and Technology (NIST) examined the economic aspects of sprinkler technology for new one- and two-family houses. The present study expands that analysis by taking into account differences in risk exposure and risk attitudes of individual homeowners. A method is explored that elicits information specific to the homeowner and incorporates it into the decision process. The results show that sprinkler systems, which are not cost effective based on average fire data and risk neutrality, may be cost-effective for individual homeowners when their unique risk exposures and risk attitudes are taken into account.

The method explored in the study is the Analytic Hierarchy Process (AHP). It was developed at the University of Pennsylvania in the 1970's and has been applied to a number of diverse decision problems that deal with both quantifiable and qualitative variables. Because the AHP allows the integration of both kinds of variables, it can include in the decision-making process homeowners' subjective judgments regarding their exposure to risk of fire, loss of life, injuries, and property loss as well as their attitudes towards these risks. It can also include difficult-to-measure aesthetic judgments.

The AHP takes into account individual risk exposure and risk attitude through a procedure of pairwise comparisons of appropriately defined criteria and alternatives. These are arranged in a hierarchy which gives the decision problem its logical structure. The pairwise comparisons generate weights, or relative priorities, for the criteria at each level of the hierarchy. The relative priorities of each level are aggregated to arrive at a ranking of the decision alternatives.

To demonstrate its potential as a decision tool for evaluating fire protection devices for houses, the model is applied to two hypothetical homeowners who are to choose among three fire protection strategies: smoke detectors, a sprinkler system, and a combination of smoke detectors and sprinklers. The hypothetical cases assume the following:

I a risk-taking homeowner with lower than average exposure to risk of fire and death, of injury, and of property loss.

II a risk-averse homeowner with higher than average exposure to risk of fire and death, of injury, and of property loss.

The homeowner of Case I has two reasons to be less interested in fire protection devices than the homeowner in Case II: lower risk exposure and a less concerned attitude.

The AHP ranked smoke detectors as the preferred choice in Case I, and a combination of smoke detectors and sprinklers in Case II. These results are in line with what one would expect based on the earlier NIST benefit-cost study.

The case studies show that the AHP can be used in a research mode to incorporate subjective judgments about individual risk exposure and risk attitudes in decisions about fire protection investments and that it is potentially useful for actual applications in the field of fire protection.

Experimental applications reveal the following advantages of the AHP as a decision tool for evaluating fire protection systems:

(a) The most important advantage of the AHP is that it is a multi-criteria decision model which enables the integration of quantifiable and qualitative inputs. This allows a homeowner's subjective evaluation of risk exposure and risk attitude to be taken into account.

(b) The hierarchical structure of the AHP allows decision-makers to clarify the problem and analyze the decision process. By doing so, they create the proper frame of reference for making decisions involving fire risks.

(c) Pairwise comparisons are a simpler way of eliciting preferences than are most conventional methods, such as utility functions, which are difficult to determine and complicated to calculate for more than two criteria.

(d) Contrary to methods that require perfect transitivity, which is rarely achievable in practical applications, the AHP allows some inconsistency in a decision-maker's judgment. More important is that it has a built-in measure of inconsistency of the decision-maker's judgments. It gives immediate feedback, and allows for revision of judgments if the inconsistency reaches a level that would jeopardize the quality of the final decision. This feature is valuable when dealing with responses that involve probabilities and subjective estimates of risks and hazards with which most people have had limited experience.

(e) It is feasible to implement the AHP on a personal computer in a way to meet the special needs of fire protection decisions.

Investigations also identified the following shortcomings of the AHP as a decision tool for fire protection decisions:

(a) The off-the-shelf computer software supporting the AHP assumes that the user is an "expert" in the area of application. This means that the user must have information on the costs of purchasing, installing, and maintaining the alternative fire protection systems, as well as information on average fire-related risks.

(b) When a large number of criteria and alternatives are used, the process of pairwise comparisons with the off-the-shelf computer program and the interpretation of results become complicated and confusing.

(c) The AHP requires the magnitudes of criteria and decision alternatives to be comparable within a scale of 1-9, which requires criteria and alternatives to be of the same order of magnitude.

(d) Unlike utility functions, pairwise comparisons of criteria and alternatives in the AHP do not explicitly measure the amount of risk aversion needed to make a homeowner choose a sprinkler system over smoke detectors. This is not a serious shortcoming if the model is used as a decision-making aid for an individual homeowner, since his or her risk attitude--though not quantified--is taken into account and reflected in the calculation of the priorities.

The conclusions and recommendations are as follows:

(a) The AHP model is well suited to the problem of deciding whether or not to purchase and install fire protection devices.

(b) To apply the model requires the user to have considerable information about alternative fire protection systems and fire-related risks. Since most people lack the necessary level of information, a way of making the information easily accessible to the user is required.

(c) Expecting homeowners to structure decisions using complicated generic, off-the-shelf AHP computer software is unrealistic.

(d) To make the AHP model a feasible decision tool for homeowners requires development of a customized computer software package which (1) structures the fire protection investment problem appropriately, and (2) provides built-in information for the user.

(e) The feasibility of developing a customized AHP software package has been demonstrated by successful development of software for other applications. For example, <u>AutoMan. Decision Support Software for Automated Manufacturing Investments</u> evaluates automated manufacturing equipment in the face of multiple decision criteria (Weber, Lippiatt, and Johnson, 1989).

(f) Adapting the AHP model to the evaluation of fire protection investment decisions is likely a more cost-effective approach than attempting to develop an expert system for the purpose.

1. INTRODUCTION

1.1 Background, Scope, and Organization

The high incidence of fire deaths and property loss in the United States has heightened interest in new strategies for mitigating residential fire losses. One promising strategy is to install fast-response sprinkler systems in one- and two-family houses. The success of this technology will hinge in large part on its acceptance by individual homeowners.[1]

A previous study (Ruegg and Fuller, 1984)[2] evaluated the benefits and costs of residential sprinklers based on average fire risks and losses, and the assumption that the homeowner is risk-neutral. Its purpose was to evaluate general economic performance of sprinklers in order to guide public policy. It pointed out that economic efficiency of sprinklers for the individual household is dependent on the degree of risk experienced by the household and on the attitude of the occupants towards risk. A conclusion drawn from the study is that a benefit-cost model exercised with average data--though useful as a policy tool--is not an adequate decision tool for an individual homeowner; a decision model is needed that takes into account risk exposure and risk attitude of individual households.

Risk exposure, in the context of this report, refers to the probability of a household's having a fire and suffering death or injury, or loss of property. It is a function of a number of factors, including physical characteristics of the house and physical and behavioral characteristics of the occupants. These factors are unique for a given household. The problem to be resolved is how to measure and account for these factors in estimating the benefits of improved fire protection for a particular household.

Risk attitude, as defined here, in the narrow context of fire protection, refers to the willingness of decision-makers to accept or reduce the degree of fire-related risk exposure characterizing their households. Risk attitude is specific to the individual. A risk-averse individual would be more likely to take measures to reduce the risk of fire than a risk-taking individual, all other things being equal. Again, it is a challenging task to measure how

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[1] Since this report deals with decision-making of individual homeowners, singular personal pronouns are often needed. To avoid the awkwardness of frequently having to say "he or she" or "her or him", the author alternates masculine and feminine pronouns from chapter to chapter.

[2] This study will be referred to as "Ruegg/Fuller" in the remainder of the report.

members of a household feel about changes affecting the safety of their lives and property and to incorporate these attitudes in the decision process.[3]

One approach to handling risk exposure is to develop functional relationships between house and occupant characteristics and probabilities of fire and death, injury, and property loss, and use these relationships to estimate individual risk exposure. An approach to handling risk attitude is to use utility theory to develop a model to quantify individual risk attitudes. But in practice, both these tasks are exceedingly difficult.

A different approach is to leave the assessment of risk exposure and risk attitude to the judgment of the individual homeowner and to provide a decision tool that captures both that and other subjective assessments. This report describes such an approach, based on an existing decision model, the Analytic Hierarchy Process (AHP). The objective of the study is to explore the use of the AHP model, with an off-the-shelf computer program, to guide homeowners' choices among alternative fire protection systems.

The AHP has been applied to a number of diverse decision problems. Many of these problems include both quantifiable and qualitative variables. This feature, to integrate quantifiable and qualitative variables, makes the AHP attractive for fire-related decisions which also hinge on both quantifiable and difficult-to-quantify factors. The application of the AHP to the problem of fire safety adds a new, not previously explored, dimension to its use: the distinction between risk exposure and risk attitude in the treatment of multi-criteria decision-making.

The decision-maker, in this case the homeowner, acts as the "expert" who controls the decision procedure. In addition to making choices based on numerical values, he makes judgments regarding personal risk exposure and risk preferences. To make the "subjective" judgments consistent with "objective" facts, he needs information on average fire risks, risk of death and injury, and property loss. To make informed judgments about numerical values, he needs information on the costs of purchasing, installing, and maintaining the alternative fire protection systems, and on the risk reduction attributed to them.

Section 2 describes the AHP, its general application, and its theoretical underpinnings. The section is meant as a tutorial; the reader who is familiar with the AHP may wish to go directly to section 3.

Section 3 explores the AHP's potential for including individual risk exposure and risk preference in fire protection investment decisions by applying the method to two hypothetical cases. One case assumes the homeowner has lower-than-average risk exposure and is risk-taking, the other assumes the

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[3] See Harold E. Marshall, Techniques for Treating Uncertainty and Risk in the Economic Evaluation of Building Investments, National Institute of Standards and Technology Special Publication 757, September 1988, for a survey of alternative techniques for treating risk exposure and risk attitude in the economic evaluation of building investments.

homeowner has higher-than-average risk exposure and is risk-averse. The data and assumptions in Ruegg/Fuller are used to provide a point of reference for defining the homeowner's degree of risk exposure.

Section 4 evaluates the potential of the AHP and the supporting software package "Expert Choice" as a decision-making aid for homeowners, and suggests how the AHP model can be adapted to actual applications.[4]

[4] "Expert Choice," Decision Support Software, Inc., McLean, VA, 1983.

2. THE ANALYTIC HIERARCHY PROCESS

2.1 Structure

The Analytic Hierarchy Process (AHP) was developed in the early 1970's by Thomas L. Saaty (1980, 1982) of the Wharton School at the University of Pennsylvania and is just coming into the mainstream of conventional decision analysis research.[5] Since the technique is not rooted in utility theory, it is potentially useful in problems where it may be too cumbersome to develop individual utility functions.

The AHP has four major features: (1) It decomposes a complex problem into its constituent elements and orders them into a hierarchy; (2) it uses pairwise comparisons to establish priorities among elements in each level of the hierarchy; (3) it provides a measurement theory to estimate the relative weights of the elements; and (4) it aggregates the relative weights to arrive at a set of ratings for decision alternatives. The simple problem of a car purchase, adapted from <u>Decision Making, Models and Algorithms</u>, by S. I. Gass (1985), illustrates how these features are applied to a decision problem.

2.1.1 <u>The Hierarchy</u>

The AHP decomposes the factors of a complex decision problem into groups according to properties they have in common and arranges these groups in a hierarchical fashion. Each level of the hierarchy consists of a manageable number of elements (Saaty suggests a maximum of nine, but this is not a necessary condition), which again are decomposed into another set of elements at the next lower level. The process continues from the overall objective of a problem down to specific criteria, that is, from the more general (and sometimes more uncertain) to the more particular and definite. The bottom level of a hierarchy usually contains the alternatives from which the choice is to be made.

Following Gass's example, the objective "best new car" appears in level 1 of the hierarchy in figure 1. The next lower level lists factors contributing to the objective, e.g., price, running costs, comfort, and status. These in turn serve as criteria for selecting the car alternatives A, B, or C which are represented in the lowermost level.

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[5] See "Selected References" for other titles on the Analytic Hierarchy Process.

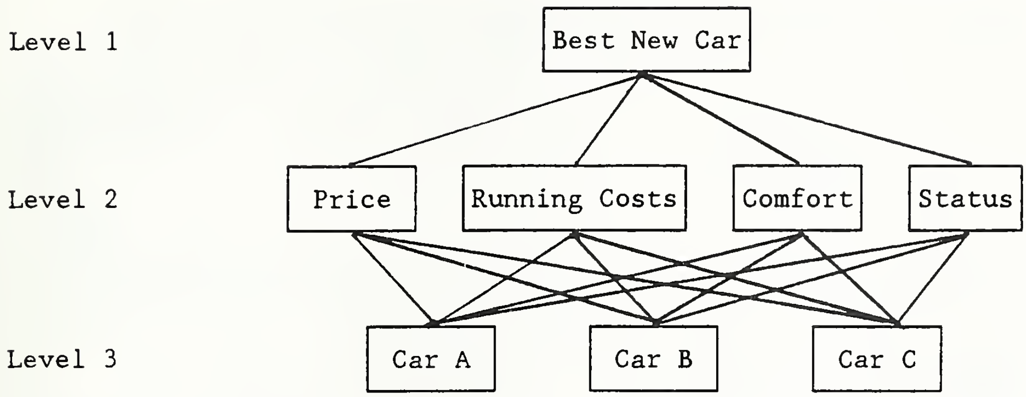

Figure 1. Three-level hierarchy for car problem.

For more complex decision problems, the hierarchy may have more levels and a greater number of criteria. And even though a hierarchy has a vertical stratification, it need not be complete, that is, an element at a higher level need not function as a criterion for all the elements in the lower level. The hierarchy can be partitioned into subhierarchies sharing only a common topmost element.

Saaty's use of the hierarchical structure is based on the precept that hierarchical classification is a natural method of the human mind to order experience, observation, and information. A hierarchy, through the interaction of the various levels, makes it easier to understand how a decision affects the overall objective at the highest level; the effect of a multitude of unordered factors is much more difficult to grasp.

Like the structuring of a problem by any other method, the design of an analytic hierarchy requires the input of individuals knowledgeable about the problem in question. What factors are relevant, how they should be grouped, and in what levels, are issues to be resolved. A relatively simple problem, such as a car purchase, may require only the input of the direct decision-maker who uses readily available sources of information. A more complex problem may require a decision-maker's consultation with experts familiar with the problem. If there are several parties involved but only a single decision-maker, the decision-maker may consult with the other parties and reflect their preferences when applying the model. If there are several decision-makers, each one of them may apply the AHP to rank the alternative solutions; these rankings can then be consolidated by taking simple or weighted averages.

2.1.2 The Pairwise Comparisons

The importance or preference of one element over another at a given level is determined by a procedure of paired comparisons. At all levels of the hierarchy each pair of criteria is compared with respect to each element in the level above to which they both contribute. For example, car A is compared with B with respect to price, running costs, comfort, and status. The decision-maker can also assign weights directly to the elements of a level. For example, instead of assigning pairwise weights, a potential car buyer could directly assign weights to price and running costs of a car. However, proponents of the AHP argue that when there are more than a few criteria, it becomes too abstract and inaccurate to assign weights directly. Pairwise comparisons, on the other hand, allow the decision-maker to reveal her preference by comparing two elements at a time.

In addition to determining the preference of one element over another, the decision-maker has the option of expressing the intensity of her preference. As shown in table 1, verbal evaluations ranging from "equal importance" to "absolute importance" translate into numerical values of 1, 3, 5, 7, or 9, with 2, 4, 6, and 8 as intermediate values between adjacent judgments.

When comparing elements in the AHP hierarchy, one needs to frame questions so they elicit the decision-maker's view of the importance (or preference) of one element versus another. For example, at level 1 of the hierarchy in figure 1, one might ask the following: "With respect to buying the best new car, price is how much more important than running costs?" A value of 2 means that the decision-maker considers the criterion of price to be moderately more important than the criterion of running costs with respect to the goal of choosing "the best new car." The reciprocal comparison of running costs and price receives a value of 1/2. When compared with itself, each element has equal importance and gets a value of 1.

It is important to ask the question in such a way that the scalar system is maintained. The smaller of two elements being compared is considered to be the unit and the larger one is assessed to be so many times more than it, using the intensity of feeling and translating it to the numerical value. But it is not necessary that the comparisons be mutually "consistent" in the strict sense of transitivity (Saaty, 1980). For example, the scale value of 9 should remain approximately three times as favorable as the scale value of 3, but if price is judged twice as important as running costs and running costs three times as important as comfort, then the final ranking is not influenced much if price is not strictly six times as important as comfort. That there is slight inconsistency in judgments is a realistic assumption to make and one that can be accommodated by the AHP.[6] Lack of consistency can have many sources, as for instance, a different frame of reference, differing opinions, stochastic elements of human response, or error (Johnson and Hihn, 1979).

Inherently, the method is not limited to a scale of 1-9, but it has been shown that there is for most people a psychological limit of at most 9 items in a simultaneous comparison (Miller, 1956). To make the elements comparable within a 1-9 scale they have to be of the same order of magnitude or close together with regard to the property on which the comparison is made. For example, when comparing prices with respect to selecting the best car, one is not likely to compare a car costing $10,000 with one costing $150,000. One could conceivably designate two values of different orders of magnitude as the

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[6] See discussion of consistency in subsection 2.2.2.

Table 1. Definitions of pairwise comparison judgments

Intensity of Importance	Definition	Explanation
1	Equal importance of both elements	Two elements contribute equally to the property
3	Moderate importance of one element over another	Experience and judgment slightly favor one element over another
5	Strong importance of one element over another	Experience and judgment strongly favor one element over another
7	Very strong importance of of one element over another	An element is strongly favored and its dominance is demonstrated in practice
9	Extreme importance of one element over another	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,& 6,8	Intermediate values between two adjacent judgments	Compromise is needed between two judgments
Reciprocals	If element i has one of the above numbers assigned to it when compared with element j, then j has the reciprocal value when compared with i.	

Source: S. I. Gass, Decision Making, Models and Algorithms (New York, NY: John Wiley & Sons, 1985), chapter. 24.

endpoints of the scale and order the remaining values proportionately in between, but it is reasonable to avoid comparing the size of a speck of dust to the size of the earth. If numbers greater than nine are needed, the elements are clustered and the clusters compared before comparing their elements.

2.1.3 Estimation of Relative Weights of Decision Elements

The solution technique of the AHP takes as inputs the values generated by the pairwise comparisons and produces as outputs the relative weights of the hierarchy elements. The weights are calculated by the eigenvector method.[7] To calculate the principal right eigenvector, the AHP needs a positive, reciprocal matrix with n rows and columns. The data from the pairwise comparisons produce such a matrix: the diagonal elements always equal one, and the lower triangle elements are the reciprocals of those in the upper triangle. Table 2 shows such a positive, reciprocal matrix for level 2 of the car hierarchy.

Table 2. Judgment matrix - Level 2

Best new car	Price	Running costs	Comfort	Status
Price	1	2	3	5
Running costs	1/2	1	5	6
Comfort	1/3	1/5	1	3
Status	1/5	1/6	1/3	1

To obtain the relative weights of the elements, the AHP normalizes the principal eigenvector and interprets it as the vector of priorities that indicates the importance of each element with respect to a criterion in the next higher level. An algorithm exists to estimate the principal eigenvector by iterative computation. For the car example, it is estimated as follows (Gass, 1985): For each row n of the matrix, take the product of the entries i in that row and denote it Π_i. Then calculate the corresponding geometric mean P_i, where $P_i = \sqrt[n]{\Pi_i}$. Normalize the P_i by calculating $P = \Sigma P_i$ and forming $p_i = P_i/P$. Each p_i is thus the ith priority or weight given to the ith criterion.

The last three columns in table 3 show the results of this approximation for the level 2 judgment matrix of the car problem. The p_i column of the matrix shows that in this case price and running costs, with priorities of 0.44 and 0.37, are the most important criteria with respect to selecting the best car. The decision-maker considers comfort, with a priority of 0.13, and status, with a priority of 0.06, much less important.

[7] The measurement theory is discussed in more detail in section 2.2.

Table 3. Judgment matrix and estimated priorities - Level 2

Best new car	Price	Running costs	Comfort	Status	Π_i	P_i	p_i
Price	1	2	3	5	30	2.34	.44
Running costs	1/2	1	5	6	15	1.97	.37
Comfort	1/3	1/5	1	3	.20	.67	.13
Status	1/5	1/6	1/3	1	.01	.32	.06
						P = 5.30	1.00

The above steps are repeated for all levels of the hierarchy. Table 4 shows the judgment matrices and the calculated priorities for level 3 of the car purchase problem. This level determines, through pairwise comparisons, which of the cars, A, B, or C, is preferred with respect to the criteria in level 2. These comparisons should be based on actual numerical data if available. For example, according to table 4, car C will be strongly preferred over car A with respect to price, if actual quotations from dealers show that car A costs about five times more than car C.

Table 4. Judgment matrices and estimated priorities - Level 3

Price	A	B	C	Π_i	P_i	p_i
A	1	1/3	1/5	.07	.41	.11
B	3	1	1/3	1.00	1.00	.26
C	5	3	1	15.00	2.44	.63
					P = 3.85	1.00

Running Costs	A	B	C	Π_i	P_i	p_i
A	1	1/5	1/2	.10	.47	.12
B	5	1	4	20.00	2.69	.68
C	2	1/4	1	.50	.79	.20
					P = 3.95	1.00

Status	A	B	C	Π_i	P_i	p_i
A	1	5	7	35.00	3.23	.71
B	1/5	1	5	1.00	1.00	.22
C	1/7	1/5	1	.03	.31	.07
					P = 4.54	1.00

Comfort	A	B	C	Π_i	P_i	p_i
A	1	3	5	15.00	2.44	.63
B	1/3	1	3	1.00	1.00	.26
C	1/5	1/3	1	.07	.41	.11
					P = 3.85	1.00

The priorities calculated from the pairwise comparisons in table 4 show that car C is preferred over the other two with respect to price (0.63), car B with respect to running costs (0.68), and car A with respect to both comfort (0.63) and status (0.71). To help decide which car to buy, however, an overall rating of the three alternatives is necessary, that is, the relative weights of the three levels have to be aggregated by computing composite priorities.

2.1.4 Aggregation of Relative Weights

All judgments are "synthesized" by factoring the influence of the preceding levels into the decision. The result is an overall priority vector for the lowest level of the hierarchy, that is, a ranking of the decision alternatives.

To get a ranking of the cars, multiply each of the level 3 priorities by the corresponding level 2 priority and sum the products. Table 5 shows the level 2 and level 3 priorities as well as the composite priorities.

Table 5. Composite priorities for car problem

Criteria		Price	Running Costs	Comfort	Status	Composite Priorities
Level 2 priorities		.44	.37	.13	.06	
Alternatives	A	.11	.12	.63	.71	.22
Level 3 priorities	B	.26	.68	.26	.22	.41
	C	.63	.20	.11	.07	.37

The composite priority of car A is calculated as follows: $0.44(0.11) + 0.37(0.12) + 0.13(0.63) + 0.06(0.71) = 0.22$; the composite priorities for cars B and C, calculated in like manner, are 0.41 and 0.37 respectively. Car B ranks highest, and car C follows closely. Car A has the lowest priority.

If there are more than three levels in the hierarchy, the various priority vectors are combined into priority matrices which yield one final priority vector for the bottom level.

2.2 Theoretical Basis of the Eigenvalue Method

2.2.1 Relationship between Eigenvalues and Priorities

There are many methods for assigning weights to judgments and calculating the associated priorities for different alternatives. Some involve a simple weighting of criteria, such as the pairwise comparisons of the AHP, others involve more complex weighting methods such as predictability, correlation, or variance. Using graph theory, Saaty has shown that with a reciprocal, positive matrix, the eigenvector method produces estimates of priorities that correctly indicate the relative importance of each alternative with respect to the others (Gass, 1985). The judgment matrix of the AHP is such a matrix. The theoretical foundation for the eigenvector method of the AHP is explained in detail in Saaty (1982) and Harker and Vargas (1984). In general, if A is an n x n matrix, then a non-zero vector b is called an eigenvector of A if Ab is a scalar multiple of b, that is,

$$Ab = \lambda b.$$

The scalar λ is called an eigenvalue of A, and b is an eigenvector corresponding to λ. For practical applications usually only the eigenvector corresponding to the largest eigenvalue is needed. The AHP, for instance, calculates priorities by normalizing the elements of the eigenvector associated with the largest eigenvalue of the judgment matrix.

2.2.2 Consistency

The relationship between the pairwise comparison ratios and the priorities is mathematically exact if the judgment matrix is a consistent matrix. For example, if the decision-maker says that car A is twice as comfortable as car B and car B three times as comfortable as car C, she will also have to say that car A is six times more comfortable than car C to be truly consistent. In situations where many factors have to be compared and where some of the judgments are subjective, it is more realistic to allow for some inconsistency. It has been shown (Saaty, 1982, ch. 7) that small deviations from consistent judgments do not change the priorities by much; information coming from all pairwise comparison values contributes to the calculation of the priorities. In case of a reciprocal matrix, small changes in some values will be offset by changes in other values because there are redundant judgments. Large inconsistencies, however, may reverse the ranking of decision alternatives. The AHP therefore includes a measure of the departure from consistency, called the consistency ratio (CR). The CR is calculated for each matrix at each level and then aggregated to provide a consistency measure for the entire hierarchy.

The CR is based on the magnitude of the largest eigenvalue of the matrix. The largest eigenvalue of a consistent, reciprocal matrix is equal to n, the number of rows and columns in the matrix; the eigenvalue of an inconsistent matrix is larger than n. The deviation from consistency can be represented by the consistency index CI = $(\lambda_{max}-n)/d.f.$, that is, the difference between the largest eigenvalue of an inconsistent matrix and the largest eigenvalue of a consistent matrix. The CI of the matrix is then compared to the RI, an index calculated from a randomly generated reciprocal matrix of the same size and scale. The CR, the measure of inconsistency, is arrived at as follows: CR = CI/RI. A CR of 0.10 or less is considered acceptable. If it is higher than 0.10, it is advisable to reexamine the judgments to eliminate the most obvious inconsistencies (Saaty, 1980).

λ_{max} can be approximated by multiplying the column sums of the judgment matrix by the corresponding priorities and adding the products, i.e.,

$$\lambda_{max} = p_1 \Sigma a_{i1} + p_2 \Sigma a_{i2} + \ldots + p_n \Sigma a_{in}$$

To illustrate how the consistency ratio is calculated, we use the level 2 judgment matrix of the car purchase example (Gass, 1985). The relevant figures are shown in table 6.

$$\lambda_{max} = 0.44(2.03) + 0.37(3.37) + 0.13(9.33) + 0.06(15.0) = 4.25.$$
$$\text{CI} = (4.25-4)/(4-1) = 0.08.$$

Dividing the CI by the RI, the random index (which is 0.90 for a matrix of size n = 4 (Gass, 1985)), determines how good the result is.

CR = 0.08/0.90 = 0.09

This is less than 0.10 and therefore within the acceptable range.

Table 6. Consistency ratios for judgment matrix

Best new car	Price	Running costs	Comfort	Status	Priorities
Price	1	2	3	5	.44
Running costs	1/2	1	5	6	.37
Comfort	1/3	1/5	1	3	.13
Status	1/5	1/6	1/3	1	.06
Column Sums	2.03	3.37	9.33	15.0	CR = .09

2.3 Critique of the AHP

A number of books and articles explain the theory and applications of the AHP. Three major books are <u>The Analytic Hierarchy Process</u> (Saaty, 1980), Decision Making for Leaders (Saaty, 1982), and The Logic of Priorities (Saaty and Vargas, 1982). Numerous articles in the management science and operations research literature (see references further below in this section) discuss theory, applications, advantages and shortcomings of the AHP. The method has been used in applications as diverse as energy policy formulation, marketing, accounting and auditing, subjective probability estimation, evaluation of expert systems, and selection of microcomputers.

These applications seem unrelated, but they share a set of common features. All cases involve a rating of decision alternatives for evaluation, selection or prediction. In all cases qualitative elements as well as quantitative elements play a role in the decision problem. It is this feature of integrating quantitative and qualitative criteria in the analysis which makes the AHP potentially useful for ranking fire protection systems.

Even though the AHP has been used to analyze successfully a number of decision problems, it is not without its critics. There are three major criticisms: Belton and Gear (1983, 1985) and Dyer and Wendell (1985) claim that it lacks a firm theoretical basis and therefore is not precise enough for analyzing decisions. The second criticism concerns the scale used to measure the intensity of preferences. The range of 1-9 is considered too narrow for some applications. Thirdly, the requirement of the AHP to explicitly state and incorporate subjective judgments is rejected by some members of the operations research and management science communities, who are reluctant to adopt a method that does not claim to be purely "objective." (Harker and Vargas, 1985).

Counterarguments to these criticisms are summarized as follows:

In a defense of the theoretical basis of the AHP, Harker and Vargas (1985) expand on Saaty's work on the eigenvector approach, develop an axiomatic foundation for the AHP, and introduce the notion of a feedback system into the simple hierarchy. They claim to show that if a matrix is inconsistent, the eigenvector approach is the only method to calculate correctly the weights for each judgment matrix; the axiomatic foundation exists and is based on the concepts of the set of criteria, the binary relation of the pairwise comparisons, and the scale of measurement; the introduction of "feedback" between criteria and alternatives into the hierarchy relaxes the assumption that the weights of the criteria are independent of the alternatives; thus the AHP, they claim, can accommodate decision problems of any complexity, and the hierarchy becomes a special case of a more general structure.

With respect to the criticism regarding the scale of measurement, Harker and Vargas claim that due to the work of Stevens (1957), Stevens and Galanter (1964), and Krantz (1972), the ratio scale resulting from the pairwise comparisons is recognized as a legitimate way of measuring the relative intensity of stimuli. Focusing on the limitations imposed by the upper limit 9, they argue as follows:

The mathematical structure of the AHP can deal with the notion of infinite preference for an alternative when compared with another alternative, but it is difficult for individuals to deal effectively with notions of infinity.

Saaty developed the 1-9 scale empirically and by appeal to Miller's "The Magical Number Seven Plus or Minus Two" (1952). His comparisons with other scales support the view that the 1-9 scale can accurately capture an individual's intensity of preference. The judgments obtained by the AHP contain redundant information since the AHP requires the individual to make n(n-1)/2 comparisons (versus (n-1) comparisons if consistency were enforced) so that even if any one judgment is inconsistent because of the 1-9 scale, the final weights are not substantially different.

Regarding the reservation about the inclusion of subjective judgments, Harker and Vargas suggest that the AHP represents indeed a radical departure from more traditional decision-making tools. They claim, however, that recent trends in the philosophy of science (Kuhn, 1962; Bunge, 1983; Rescher, 1984) support the view that subjectivity plays a role in scientific analysis and that there is a linkage between scientific methods, cognition, and beliefs. Harker and Vargas do not discuss further whether subjectivity should be incorporated into analyses of any kind but restrict their arguments to supporting the view that the AHP is a valid and acceptable method of eliciting and analyzing subjective judgments.

As to the problem of whether the AHP comprises the proper methodology to elicit unambiguous judgments, Harker and Vargas (1985) draw attention to the fact that all preference-eliciting methods have to deal with the problem of ambiguity. They cite research that shows that in assessing, for instance, multi-attribute utility functions, the responses depend to a large extent on the frame of reference. Harker and Vargas say that "... excessive ambiguity not explicable within the frame of reference is not a failure of the method being used but rather a failure of the analyst or decision maker to fully comprehend the issue at hand and state questions which meaningfully address it."

As far as the analysis of subjective judgments is concerned, Harker and Vargas refer the critics to Saaty's theoretical exposition of the eigenvector method and to their development of the relevant axioms. Their work, they claim, shows that the method correctly calculates the priorities for any number of planned alternatives.

The AHP has been tested in a number of studies involving verifiable outcomes or comparisons with other methods. In one study, which compared five different approaches to determining the weights for additive utility functions (Shoemaker and Waid, 1982), the AHP was found to perform well with respect to weight determination, perceived ease of application and trustworthiness, and only slightly less well than the other methods with respect to predictive ability. (The four other methods were multiple regression, direct tradeoffs, point allocations, and unit weighting.) In some other experiments, the AHP accurately reproduced available real measurements. For example, in one validation experiment, four chairs were arranged in a straight line from a light source, and the pairwise judgments of the relative brightness resulted in numbers that were very close to those calculated by the inverse square law of brightness as a function of distance (Forman, 1983).

Saaty and his colleagues do not insist that the AHP is the only valid method to analyze decision problems or that it is applicable to all problems. But, after taking its assumptions and limitations into account, they offer it as one among several aids to decision-making for problems that include qualitative or intuitive judgments or are too unstructured for traditional techniques.

3. THE AHP APPLIED TO FIRE PROTECTION INVESTMENT DECISIONS

3.1 Defining the Case Studies

It is assumed that homeowners, in deciding whether or not to install a fire protection device--a sprinkler system, for example--try to get the most for their money. In economic parlance they "maximize the expected utility obtainable from available funds." Ruegg/Fuller calculated expected benefits and costs of a sprinkler system and of a combination of smoke detectors and sprinklers for a hypothetical homeowner. They based their calculations on estimates for a typical new one-family house, average family size, and average probabilities of fire, death, injury, and property loss. The individual homeowner was assumed to be risk neutral, meaning that the threat of a loss has exactly the same weight in the homeowner's decision as the possibility of an equivalent gain. (To a risk-averse decision-maker, the threat of a loss would have greater weight than the possibility of an equivalent gain, and the opposite is considered true of a risk-taking decision-maker.)

The use of average values served the purpose of evaluating the cost-effectiveness of sprinkler systems on the average. But it did not address the situation of individual homeowners who are subject to higher- or lower-than-average risk exposure. The assumption of a risk-neutral attitude also constituted a limitation of the model in that homeowners exhibit varying degrees of risk preference; they tend to be risk-averse, as indicated by their purchase of insurance against events with very low probabilities. To make sound investment decisions about fire protection equipment, homeowners need a decision model that reflects their individual risk exposure and risk attitude.

In theory it is possible to develop probability functions to measure individual risk exposure and to develop utility functions to measure individual risk attitude. But these conventional methods are often of little practical use; the functions are difficult to assess and cumbersome to use for calculations. Data to develop functional relationships between risk exposure and housing and homeowner characteristics are insufficient. Often these methods assume away inconsistencies resulting from imperfect information or lack of rationality on the part of decision-makers, and do not do justice to the way people respond when subjected to choices involving dread and fear, or to choices involving events with low probabilities but high consequences.

For the problem at hand, therefore, the Analytic Hierarchy Process (AHP) is of keen interest. The AHP is a multi-attribute decision method that accommodates the above concerns by including in the analysis non-quantitative information elicited directly from each individual decision-maker.

At the exploratory stage described in this report, the AHP is applied to two hypothetical test cases, one in which the homeowner is assumed to have lower-than-average exposure to fire-related risks and a risk-taking attitude (Homeowner I), and another in which the homeowner is assumed to have higher-than-average exposure and a risk-averse attitude (Homeowner II).
The application demonstrates how the homeowner implicitly expresses his risk attitude by judging the relative importance to him of criteria such as life

safety, property loss, system price, future costs, or aesthetics. The homeowner evaluates his risk exposure in relation to the average risk exposure given by U.S. fire statistics. Data generated by the decision-maker's evaluations enter into calculation of priorities that determine the relative rankings of alternative fire protection systems considered for purchase and installation.

The remainder of section 3 discusses the data and assumptions for the case studies, defines criteria, subcriteria, and decision alternatives and shows how they are structured into a hierarchy. It then goes step-by-step through the pairwise comparisons for the two hypothetical homeowners and demonstrates how the AHP is capable of taking into account differences in risk exposure and risk attitude as they relate to decisions on fire protection.

3.2 Data and Assumptions

The AHP assumes that the decision-maker is an "expert" in the field and that the numerical and qualitative information he has available will cause his judgments to reflect objective facts. But a potential homeowner visiting a builder's office is unlikely to be an expert in fire prevention and may not even be aware of the risks he faces. To take an extreme example, a homeowner may have the habit of smoking in bed while intoxicated and may live on an upper floor of a house with poor egress but nevertheless believe that he has a lower-than-average fire risk. To make a good decision, this person has to bring his belief closer to objective reality. As another example, suppose a homeowner believes that if he has sprinklers, large costs are highly likely to result from water damage caused by accidental sprinkler activation. The homeowner must be made aware that the likelihood is in fact very small. These examples show that a key question in adapting the AHP to fire protection decisions is how to make the needed information available to the decision-maker.

In the present exploratory applications, information needed to define the criteria and alternatives is taken from Ruegg/Fuller. The analyst makes the pairwise comparisons in place of actual homeowners, based on plausible assumptions about risk exposure and risk attitude.

The benefits identified in Ruegg/Fuller as crucial to economic efficiency of fire protection investment decisions were: reductions in risk of death and injury, reductions in direct and indirect property losses, benefits of insurance savings, and, under limited conditions, possible reductions in costs of community fire protection. The costs were identified as purchase and installation costs, operating and maintenance costs, replacement costs, and increased property tax. These costs and benefits were calculated as expected present values for two alternative fire protection strategies: the installation of a sprinkler system, assuming no prior fire protection device, and the addition of a sprinkler system, assuming existing smoke detectors.

To provide a point of reference for the results of the present study, data from Ruegg/Fuller--updated to 1988 values where appropriate--are used as a basis to structure the AHP hierarchy. The benefits and costs define the criteria of the hierarchy; the decision alternatives are essentially the same, namely smoke detectors alone, a sprinkler system alone, and a combination of sprinklers and smoke detectors, all assumed to be installed in a new one-family house.

The application of the AHP is of course not limited to these assumptions. In fact, it may be well suited to retrofit decisions by owners of older houses whose exposure to fire-related risks is more likely to be above the national average. It would also be more realistic, and would better exploit the AHP's potential, to have a greater number and more diverse alternatives to choose from. Other fire protection devices could be included, or combinations of fire protection devices, such as smoke detectors and fire doors, or smoke detectors and improved egress. Alternatively, sprinkler installation could be combined with cost-reducing construction changes, such as one-hour walls instead of fire-proof walls for certain parts of the house.

3.2.1 Construction of Hierarchy

Figure 2 shows the suggested hierarchy for the fire protection problem. The intention is to include in the hierarchy all factors that are relevant and significant and to dissect them to a point at which comparisons of their relative differences may reasonably be made.

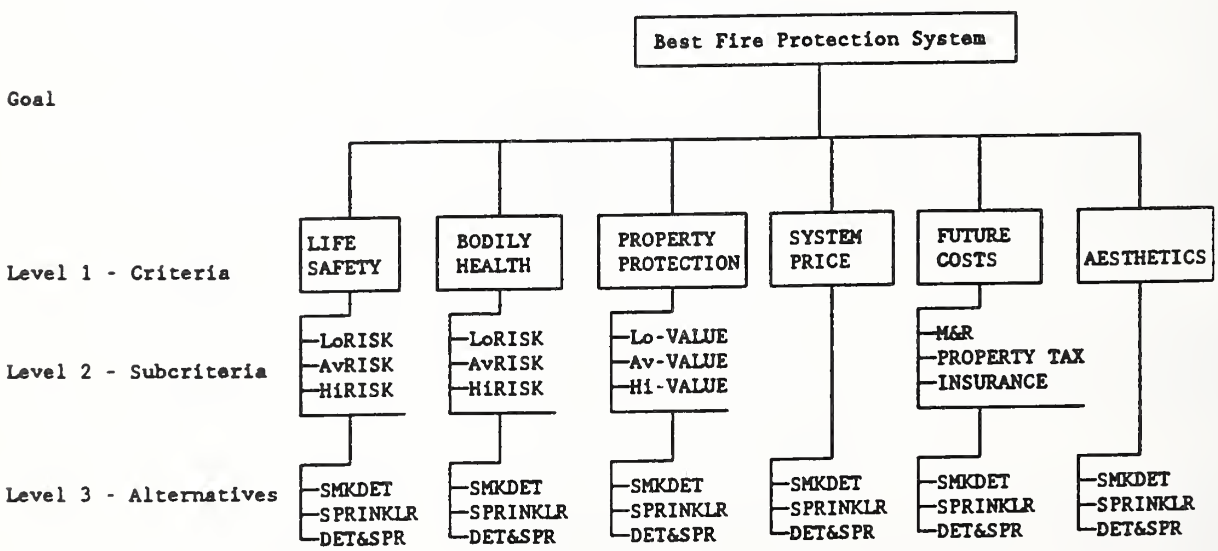

Figure 2. Hierarchy for fire protection problem.

The goal of the homeowner is to select the BEST FIRE PROTECTION SYSTEM. The best fire protection system is different for each homeowner depending on his exposure to fire-related risks of death, injury, and property loss; how much he wants to spend now and in the future for a fire protection system; how risk-averse he is; and how concerned he is about the appearance of the system in his home. The circumstances that define these aspects of the problem are captured in level 1 in the criteria LIFE SAFETY, BODILY HEALTH, PROPERTY PROTECTION, SYSTEM PRICE, FUTURE COSTS, and AESTHETICS.

Some of the criteria are broken down into subcriteria in level 2 to allow for an additional level of detail. The subcriteria LoRISK, AvRISK, and HiRISK belonging to Life Safety and Bodily Health, and LoVALUE, AvVALUE, and HiVALUE belonging to Property Protection, distinguish between lower-than-average, average, and higher-than-average risk, where "average" refers to U.S. average fire statistics. The subcriteria M&R, PROPTAX, and INSRNCE divide Future Costs into Maintenance and Replacement Costs, Property Tax, and Insurance Savings.

Level 3 contains the alternative fire protection strategies, i.e., smoke detectors (SMKDET), sprinklers (SPRINKLR), and a combination of detectors and sprinklers (DET&SPR).

Risk attitude and risk exposure are incorporated into the hierarchy as follows:

The homeowner implicitly expresses his risk attitude by giving more or less weight to the criteria in level 1 of the hierarchy. If, for example, when making pairwise comparisons with respect to choosing the best fire protection system, he judges LIFE SAFETY extremely more important than SYSTEM PRICE, he implicitly expresses a more risk-averse attitude than another homeowner who decides that SYSTEM PRICE is extremely more important to him than LIFE SAFETY. Or, as another example, it may be assumed that a homeowner who considers the FUTURE COSTS of maintaining and operating a sprinkler system moderately more important than PROPERTY PROTECTION, exhibits a somewhat more risk-taking attitude than a homeowner who gives the opposite valuation.

Risk exposure is expressed in level 2 by comparing the subcriteria with respect to their criterion in level 1. For example, when looking at the subcriteria belonging to LIFE SAFETY, the homeowner asks the question (assuming that he is aware of what constitutes average risk of fire death): Is it more likely that I have a higher-than-average, or an average, or a lower-than average risk of fire death? And how much more likely? Strongly? Extremely? or Moderately?" The AHP uses the responses to these questions, which are recorded in judgment matrices, to calculate the priorities of the criteria and to rank the alternatives.

The treatment of risk in the AHP differs from that of other decision models. In utility theory the decision-maker generally has the problem of choosing the alternative that, under the given conditions, offers the most attractive mixture of payoffs and probabilities that those payoffs will be received. His choice is a gamble. The AHP considers situations in which it is more natural to say that each alternative has a definite, fixed worth. The problem is simply one of deciding which worth is largest. This sort of decision can be called a "risk-less" choice (Saaty, 1987). In the present study both kinds of decisions are in a sense made cooperatively: The homeowner is asked to make subjective judgments regarding his risk exposure and risk aversion; these judgments are made by means of pairwise comparisons that require a decision only "on which worth is largest."

The method used in this application is one suggested way of including risk exposure and risk attitude. Other, more direct, specifications are conceivable. For example, risk exposure and risk attitude could be captured in one criterion called "RISK", as is usually done in the AHP. A more detailed treatment was chosen in this application to permit a differentiation of risk exposure and risk attitude.

3.2.2 Discussion of Criteria, Subcriteria, and Alternatives

The discussion of criteria, subcriteria, and alternatives serves several interrelated purposes: (1) to define criteria, subcriteria, and alternatives in a way that captures all relevant aspects of the decision problem; (2) to give the reader an idea of the kind of background information needed to make the pairwise comparisons; (3) to clarify in what way subjective information is relevant to making decisions about fire protection; and (4) to relate the data from Ruegg/Fuller to the application of the AHP.

The discussion of the criteria of level 1 of the hierarchy (fig. 2) focuses on the risk attitude of the decision-maker. To express his risk attitude, he weights the criteria in level 1 according to how important they are to him. Because the AHP requires an "expert" to structure the hierarchy, define the criteria, and make the judgments, the decision-maker presumably compares the criteria within the proper frame of reference. In the fire protection problem, the homeowner is assumed to have a fairly good idea of the cost of smoke detectors, sprinkler systems, their repair and maintenance costs, their impact on property taxes and insurance rates, and their performance with respect to risk reductions. He also is aware of what constitutes the average risk of exposure to fire, death, injury, and property loss, and he knows the values of his real property. Consequently, he compares, for example, LIFE SAFETY and AESTHETICS not in an absolute sense but with respect to choosing the best fire protection strategy. When he considers LIFE SAFETY he thinks in terms of a small reduction in the risk of dying in a fire, and when he considers AESTHETICS, he can visualize smoke detectors or sprinklers in the ceilings of his home.

The discussion of the subcriteria of level 2 defines low, high, or average exposure to risks of fire and death, injury, and property loss. In level 2 the homeowner makes a qualitative judgment on the likelihood of his household's having average, high or low exposure to fire-related risks. Because he is informed about fire statistics, he can compare his own household's risk exposure with that of the average household and weight it accordingly. The other subcriteria in level 2, which comprise the future costs and savings of alternative fire protection devices, are weighted based on the numerical estimates of Ruegg/Fuller.

The decision alternatives of level 3 are discussed in terms of how their characteristics relate to the criteria and subcriteria in the levels above. In level 3 the homeowner compares smoke detectors, the sprinkler system and the detector/sprinkler combination pairwise with each other based on what impact they have on fire-related risks, purchase and installation costs, future costs, and aesthetics. These impacts have been estimated numerically in Ruegg/Fuller for all alternatives, except for the impacts on AESTHETICS for which the homeowner makes qualitative judgments.

The information considered relevant to a decision on the economic efficiency of fire protection strategies is presented and discussed below under headings corresponding to the structure of the hierarchy:

Criterion - Level 1

LIFE SAFETY

Considerable controversy surrounds the question of whether or how to assign a dollar value to a life saved. Should its value be measured in terms of the input lost when a person dies or in terms of the output of remaining life-years had he lived? Should the value of life reflect differences in age, health, attitude, family situation, income, and so on? What is a life worth to society and what is it worth to a person? Can or should life-years be discounted or not? What amount of money would a person sacrifice to avoid the risk of death? Is there an amount of money a person would accept to give up his life, or is life priceless to him? Does his willingness to purchase goods and services that improve life safety indicate the value he places on his life? These and many other questions have been asked and no unanimous answers have emerged.

For the problem at hand it is the value a person attaches to his own life that is relevant. Though it may well be that to an individual life is priceless--no one would give up his life for any amount of money--many people accept probabilistic risks to life in exchange for dollars. For example, some people willingly work in a dangerous environment in return for a higher wage. Conversely, they are willing to pay just so much to reduce a risk, and the amount is different for each person. For example, one person pays more for automatic safety features, while another, with equal wealth, passes them up. Because people differ in their preferences for the level of risk they tolerate, they differ in the values they ascribe to reductions in risk.

Moreover, experiments with hypothetical questions have shown that individuals' choices change when the frame of reference changes (Kahneman & Tversky, 1982). For example, choices in response to questions about fire prevention may yield different risk preferences than choices in response to questions about hypothetical gambling gains and losses. People have been shown to be more risk-averse if their choices take account of concern for others (presumably mainly the safety of family and friends) (Jones-Lee, Hammerton, and Philips, 1985). They tend to be more risk-taking when the risk is voluntary rather than involuntary. For example, a person who chooses to be a scubadiver or skydiver may nevertheless demand a comparatively low risk exposure to a nuclear power plant near his home. Choices also differ depending on the initial level of risk, and they differ with time (Bodily, 1980). In short, circumstances influence valuations.

An important feature of the AHP is that it makes it possible to circumvent the difficulty of explicitly assigning a value to life. It has the capability to elicit "strength-of-feeling" information from the homeowner individually and to integrate quantitative and non-quantitative inputs. No dollar value need be assigned to the criterion of LIFE SAFETY.[8] Instead, the homeowner makes a subjective valuation of life safety--strictly speaking, of a small reduction in the risk of losing one's life in a fire--in relation to the other criteria with which it is compared.

To put a reduction in the risk of fire and death in the proper perspective, the following fire statistics are quoted:

Based on 1981 fire data, the average probability of fire for one- and two-family houses in the U.S. is between 8 and 9 in 1,000; the average risk of death per fire is about 8 in 1,000 assuming neither smoke detectors nor sprinklers; the joint probability of fire and death is thus about 7 per 100,000 houses (0.00856 x 0.00821 = 0.0000703). These fire death rates have been hovering around this number for the last several years.[9]

<u>Subcriteria</u> - Level 2

LoRISK - Lower-than-average Risk of Fire and Death
AvRISK - Average Risk of Fire and Death
HiRISK - Higher-than-average Risk of Fire and Death

Fire statistics do not relate fire frequency to either age of house or structural characteristics. Neither do they take into account household characteristics such as size, age, or state of health.[10] These differences are however associated with different risk exposures and bear on fire

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[8] In the base case of Ruegg/Fuller (1984) a value of life of $500,000 was assumed for calculating expected benefits of a risk reduction. This figure was adopted from the NBS/SRI Fire Loss Model. It was derived from a "willingness-to-pay" approach described in Graham and Vaupel, 1981.

[9] The fire loss data were taken from <u>Fire in the United States</u> (1982), and from 1987 reports to the National Fire Protection Association as quoted in Karter (1988)).

[10] The average U.S. household has 2.64 persons, 0.70 under age 18 (Census 1988). The median one-family house has 6.0 rooms, slightly more than half have 3.0 bedrooms (Census 1980).

protection decisions. The AHP allows the homeowner, when he compares the subcriteria with respect to LIFE SAFETY, to weight his own perceived level of risk to life safety relative to the national average. For example, a homeowner who has small children or an elderly, bed-ridden relative living in his household will probably conclude that his family's risk of fire death or injury is higher than average. Or, a homeowner whose household consists of two grown-ups who do not smoke or drink and who live in a ranch-style house with easy egress will probably judge his risk exposure to be lower than the national average.

When adapting the AHP to an actual application, it may be kept in mind that individuals find it difficult to process information on probabilities, especially when the probabilities are small or when it comes to risks and hazards with which they have had limited experience (Kahneman & Tversky, 1982). Therefore, it may be preferable to present information on risks in a form other than probabilities, perhaps as percentages or as comparisons with other, more familiar risks, such as risk of dying in a car accident or dying of cancer. Additional research is needed to determine the most suitable way of stating the information to the homeowner. In the present study the average risk is known to the analyst who then judges risk exposure as relatively lower or higher, depending on whether it is Homeowner I or Homeowner II that is assumed to be the decision-maker.

<u>Alternatives</u> - Level 3

The rates of reduction in the combined risk of fire and death attributable to smoke detectors and sprinklers were developed by the NBS/SRI Fire Loss Model (Gomberg et al., 1982) based on U.S fire data, expert judgment, and extrapolation from results of laboratory and field tests. The reductions are stated in percentages. The base assumes that no fire protection device is present, that is, no sprinklers and no smoke detectors.

<u>Estimated reductions in combined risk of fire and death</u>

SMKDET - Smoke Detectors alone	52%
SPRINKLR - Sprinkler System alone	69%
DET&SPR - Smoke Detectors and Sprinklers combined	82%

In the pairwise comparisons of level 3, these figures are used to calculate the relative effectiveness of the fire protection devices in reducing the risk of fire and death. The resulting ratios are entered directly into the judgment matrix.

The alternative fire protection strategies have been limited to smoke detectors, a sprinkler system, and a combination of the two in order to maintain the results of Ruegg/Fuller as a point of departure. Of course, smoke detectors are usually mandated. Also, sprinkler systems are seldom installed without smoke detectors. However, there are special cases in which a smoke detector is not effective because a building is either unoccupied or the occupants are unable to respond. The three alternatives demonstrate the capabilities of the AHP decision-making process. An actual application may include additional fire protection alternatives.

Criterion - Level 1

BODILY HEALTH

In many analyses the value of a life saved and the value of an injury averted are treated similarly or even together from the point of view of risk reduction. But in this analysis a separate criterion, BODILY HEALTH, is included to designate injuries averted. There are degrees of seriousness of injury, and people's attitudes to risk of injury differ depending on whether they consider a serious injury better or worse than, or equal to death. In a survey done in England (reported in Jones-Lee, Hammerton, and Philips, 1985) 30% of the people questioned considered worse than death the fate of being permanently bedridden, and 24% considered worse than death the fate of being confined to a wheelchair for the rest of one's life.

Assigning a dollar value to an injury averted is subject to similar problems as assigning a dollar value to a life saved.[11] The AHP allows the individual decision-maker to express his preferences, and the intensity of his preferences, with respect to fire-related injuries, relative to the other criteria in the hierarchy. If, for example, someone had survived a fire in which he was injured or knew someone who was, he might have stronger feelings about avoiding injuries than about avoiding death. The additional information can be taken into account in the AHP and will result in a decision more consistent with an individual's total system of beliefs than if it is ignored.

The relevant fire statistics are quoted as follows: According to 1981 data, the joint probability of a fire occurring and of someone getting hurt in a one- or two family house was 2.2 per 10,000 houses (= 13,851 injuries in 522,175 fires occurring in a housing stock of 61 million one- and two-family dwellings). In 1987, 433,000 fires took place in one and two-family houses and there were 15,200 injuries, an increase from 1981. It is important to note that estimates of injuries are on the low side because injuries occurring at smaller fires, to which fire departments do not respond, are not recorded.

Subcriteria - Level 2

LoRISK - Lower-than-average Risk of Fire and Injury
AvRISK - Average Risk of Fire and Injury
HiRISK - Higher-than-average Risk of Fire and Injury

The fire statistics are again average values which might not reflect any one homeowner's exposure to the combined risk of fire and injury, but they do

[11] Ruegg/Fuller (1984) assumed an average value of $20,000 for an injury averted.

serve as background information to facilitate the homeowner's judgment as to whether his own household's risk of injury in case of a fire is likely to be lower or higher.

Alternatives - Level 3

As with the reductions in the combined risk of fire and death, the percentage reductions in combined risk of fire and injury, attributable to the alternative fire protection systems, are based on the simulation data of the NBS/SRI Fire Loss Model. They are used to express the relative effectiveness of the fire protection alternatives in reducing the risk of fire injuries.

Estimated reductions in combined risk of fire and injury

SMKDET - Smoke Detectors alone	5%
SPRINKLR - Sprinkler System alone	46%
DET&SPR - Smoke Detectors and Sprinklers combined	46%

Smoke detectors alone improve the risk of fire-related injuries only slightly, whereas sprinkler systems have a marked effect. The percentage reductions in the risk of fire and injury are again derived from simulated test data from the NBS/SRI Fire Loss Model.

Criterion - Level 1

PROPERTY PROTECTION

When looking at property protection, a homeowner should keep in mind that there are both quantifiable and non-quantifiable losses involved should he suffer a serious fire. He might lose his real property, that is, his house and his material possessions. Indirect costs may be significant also. He may incur expenses for medical bills, psychiatric counseling, missed work, temporary shelter, legal fees, extra food and transportation, child care, or funeral costs. Part of these expenses are usually reimbursed by his insurance company. But no amount of insurance payment for property loss may compensate him for the emotional cost of having experienced a serious fire or of having lost an heirloom or his family's personal possessions of sentimental value.

When making judgments about the importance of property protection relative to other criteria, the homeowner will want to take into account these non-quantifiable considerations as well as the dollar value of direct and indirect property losses that he might suffer in case of a fire. The relevant statistics on property values and property losses are as follows: The median sales price of a new single-family house in the U.S. is reported as $118,800 (July 1988) by the Census Bureau. As a rule, insurance companies value the contents at 75% of the home's replacement value. Hence, the median value of the furnishings and personal property contained in a home can be estimated at about \$89,000. Summing the two brings the estimated total median value of direct property to be protected to about \$208,000.

Following an upward trend since 1978, the average direct property loss from fires in one- and two-family houses has increased from about \$1.8 billion in 1981 to about 3 billion in 1987. This means that, in current dollars, property loss per fire in a one- or two-family house more than doubled, from about \$3,400 to about \$7,000 (\$1.855 billion in property loss in 552,175 fires = \$3,360 per fire in 1981; \$3.078 billion in 433,000 fires = \$7,108 per fire in 1987). National fire statistics do not include indirect property losses.

Subcriteria - Level 2

LoVALUE - Low property value
MdVALUE - Median property value
HiVALUE - High Property Value

When looking at the subcriteria of PROPERTY PROTECTION, an individual homebuyer can compare the market value of his home with the median and enter the proper judgment. If he owns a valuable art collection or antique furniture, he can take this circumstance into account by varying the intensity of his statement. For example, a homeowner with a valuable heirloom in his \$500,000 home may make the judgment that his direct property value is "strongly" more likely of higher value than that of the average homeowner.

Alternatives - Level 3

Again, the impact of sprinkler systems on the reduction of direct property losses is considerably higher than that of smoke detectors alone. property The same percentage reductions are assumed for direct and indirect property losses.

Estimated average reductions in property losses per fire

SMKDET - Smoke Detectors alone	22%
SPRINKLR - Sprinkler System alone	70%
DET&SPR - Smoke Detectors and Sprinklers combined	70%

As in the cases of risks of death and injury, estimated property loss reductions are entered directly as ratios in the judgment matrices to express the relative impact of the fire protection devices.

Criterion - Level 1

SYSTEM PRICE

System price is compared with the other criteria in level 1 to express risk attitude. A homeowner will--depending on how highly he values a reduction in fire-related risks--assign a relatively smaller or greater weight to SYSTEM PRICE. As with the pairwise comparisons of other criteria, his evaluation depends on purchase and installation costs but also on average fire-related risks, past experiences, personal circumstances, and on how the questions are framed.[12] With respect to system price, the framing effect may be especially relevant: The cost of a sprinkler system is considered rather high when looked at independently or as a retrofit to an existing house. But if the purchase of the system is made at the same time as the purchase of a new home, it is treated as an increment over the price of the house and may cause little distress. So, if the cost of the fire protection systems is placed in the larger account of a home mortgage, the attractiveness of a reduction in fire-related risks may be greater.

When going through the process of pairwise comparisons, the homeowner knows that the cost of smoke detectors is negligible compared with that of a sprinkler system. He takes this into account when he weights system price relative to the other criteria to express his risk attitude.

Alternatives - Level 3

Purchase and installation costs for sprinkler systems were estimated in Ruegg/Fuller. The costs for 1/2" polybutylene pipe, including financing (as part of a mortgage) over 30 years and income tax effects, are listed below. The base-case price ignores additional costs that may arise in some cases if municipalities have special requirements for sprinklered houses, such as larger water mains, backflow prevention valves, or monthly water standby charges.

The price of smoke detectors is the average of several price quotations obtained from retailers in Maryland, and the price for the combination of smoke detectors and sprinklers is the sum of the two.

Net present values of purchase and installation costs

SMKDET - Smoke Detectors (four per house)	$80
SPRINKLR - Sprinkler System (21 sprinkler heads)	$1,800
DET&SPR - Smoke Detectors & Sprinklers	$1,880

[12] For an in-depth treatment of the psychology of choice, see Kahneman and Tversky (1982); and Tversky and Kahneman (1974, 1981).

When comparing systems on the basis of their prices, it becomes obvious that the prices do not fit into a scale of 1-9 as theoretically required by the AHP. The discrepancy is not too serious, however, if the lowest and the highest number are looked at as the boundaries, that is, one as "extremely more preferable" than the other. The AHP takes the two extremes, when expressed verbally, and calculates proportionate priorities for the in-between values. In this application this is the interpretation chosen.

It may not even be desirable to enter the exact numerical values, if one looks at system prices from a "utility" point of view. An amount of 1,800 may be perceived as less than 22.5 times 80 if considered as part of a $100,000 mortgage. In other words, a monetary value of twice the amount does not mean that one criterion receives exactly twice the weight of the other as would be the case in an expected-value calculation.

<u>Criterion</u> - Level 1

FUTURE COSTS

Much of what was discussed under the criterion of SYSTEM PRICE is also relevant to FUTURE COSTS. Decision-makers compare the importance of future costs with that of other criteria, implicitly expressing their risk attitudes. Future costs of sprinkler systems loom large in many people's minds because of fear that sprinklers may accidentally activate and cause extensive water damage, or that pipes may leak, or that water damage from sprinklers may be extensive when there is a fire. These perceptions are not substantiated in practice by the performance of commercial sprinkler systems. Accidental activation is very rare--only one per year for each 3 million sprinklers--and is usually limited to one sprinkler head. The pipe system performs as well as or better than that for a building's non-sprinkler water supply. Water damage from conventional fire fighting is usually much larger than that caused by sprinklers because fires tend to grow larger in the absence of sprinklers (Jensen & Associates, 1977). The homeowner is assumed to be aware of these facts. He also knows that future costs range from about $200 for smoke detectors to about $900 for sprinklers, and that insurance savings may range from zero to about $700.

<u>Subcriterion</u> - Level 2

M&R - Maintenance and Replacement Costs

In level 2 the homeowner weights the relative importance of maintenance and replacement costs relative to other future costs associated with the three fire protection alternatives. In Ruegg/Fuller operating costs for sprinklers, such as water costs, water damage costs, and electricity costs for pumps were estimated to be trivial amounts on average; so they were omitted from the analysis. Estimates of maintenance, repair, and replacement costs assumed that an annual maintenance program precludes other repairs. Replacement costs were based on a schedule that replaces one half of the sprinkler heads over the life of the system. The maintenance and replacement costs of the four smoke detectors were calculated for a change of batteries every year and a replacement of each smoke detector once over 30 years.

Net present values of maintenance and replacement costs

SMKDET	- Smoke Detectors (four per house)	$170
SPRINKLR	- Sprinkler System (21 sprinkler heads)	$480
DET&SPR	- Smoke Detectors & Sprinklers	$650

Alternatives - Level 3

The pairwise comparisons of level 3 determine the preference of one fire protection system over another with respect to maintenance and replacement costs.

Subcriterion - Level 2

PROPTAX - Property Tax Increase

The installation of a sprinkler system may increase property taxes because it is a capital-intensive investment and may raise the tax assessment basis of the home. On the other hand, property tax increases on sprinkler systems may be waived by the municipality if the installation of sprinklers reduces the need for additional fire fighting equipment, personnel, or the need for additional fire stations. A property tax waiver would only become possible, however, if a large number of homeowners chose to install sprinkler systems. The installation of smoke detectors would leave a home's tax assessment unchanged.

The estimated property tax increase for a sprinkler system using 1/2" polybutylene pipe is based on an effective property tax rate of 2.15% (averaged across 30 cities and held constant over 30 years) and a straight-line obsolescence rate.

Net present values of property tax increase

SMKDET	- Smoke Detectors	$0
SPRINKLR	- Sprinkler System (21 sprinkler heads)	$230
DET&SPR	- Smoke Detectors & Sprinklers	$230

Alternatives - Level 3

The pairwise comparisons of level 3 determine the preference of one fire protection system over another with respect to property tax increase.

Subcriterion - Level 2

INS - Insurance Cost Savings

Ruegg/Fuller included savings in homeowner insurance premiums as a benefit of sprinkler systems and smoke detectors. A 2% reduction for smoke detectors and an additional 13% for sprinklers was recommended by an ad hoc Insurance Committee on Residential Sprinklers in 1980. In the meantime, insurance companies generally reduce premiums for homes equipped with smoke detectors, and a few have begun to reduce premiums also for sprinklered homes.

Under the assumptions of Ruegg/Fuller, the present value reductions over 30 years in insurance premiums covering structure and contents of a one-family home of average purchasing price are as follows:[13]

Net present values of insurance premium reductions

SMKDET - Smoke Detectors (2 percent)	$90
SPRINKLR - Sprinkler System (13 percent)	$577
DET&SPR - Smoke Detectors & Sprinklers (15 percent)	$665

Alternatives - Level 3

The pairwise comparisons of level 3 determine the preference of one fire protection system over another with respect to insurance savings.

Criterion - Level 1

AESTHETICS

Some people find residential sprinklers unattractive, even though they are specially designed to be inconspicuous. The AHP allows the homeowner to express and include in the decision whether he holds this opinion, and with what intensity, by comparing smoke detectors and sprinklers with respect to this criterion. It is assumed here that sprinklers, and the detector/sprinkler combination are slightly less attractive than smoke detectors alone.

Alternatives - Level 3

Smoke detectors, a sprinkler system, and the detector/sprinkler combination are compared pairwise with each other to determine the homeowner's preference with respect to aesthetics.

[13] For these calculations, the CPI for household insurance rates has been used rather than the CPI for all urban consumers. As quoted by the U.S. Labor Department, it averages 129.0 for 1988 (1982 = 100).

3.3 Hypothetical Case Studies

To apply the AHP to the two hypothetical case studies, "Expert Choice", an interactive computer software package, is used. Expert Choice was developed to facilitate the application of the AHP. It is programmed to allow the user to structure the decision problem, elicit responses to the pairwise comparisons, and calculate priorities and rankings as required by the AHP. It works in a numerical or verbal mode. As one of its options, it performs sensitivity analysis for each criterion to show how a change in any of the weights affects the ranking of decision alternatives.

Expert Choice is a generic, off-the-shelf program; it does not contain background information or default values for fire risks or benefits and costs of available fire protection systems. In the trial uses of the software, the user is an analyst familiar with fire statistics and system performance. Without prior experience and special information, a user would likely not know how to structure the problem or how to make reasonable judgments in the pairwise comparisons. A customized version of the software is needed to make it possible for a homeowner to apply the AHP to a personal fire protection decision. The software can be structured to fit fire protection decisions, and background data can be provided on information screens as part of the model. Constant values for average fire-related risks, purchase costs, or performance data, for example, might be programmed as default values, so that the homeowner need enter only the judgmental comparisons of his own risk exposure and risk attitude relative to the average, or of other non-numerical criteria.

3.3.1 <u>Hypothetical Case I: A homeowner with lower-than-average risk exposure and a risk-taking attitude</u>

3.3.1.1 Assumptions:

The analyst adopts the persona of a homeowner whose household consists of two young adults without physical or mental handicaps, and who do not drink or smoke. Further, the home, a new one in the pre-construction phase, is to be built of brick without open fireplaces or woodburning stoves. The property value at risk in case of a fire is assumed to be slightly lower than the average property losses stated in the U.S. fire statistics.

The risk-taking attitude of Homeowner I is characterized by assuming that the cost of purchasing and maintaining a fire protection system weighs more heavily in making a decision than a reduction in the risk of dying or being injured in a fire or of losing possessions. This attitude is plausible if one assumes that the prospective homeowners are a young couple without children, first-time buyers, with limited financial means. They are likely more concerned about meeting current expenses and saving money than about reducing risks of low probability.

As discussed in section 3.2, the prices and future costs of the fire protection systems are assumed to be those of an average sprinkler system and smoke detector system as estimated in Ruegg/Fuller. Likewise, average risk-reduction values from that study are used as reference points by the analyst for the relevant pairwise comparisons.

3.3.1.2 Pairwise Comparisons:

Exhibits A to I show the output of Expert Choice for Homeowner I.[14] In exhibit A appear the entries of the first set of pairwise comparisons in level 1 of the hierarchy and the priorities calculated from them. For example, when comparing LIFE SAFETY with SYSTEM PRICE, Homeowner I makes the judgment that, with respect to selecting the best fire protection strategy, SYSTEM PRICE is strongly more important to him than LIFE SAFETY.[15] This judgment translates into an entry of 1/5 (shown as (5.0) in the computer printout) in row 1, column 4, of the matrix. PROPERTY PROTECTION to this homeowner is moderately to strongly less important than SYSTEM PRICE, as is shown by the entry of 1/4 in row 3, column 4.

In each case, the reciprocal comparisons generate inverse entries in the lower half of the matrix: if A compared with B is twice as important, B compared with A is one half as important. Each comparison of a criterion with itself receives an entry of 1 along the diagonal: compared with itself a criterion is of equal importance. (The computer printouts of the matrices do not show these entries.)

The priorities calculated by Expert Choice from the entire set of pairwise comparisons in level 1 show, as is intuitively to be expected from a decision-maker with a risk-taking attitude, that SYSTEM PRICE with a priority of 0.399 and FUTURE COSTS with a priority of 0.288 are weighted more heavily in the decision-making process than LIFE SAFETY (0.065) or BODILY HEALTH (0.044) or PROPERTY PROTECTION (0.042). The homeowner even feels that AESTHETICS (0.161) is more important than diminishing the risks of death, injury, and property loss.

Exhibit B shows the computer print-out for a set of comparisons in level 2 of the hierarchy. (Level 2 is a partial level for only those criteria that have subcriteria.) Here the homeowner makes the judgment that his particular circumstances--only two household members, no children, new house, no fire places--is extremely likely to put him into the lower-than-average risk category with respect to LIFE SAFETY. This is indicated by an entry of 1/9 in row 2, column 3 of the judgment matrix. Expert Choice calculates a priority of 0.763 for the likelihood of a lower-than-average risk category, a priority of 0.176 for the likelihood of an average risk category, and a priority of 0.061 for the likelihood of a higher-than-average risk category.

Exhibit C, criterion BODILY HEALTH, shows the comparisons of different degrees of exposure to risk of fire and injury. The likelihood of lower-than-

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[14] Expert Choice calls the first level below the goal or below a criterion "nodes" and the second level "leaf nodes".

[15] Strictly speaking, what is meant here is a (small) reduction in the risk of death from fire.

average risk exposure gets the highest priority, namely 0.772, compared with 0.173 for average and 0.055 for higher-than-average risk exposure.

The priorities in exhibit D show that Homeowner I, taking into account the background information available to him and considering his particular circumstances, makes the judgment that the property he might lose in case of a fire is more likely of lower-than-average value (0.537) than of average value (0.364) or of higher-than-average value (0.099).

Going to level 3 of the hierarchy, Homeowner I looks at the three fire protection technologies available to him. He compares SMOKE DETECTORS, a SPRINKLER SYSTEM and a combination of SMOKE DETECTORS AND SPRINKLERS pairwise with each other with respect to each one of the criteria or subcriteria in the preceding level. Exhibit E illustrates the comparisons for the criterion LIFE SAFETY. The entries for the pairwise comparison of the alternatives are calculated directly from the estimated average reductions in the risk of fire and death, attainable with smoke detectors (52%), a sprinkler system (69%), or a combination of smoke detectors and sprinklers (82%). This means that the risk reduction attainable with a detector/sprinkler combination is 1.6 (=82/52) times that of smoke detectors, or 1.2 (=82/69) times that of a sprinkler system alone, or a sprinkler system is 1.3 (=69/52) times as effective as smoke detectors alone. Given this fact--and, for the time being, looking at this aspect alone--Expert Choice rates the detector/sprinkler combination (0.407) higher than the sprinkler system alone (0.336) or smoke detectors alone (0.257).

As with the values for risk reductions, for which numerical data are available, ratios for some of the other comparisons of fire protection alternatives can be entered directly. For criteria, such as SYSTEM PRICE, M&R COSTS, PROPERTY TAX, and INSURANCE, numerical data are available.[16] For example, the present value maintenance and replacement costs for the three fire protection strategies were estimated in Ruegg/Fuller at $170 for smoke detectors, $480 for a sprinkler system, and $650 for the detector/sprinkler combination (see subsection 3.2.2). This means that the M&R costs of sprinklers are 2.8 (=480/170) times the M&R costs of smoke detectors, and the M&R costs of the detector/sprinkler combination are 3.8 (=650/170) times the M&R costs of smoke detectors and 1.4 times the M&R costs of a sprinkler system alone (exh. F). Given these entries, Expert Choice calculates the priority of smoke detectors to be 0.617. This means that, with respect to M&R costs, smoke detectors are the preferred fire protection system. The sprinkler system comes in second (0.223), and the detector/sprinkler combination is third (0.161)--all with respect to M&R costs.

With respect to PROPERTY PROTECTION, Expert Choice again gives a higher weight to the sprinkler system and the detector/sprinkler combination than to smoke detectors, which follows from the higher property loss reductions attributable to the sprinkler alternatives (exh. G).

[16] SYSTEM PRICE is a special case; see comments in subsection 3.2.2.

Remember that the priority of 0.407 for the detector/sprinkler combination with respect to reduced risk to LIFE SAFETY, or the priority of 0.617 for smoke detectors with respect to M&R costs, are partial or "local" priorities; they establish the relative desirability of the alternative with respect to any one criterion. The local priorities will be combined with all other local priorities to produce the final or "global" priorities which rank the fire protection systems after all comparisons have been made.

3.3.1.3 Ranking:

Expert Choice aggregates and "synthesizes" the priorities of criteria, subcriteria, and decision alternatives from each level of the hierarchy; that is, it sums and normalizes the contributions made by the comparison towards the final ranking of the decision alternatives.

Exhibit H shows the Expert Choice tally of all priorities, and exhibit I shows a bar graph of the global priorities for the fire protection technologies. Given Homeowner I's judgments during the decision process, Expert Choice ranks the alternatives as follows:

Rank	Alternatives	Priorities
(1)	SMOKE DETECTORS	0.562
(2)	SPRINKLER SYSTEM	0.227
(3)	SMOKE DETECTORS AND SPRINKLERS	0.211

What these results say is that for a decision-maker such as Homeowner I, with a lower-than-average risk exposure and a risk-taking attitude, Expert Choice finds smoke detectors to be the "best" fire protection technology.

At this stage, it might be interesting for the decision-maker to ask himself how the ranking of the alternatives would change if he weighted any one of the criteria differently. Expert Choice facilitates sensitivity analysis by showing the decision-maker how a change in the weight of any one criterion would change the ranking of the alternatives.

3.3.1.4 Sensitivity Analysis for Case I:

Expert Choice performs sensitivity analysis and produces the corresponding graph for the nodes below the "current" criterion (see figs. 3 and 4). Each graph contains curves--straight lines since the relationships are assumed to be linear--representing the priorities for the decision alternatives. The left-hand axis of each graph represents a priority of zero (no weight assigned to the criterion examined), the right-hand axis a priority of 1 (total weight assigned to the criterion examined). The dashed vertical line represents the priority of the criterion examined as calculated from the judgments previously entered in the model. When the weight of one criterion is changed during sensitivity analysis, Expert Choice distributes the change of weight to the other criteria in direct proportion to their existing weights.

Graph 3a depicts the sensitivity of the choice of fire protection systems to changes in the priority of LIFE SAFETY. The vertical line represents the priority of LIFE SAFETY as calculated from the judgments previously entered in the model. The intersection of the curves with the vertical line indicates the ranking of the alternative fire protection systems. By extrapolation the graph shows how the ranking of the fire protection systems changes if more or less weight is assigned to LIFE SAFETY, that is, in this case if a more or less risk-averse attitude is adopted. Graph 3a indicates that if Homeowner I weighted LIFE SAFETY much more heavily (about 0.700 instead of 0.065), i.e., if he becomes more risk-averse, the detector/sprinkler combination will be ranked as the preferred fire protection system.

Similarly, the sensitivity analysis for PROPERTY PROTECTION in graph 3b shows that if Homeowner I assigned more weight to this criterion, the priorities for the sprinkler system and the detector/sprinkler combination would increase, the priority for smoke detectors decrease, and the ranking would eventually be reversed.

In contrast, graph 3c shows that even if less weight is assigned to SYSTEM PRICE alone, considering all other judgments made by the homeowner, smoke detectors remain the preferred choice.

To see how the priorities for the systems change with changes in risk exposure, M&R costs, property tax, or insurance savings, one would analyze the subcriteria in the next lower level. Graph 3d shows the effect of changes in the risk reductions attributable to the alternative fire protection systems. The risk reductions are expressed in percentages. The same percentages apply whether higher-than-, lower-than-, or average risk exposure is specified. This is shown by the horizontal lines indicating that with respect to the criterion LIFE SAFETY, the detector/sprinkler combination is the most effective, followed by sprinklers alone and smoke detectors alone. (Reminder: Expert Choice uses the information from only the nodes below the "current" node to perform sensitivity analysis. So, in this case, it calculates the priorities of the alternatives with respect to the current node, LIFE SAFETY, rather than with respect to the goal, BEST FIRE PROTECTION SYSTEM.)

In a similar way one can examine how M&R COSTS (graph 3e) or INSURANCE (graph 3f) influence the priorities of the fire protection alternatives with respect to FUTURE COSTS, or how any other criterion or subcriterion influences the ranking or the priorities of the decision alternatives. Expert Choice factors in any "local" change in weighting (if made permanent) when synthesizing the weights of the entire hierarchy and adjusts the "global" priorities of the fire protection alternatives accordingly.

3.3.2 Hypothetical Case II: A homeowner with higher-than-average risk exposure and a risk-averse attitude

3.3.2.1 Assumptions:

In this case the analyst adopts the persona of a homeowner who is exposed to higher-than-average risk: his household consists of a greater-than-average

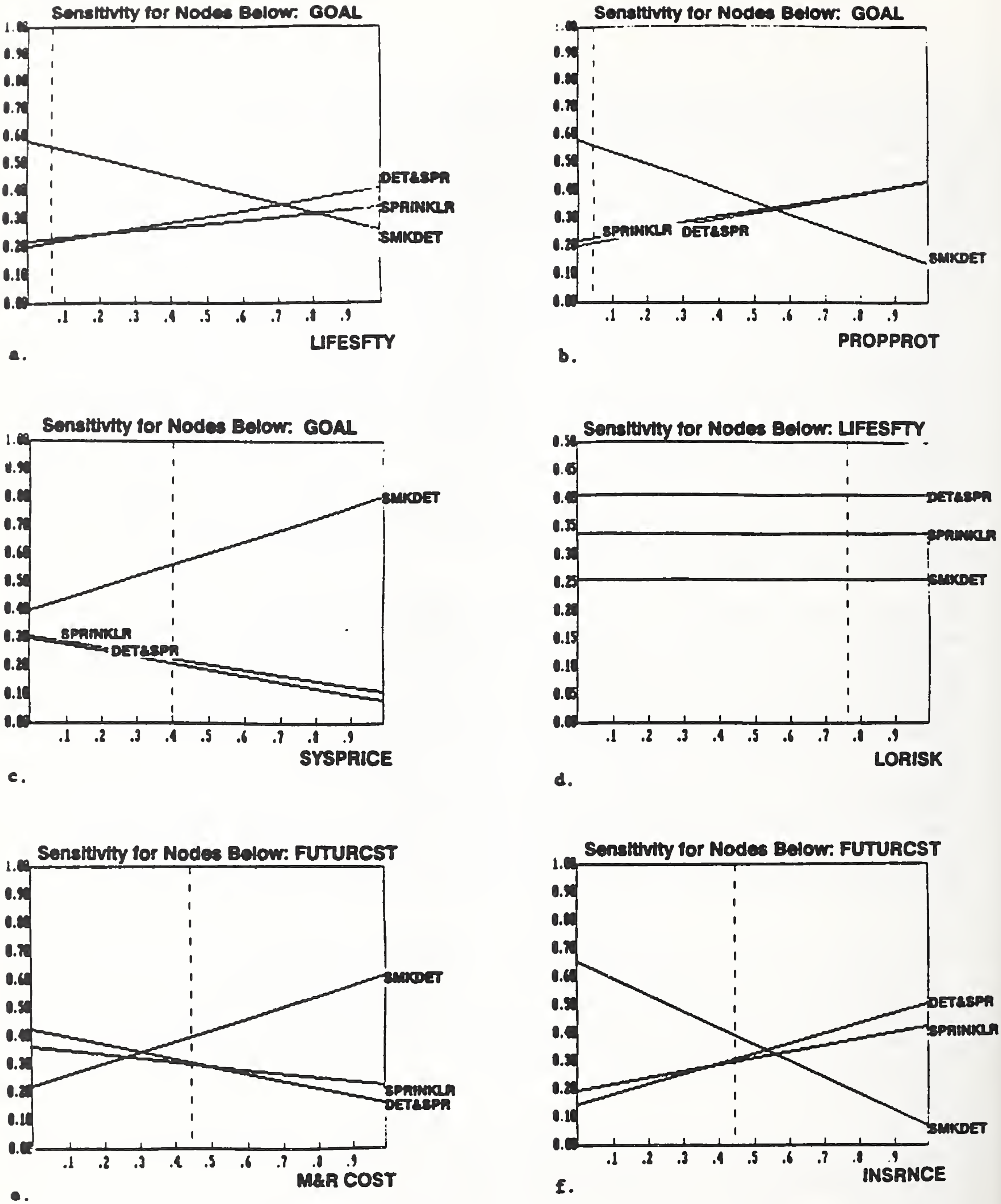

Figure 3. Sensitivity Analysis
CASE I—Lower-than-average risk exposure
risk-taking attitude.

number of people: adults who smoke, one of them handicapped, and three small children. The house is to be constructed partly of brick and partly of wood, with an open fireplace and a woodstove. It is being built in an area that is difficult to reach by municipal fire protection services. In addition, the family owns a valuable collection of antiques, which makes it likely that the household's property loss in case of a fire would be above average.

Homeowner II's attitude is risk-averse; one of the household members has survived a previous residential fire, and so safety is of serious concern. For these reasons the homeowner assigns greater weight to LIFE SAFETY and BODILY HEALTH than to SYSTEM PRICE and FUTURE COSTS.

As in the case of Homeowner I, the prices and future costs, as well as the fire risk reductions attributable to the three fire protection alternatives, are assumed to be known to the homeowner.

3.3.2.2 Pairwise Comparisons:

Exhibits J to V display the Expert Choice computer printouts for Homeowner II's application of the AHP. Exhibit J shows the judgment matrix for the criteria in level 1 and the priorities calculated from them. A comparison of these priorities with those for Homeowner I is as follows:

	Homeowner I (risk-taking) Priorities	Homeowner II (risk-averse) Priorities
LIFE SAFETY	0.065	0.391
BODILY HEALTH	0.044	0.281
PROPERTY PROTECTION	0.042	0.126
SYSTEM PRICE	0.399	0.120
FUTURE COST	0.288	0.054
AESTHETICS	0.161	0.029

It is evident that these priorities express a greater risk aversion for Homeowner II than for Homeowner I.

The priorities shown in exhibits K, L, and M indicate that in level 2 of the hierarchy, Homeowner II judges his risk exposure most likely to be HIGHER-THAN-AVERAGE with respect to LIFE SAFETY, BODILY HEALTH, and PROPERTY PROTECTION. For example, with respect to the risk to LIFE SAFETY, Expert Choice calculates a priority of 0.699 for the likelihood of HIGHER-THAN-AVERAGE exposure as opposed to 0.237 and 0.064 for the likelihood of AVERAGE or LOWER-THAN-AVERAGE exposure to this risk.

Since the performance of the fire protection alternatives is independent of whether higher-than-, average, or lower-than-average risk exposure is looked at, Expert Choice again calculates the highest priority for the detector/ sprinkler combination in level 3 of the hierarchy, with respect to LIFE SAFETY, BODILY HEALTH, and PROPERTY PROTECTION (exhs. N, O, and P).

As in Case I the comparisons of the fire protection systems with respect to SYSTEM PRICE (exh. Q) and FUTURE COSTS (exh. R) give the advantage to smoke detectors. In the final synthesis of the judgments, however, this influence is more than offset by the higher-than-average risk exposure and more risk-averse attitude of Homeowner II and by the better performance of sprinklers in reducing risks.

With respect to PROPERTY TAX (exh. S) and AESTHETICS (exh. T), smoke detectors get the highest priority, since the installation of smoke detectors does not increase property taxes, and Homeowner II is assumed to find smoke detectors slightly less conspicuous than a sprinkler system.

3.3.2.3 Ranking:

The Expert Choice tally of the "synthesized" priorities for Homeowner II's pairwise comparisons is shown in exhibit U and the final ranking of the fire protection systems in the bar graph of exhibit V. The final ranking of the decision alternatives is as follows:

Rank	Alternative	Priorities
(1)	SMOKE DETECTORS AND SPRINKLERS	0.379
(2)	SPRINKLER SYSTEM	0.354
(3)	SMOKE DETECTORS	0.267

As intuitively expected, the AHP, via Expert Choice, ranks the detector/ sprinkler combination as the preferred choice of a homeowner with higher-than-average risk exposure and a risk-averse attitude. The AHP gives expectations a legitimate place in the decision process. Since the decision-maker is the expert, the outcome should be in line with what he expects. If this is not the case, then he should reexamine the criteria selected and the judgments made to make sure they adequately encompass all aspects of the problem and represent his ideas on the subject (Saaty 1986). Since the homeowner is typically not an expert in fire protection decisions, a means is needed of making him into an expert for the purpose of making comparisons. This is a major challenge in adapting the AHP as a decision tool for homeowners.

3.3.2.4 Sensitivity Analysis:

Graph 4a, depicting the sensitivity analysis for LIFE SAFETY (in level 1 where risk attitude is expressed), indicates that Homeowner II clearly prefers the detector/sprinkler combination smoke detectors. The sprinkler system alone is a close second. From the graph it is evident that, given Homeowner II's other judgments relating to risk attitude and risk exposure, a lower weight assigned to LIFE SAFETY alone would not change his preference for one of the sprinkler alternatives. Similarly, a lower weight assigned to PROPERTY PROTECTION alone would not switch the ranking to smoke detectors, as shown in graph 4b.

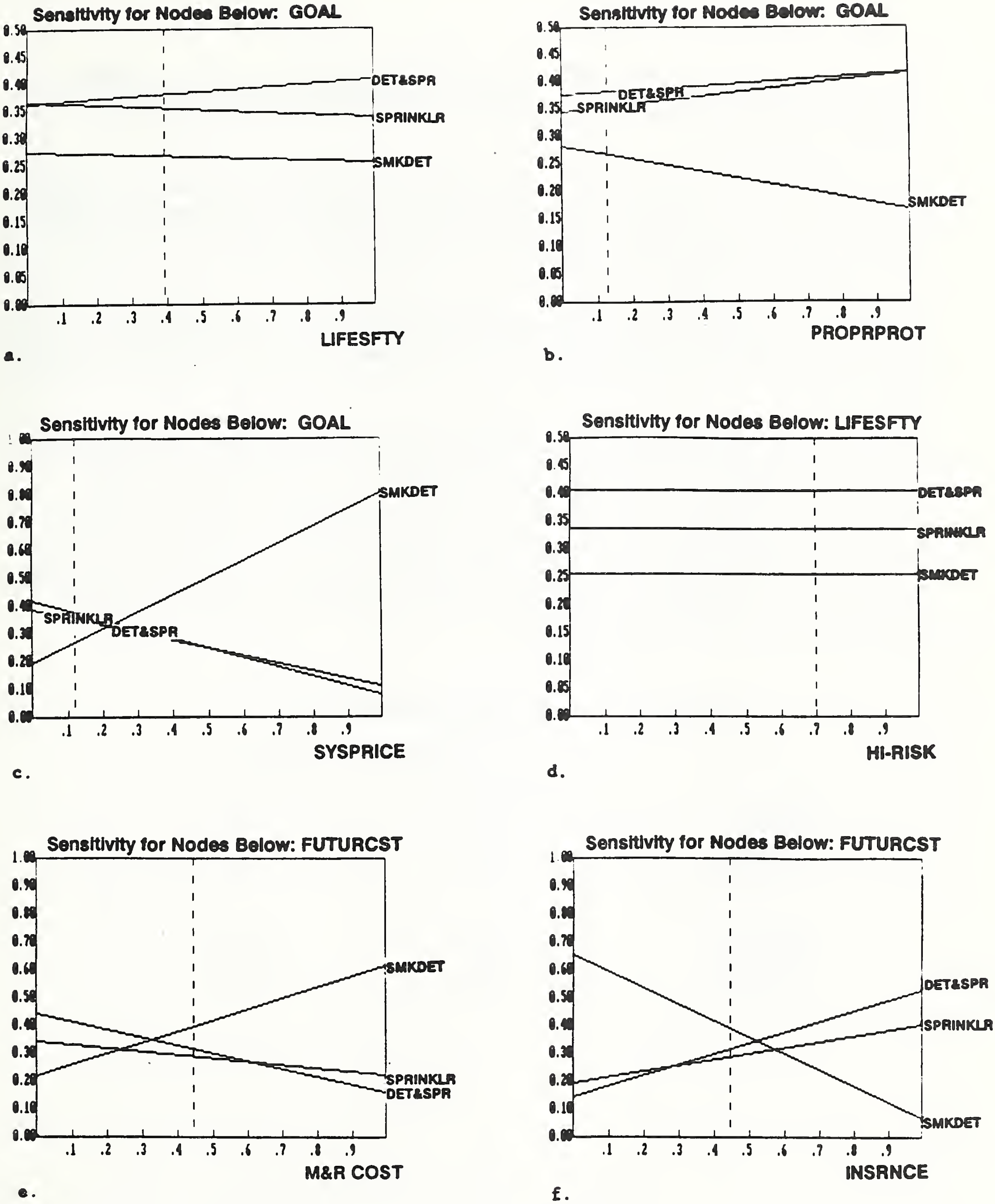

Figure 4. Sensitivity Analysis
CASE II--Higher-than-average risk exposure
risk-averse attitude.

In contrast, graph 4c, depicting the sensitivity of the outcome to SYSTEM PRICE, shows that if this criterion took on greater weight in Homeowner II's judgments, the ranking would switch and smoke detectors would become the preferred choice.

At the next-lower level, graph 4d shows that regardless of the degree of risk exposure, the fire protection alternatives are ranked--with respect to LIFE SAFETY--according to their contribution in reducing the risk: sprinklers offer a higher reduction (in percent) than smoke detectors.

The graphs for M&R costs and insurance savings (4e and 4f) are the same as for those for Case I. The relationship between M&R costs and insurance savings within the category FUTURE COSTS is based on numbers which are the same for both Case I and Case II.

As mentioned in the description of the criteria in section 3.2.2, Ruegg/Fuller assumed savings in homeowner insurance premiums for residential sprinkler systems. In practice, such savings may not be widely available. To examine how the absence of INSURANCE savings for sprinkler systems would influence the final ranking of the decision alternatives (rather than how a different weighting of insurance savings would influence the priorities of the alternatives with respect to FUTURE COSTS) the model was rerun omitting the subcriterion INSURANCE. The omission did not change the final ranking of the fire protection systems and increased only slightly the priorities in favor of smoke detectors, as is shown below:

Ranking of fire protection alternatives

	Insurance Savings	
	Included	Omitted
Case I		
SMKDET	0.562	0.638
SPRINKLR	0.227	0.197
DET&SPR	0.211	0.165
Case II		
DET&SPR	0.379	0.372
SPRINKLR	0.354	0.351
DET&SPR	0.267	0.277

These results underscore the crucial role the differences in risk exposure and risk attitude play in the ranking of fire protection alternatives by individual homeowners.

From the sensitivity analysis of Homeowner II's decision one can see that even though the criteria expressing risk aversion and high risk exposure are weighted more heavily than those relating to the costs of the systems, a relatively small increase in the weight of cost-related criteria (for example, SYSTEM PRICE from 0.12 to approximately 0.25 in fig. 4c) would change the ranking and make smoke detectors the preferred choice. This makes sense intuitively considering the relatively high price of residential sprinkler systems. At the same time it shows that it is the difference in risk exposure and risk attitudes which may make the investment in a sprinkler system attractive for some homeowners.

4. SUMMARY, RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

4.1 Summary

Improved investment decisions with respect to fire suppression and fire mitigation systems for individual houses would contribute to cost-effective fire protection. Sound investment decisions should reflect the risk exposure and risk attitudes of the individual homeowner. But explicit data necessary to incorporate individual risk exposure and risk attitudes in benefit-cost analysis are lacking.

This study explores the use of a method that allows the integration of quantifiable and qualitative variables to arrive at a preference ordering of various fire protection systems. The potential of the methodology is that it may help overcome the lack of data by eliciting from individuals information uniquely pertaining to their own situation. This information is used to derive weights and priorities reflecting their preferences. By using these weights in comparing relevant factors, it may be possible to improve fire protection investment decisions.

The method investigated is the Analytical Hierarchy Process developed by Thomas Saaty (1980, 1982). Although it lacks a formal technique for including individual risk exposure and risk attitudes, its feature of integrating quantitative and qualitative variables allows one to include these aspects implicitly.

The AHP uses a hierarchical classification of the criteria and alternatives that comprise a decision problem. Pairwise comparisons at each level of the hierarchy determine the interrelations of criteria and alternatives and the intensity of those interrelations. The comparisons are mapped into a ratio scale of real numbers from which priorities are computed for each level of the hierarchy. The synthesis of all priority vectors gives an overall ranking for the alternatives considered in the decision problem. Sensitivity analysis of each criterion's importance indicates how different weights change the final ranking of the decision alternatives.

The study adapts the AHP to a specific fire protection decision involving choice among smoke detectors, a sprinkler system, or a combination of the two. The hierarchy is structured to incorporate individual risk attitudes by specifying criteria such as Life Safety, Bodily Health, Property Protection, System Price, Future Costs, and Aesthetics, and asking homeowners to judge their relative importance through pairwise comparisons. Risk exposure is included by homeowners' comparing their perceived own exposure to fire-related risks of death, injury, and property loss with average risk exposure derived from U.S. fire loss data.

The model is applied to two hypothetical cases assuming (1) a risk-taking homeowner with lower-than-average risk exposure, and (2) a risk-averse homeowner with higher-than-average risk exposure.

The two case studies show that the choice of fire protection systems can be modeled and decided upon by using the AHP. If the decision-making process takes into account differences in risk exposure and risk attitude, the installation of a sprinkler system may be the preferred choice for a homeowner with higher-than-average risk exposure and a risk-averse attitude. Concurrently, a homeowner with lower-than-average risk exposure and a risk-taking attitude was shown to rank smoke detectors higher than sprinklers.[17]

4.2 Results and Conclusions

The assumptions of the two hypothetical cases made one homeowner clearly risk-averse and subject to higher-than-average fire-related risks, and the other one clearly risk-taking and subject to lower-than average fire-related risks. These two cases are extreme cases, and the results of the analysis confirm what can intuitively be expected: one homeowner clearly ranks the combination of smoke detectors and sprinklers highest, the other clearly prefers smoke detectors. In between these two extremes there exist many possible combinations of risk exposure and risk attitude for which decisions are likely to be less clear-cut and a decision support system even more called for.

The investigation also pointed out several advantages and limitations of the AHP as far as an application to fire protection investment decisions is concerned:

(a) Advantages:

The basic advantage of the AHP is that it allows the integration of quantifiable and qualitative variables. Considering that in homeowners' decisions about fire protection hard-to-quantify risk evaluations and aesthetic concerns need to be included, the AHP represents a method uniquely suited to meet this requirement.

Another feature of the AHP that promotes its use for the intended application is that it provides a method for structuring a multi-dimensional problem systematically and logically. The structure of the hierarchy clarifies the issue and records the decision-making process; it leads the decision-maker rationally through the steps of the decision process and makes clear to him what variables are considered and exactly what goes into the decision.

A related advantage of the AHP is that decision-makers get immediate feedback as to the implications of their judgments. The judgments can be examined through sensitivity analysis and conveniently updated if new information becomes available. Also, the AHP points out inconsistencies and intransitive judgments through the inconsistency index. Thus, the

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[17] An entirely different problem, which has not been addressed in this study, is whether intended action will actually be translated into behavior. People do not always carry out what they decide to do, and so there is no guarantee that homeowners will actually install sprinklers even if the decision model ranks them highest.

AHP has intuitive appeal in that it tells decision-makers what decisions will maximize the achievement of their goals, given the knowledge they have about the problem. These features of the AHP are a distinct advantage over utility assessment which yields very little feedback once the responses are given.

The fact that the AHP can easily be implemented on personal computers is another advantage. Although the existing software is not well suited to the need considered, it is possible to develop customized AHP software to meet the special needs of fire protection decisions.

(b) Limitations:

Probably the most troublesome limitation to applying the AHP to fire protection decisions has to do with the question of how to make available to a homeowner the appropriate background information so that she will be able to make a "good" decision. The AHP presumes that the decision-maker is an expert with respect to the decision problem to be analyzed. In order to guarantee a good, that is, an objective decision, a user of Expert Choice would have to be well informed about her risk exposure, the performance of fire protection systems, their costs and benefits, and their appearance, and she would have to have some awareness of her risk attitude.

On the theoretical side, the AHP has the shortcoming that it does not explicitly measure the amount of risk aversion that a homeowner would have to have to choose a sprinkler system over smoke detectors. The disadvantage is offset to some extent by the use of sensitivity analysis which gives some idea of how decisions would change with variations in risk attitude. Moreover, if the model is used as a decision-making aid for an individual homeowner, it is not essential to have an exact measure of risk aversion as long as it is accounted for in the computation of the priorities that are used to rank the alternatives.

Another theoretical limitation is that the AHP requires the criteria, subcriteria, and decision alternatives to be comparable within a scale of 1-9. The purchase and installation costs of smoke detectors and sprinkler systems are far apart in magnitude. It is intuitively difficult to compare them. If, as has been done in this study, one enters the price of the smoke detectors and the price of the detector/sprinkler combination as the two extremes and lets the AHP compute the other values proportionately, one loses some precision. A better solution might be to add other fire protection alternatives, such as "fire escape" or "fire-safe building materials," with which to combine "smoke detectors" to bring their price and the price of a sprinkler system within a scale that is easier to compare.

Limitations of this kind are not unique to the AHP. Any preference assessment method requires dealing with similar or even more serious problems. One author, describing the assessment of multi-attribute utility functions for specific applications, suggests that because of its drawbacks the utility-theoretic approach should be abandoned in favor of more practical methods (such as the AHP) even if less explicit and maybe theoretically less well-established (Sicherman, 1975).

It appears therefore that despite its limitations the AHP is well suited to support economic decisions on fire protection strategies. These are challenging decisions not only for prospective homeowners but likewise for policy makers concerned with fire safety on a national scale.

4.3 Recommendations

The recommendations focus on the application of the AHP. The two case studies demonstrate that (1) it is complicated to structure the problem for solution; (2) expert information is needed to implement the method, and (3) it takes some effort to do the pairwise comparisons and to interpret the printouts of the existing off-the-shelf computer software.

The difficulty in execution far exceeds the effort that could reasonably be expected of most homeowners. Suggestions for going beyond the research application of the AHP have been made throughout the report. They are summarized as follows:

(1) Develop customized decision-support software

- (i) specifically structured for fire protection investment decisions and designed for potential owners of single-family homes;

- (ii) versatile enough to allow investigation of a variety of fire protection strategies.

(2) Provide decision-makers with enough background information to allow them to make judgments with reasonable objectivity. Include in the software--as information screens, default values, or risk profiles--for example, information on fire protection alternatives and fire-related risks. The objective should be to enable lay users to make expert judgments regarding fire protection quickly and easily and to understand reported results.

(3) Explore also accommodating

- (i) the developer as a decision-maker determining trade-offs between fire prevention systems and building materials; or a municipal fire department examining changes in zoning laws in exchange for sprinklered developments;

- (ii) uses other than decision-making, such as studying the public's attitudes about fire protection.

(4) Adapt the AHP model to the problem of fire protection rather than attempt to develop an expert system for the purpose. The

feasibility of this recommendation is supported by development of customized AHP software for other applications. For example, <u>AutoMan. Decision Support Software for Automated Manufacturing Investments</u> is a dedicated software package, based on the AHP, for managers of manufacturing facilities to evaluate automated manufacturing equipment in the face of multiple decision criteria (Weber, Lippiatt, and Johnson, 1989).

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Exhibit A Expert Choice Sample Printout for Case I
Homeowner with lower-than-average risk exposure, risk-taking attitude

Judgments and priorities determining risk attitude - Level 1

JUDGMENT AND PRIORITIES WITH RESPECT TO GOAL TO SELECT BEST FIRE PROTECTION SYSTEM

	LIFESFTY	BODYHLTH	PROPPROT	SYSPRICE	FUTURCST	AESTHETC
LIFESFTY		2.0	3.0	(5.0)	(7.0)	(5.0)
BODYHLTH			2.0	(6.0)	(8.0)	(5.0)
PROPPROT				(4.0)	(5.0)	(4.0)
SYSPRICE					3.0	4.0
FUTURCST						3.0
AESTHETC						

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more IMPORTANT than COLUMN element
unless enclosed in parenthesis.

LIFESFTY :Life Safety
BODYHLTH :Bodily Health
PROPPROT :Property Protection
SYSPRICE :System Price
FUTURCST :Future Costs
AESTHETC :Aesthetics

0.065
LIFESFTY XXXXXXXXXXX

0.044
BODYHLTH XXXXXXXX

0.042
PROPPROT XXXXXXX

0.399
SYSPRICE XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.288
FUTURCST XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.161
AESTHETC XXXXXXXXXXXXXXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.110

Exhibit B Expert Choice Sample Printout for Case I
Homeowner with lower-than-average risk exposure, risk-taking attitude

Judgments and priorities determining risk exposure with respect to Life Safety - Level 2

JUDGMENTS AND PRIORITIES WITH RESPECT TO
LIFESFTY < GOAL

	AVRISK	HIRISK	LORISK
AVRISK		4.0	(6.0)
HIRISK			(9.0)
LORISK			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more LIKELY than COLUMN element
unless enclosed in parenthesis.

AVRISK :Average risk of fire and death
HIRISK :Higher-than-average riks of fire and death
LORISK :Lower-than-average risk of fire and death

0.176
AVRISK XXXXXXXXXXXXXXXXXX

0.061
HIRISK XXXXXX

0.763
LORISK XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.093

Exhibit C Expert Choice Sample Printout for Case I
Homeowner with lower-than-average risk exposure, risk-taking attitude

Judgments and priorities determining risk exposure with respect to Bodily Health - Level 2

JUDGMENTS AND PRIORITIES WITH RESPECT TO
BODYHLTH < GOAL

	AV-RISK	HI-RISK	LO-RISK
AV-RISK		5.0	(7.0)
HI-RISK			(9.0)
LO-RISK			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more LIKELY than COLUMN element
unless enclosed in parenthesis.

AV-RISK :Average risk of fire and injury
HI-RISK :Higher-than-average riks of fire and injury
LO-RISK :Lower-than-average risk of fire and injury

0.173
AV-RISK XXXXXXXXXXXXXXXX

0.055
HI-RISK XXXXX

0.772
LO-RISK XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.180

Exhibit D Expert Choice Sample Printout for Case I
Homeowner with lower-than-average risk exposure,
risk-taking attitude

Judgments and priorities determining risk exposure with respect to Property Protection - Level 2

```
                JUDGMENTS AND PRIORITIES WITH RESPECT TO
                           PROPPROT < GOAL

          AV-VALUE  HI-VALUE  LO-VALUE
 AV-VALUE             5.0      (2.0)
 HI-VALUE                      (4.0)
 LO-VALUE

Matrix entry indicates that ROW element is ___
  1 EQUALLY   3 MODERATELY   5 STRONGLY   7 VERY STRONGLY   9 EXTREMELY
more LIKELY than COLUMN element
    unless enclosed in parenthesis.


AV-VALUE :Average value of property
HI-VALUE :Higher-than-average value of property
LO-VALUE :Lower-than-average value of property





0.364
AV-VALUE XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.099
HI-VALUE XXXXXXXXXXXXX

0.537
LO-VALUE XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

                      INCONSISTENCY RATIO = 0.081
```

EXHIBIT E Expert Choice Sample Printout for Case I
Homeowner with lower-than-average risk exposure,
risk-taking attitude

Judgments and priorities determining alternative with respect
to lower-than-average risk to Life Safety - Level 3

JUDGMENTS AND PRIORITIES WITH RESPECT TO
LORISK < LIFESFTY < GOAL

	SMKDET	SPRINKLR	DET&SPR
SMKDET		(1.3)	(1.6)
SPRINKLR			(1.2)
DET&SPR			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more IMPORTANT than COLUMN element
unless enclosed in parenthesis.

SMKDET :Smoke detectors
SPRINKLR :Sprinkler system
DET&SPR :Combination of smoke detectors and sprinklers

0.257
SMKDET XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.336
SPRINKLR XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.407
DET&SPR XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.000

EXHIBIT F Expert Choice Sample Printout for Case I
Homeowner with lower-than-average risk exposure, risk-taking attitude

Judgments and priorities determining alternative with respect to M&R costs - Level 3

JUDGMENTS AND PRIORITIES WITH RESPECT TO
M&R COST < FUTURCST < GOAL

	SMKDET	SPRINKLR	DET&SPR
SMKDET		2.8	3.8
SPRINKLR			1.4
DET&SPR			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element
unless enclosed in parenthesis.

SMKDET :Smoke detectors
SPRINKLR :Sprinkler system
DET&SPR :Combination of smoke detectors and sprinklers

0.617
SMKDET XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.223
SPRINKLR XXXXXXXXXXXXXXXXXXXXXXXXX

0.161
DET&SPR XXXXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.000

EXHIBIT G

Expert Choice Sample Printout for Case I
Homeowner with lower-than-average risk exposure, risk-taking attitude

Judgments and priorities determining alternative with respect to lower-than-average value of property protection - Level 3

JUDGMENTS AND PRIORITIES WITH RESPECT TO
LO-VALUE < PROPPROT < GOAL

	SMKDET	SPRINKLR	DET&SPR
SMKDET		(3.2)	(3.2)
SPRINKLR			1.0
DET&SPR			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more IMPORTANT than COLUMN element
unless enclosed in parenthesis.

SMKDET :Smoke detectors
SPRINKLR :Sprinkler system
DET&SPR :Combination of smoke detectors and sprinklers

```
0.135
SMKDET   XXXXXXXXXXXXXXXXXXXXXX

0.432
SPRINKLR XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.432
DET&SPR  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

INCONSISTENCY RATIO = 0.000

EXHIBIT H Expert Choice Sample Printout for Case I
Homeowner with lower-than-average risk exposure, risk-taking attitude

Tally for synthesis of priorities for alternatives

```
                    SELECT BEST FIRE PROTECTION TECHNOLOGY
          TALLY FOR SYNTHESIS OF LEAF NODES WITH RESPECT TO   GOAL

LEVEL 1          LEVEL 2          LEVEL 3          LEVEL 4          LEVEL 5
-------          -------          -------          -------          -------

LIFESFTY =0.065
.                AVRISK   =0.011
.                .                SMKDET   =0.003
.                .                SPRINKLR =0.004
.                .                DET&SPR  =0.005
.                HIRISK   =0.004
.                .                SMKDET   =0.001
.                .                SPRINKLR =0.001
.                .                DET&SPR  =0.002
.                LORISK   =0.050
.                .                SMKDET   =0.013
.                .                SPRINKLR =0.017
.                .                DET&SPR  =0.020
BODYHLTH =0.044
.                AV-RISK  =0.008
.                .                SMKDET   .40E-03
.                .                SPRINKLR =0.004
.                .                DET&SPR  =0.004
.                HI-RISK  =0.002
.                .                SMKDET   .12E-03
.                .                SPRINKLR =0.001
.                .                DET&SPR  =0.001
.                LO-RISK  =0.034
.                .                SMKDET   =0.002
.                .                SPRINKLR =0.016
.                .                DET&SPR  =0.016
PROPPROT =0.042
.                AV-VALUE =0.015
.                .                SMKDET   =0.002
.                .                SPRINKLR =0.007
.                .                DET&SPR  =0.007
.                HI-VALUE =0.004
.                .                SMKDET   .57E-03
.                .                SPRINKLR =0.002
.                .                DET&SPR  =0.002
.                LO-VALUE =0.023
.                .                SMKDET   =0.003
.                .                SPRINKLR =0.010
.                .                DET&SPR  =0.010
SYSPRICE =0.399
.                SMKDET   =0.322
.                SPRINKLR =0.044
.                DET&SPR  =0.033
FUTURCST =0.288
.                M&R COST =0.128
.                .                SMKDET   =0.079
.                .                SPRINKLR =0.029
.                .                DET&SPR  =0.021
.                PROPTAX  =0.032
.                .                SMKDET   =0.026
.                .                SPRINKLR =0.003
.                .                DET&SPR  =0.003
.                INSURNCE =0.128
.                .                SMKDET   =0.009
.                .                SPRINKLR =0.055
.                .                DET&SPR  =0.065
AESTHETC =0.161
.                SMKDET   =0.101
.                SPRINKLR =0.035
.                DET&SPR  =0.024
```

EXHIBIT I Expert Choice Sample Printout for Case I
Homeowner with lower-than-average risk exposure, risk-taking attitude

Ranking of decision alternatives with respect to selecting the best fire protection system

---

SELECT BEST FIRE PROTECTION SYSTEM

```
- SYNTHESIS OF LEAF NODES WITH RESPECT TO   GOAL

OVERALL INCONSISTENCY INDEX =  0.07

SMKDET    0.562 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

SPRINKLR  0.227 XXXXXXXXXXXXXXXXXXXXXXXXX

DET&SPR   0.211 XXXXXXXXXXXXXXXXXXXXXXXX

          =====
          1.000


DET&SPR  --- Combination of smoke detectors and sprinklers
SMKDET   --- Smoke detectors
SPRINKLR --- Sprinkler system
```

Exhibit J Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure, risk-averse attitude

Judgments and priorities determining risk attitude - Level 1

JUDGMENTS AND PRIORITIES WITH RESPECT TO
GOAL TO SELECT BEST FIRE PROTECTION SYSTEM

	LIFESFTY	BODYHLTH	PROPPROT	SYSPRICE	FUTURCST	AESTHET
LIFESFTY		2.0	4.0	4.0	7.0	7.0
BODYHLTH			3.0	4.0	5.0	7.0
PROPPROT				2.0	2.0	5.0
SYSPRICE					4.0	7.0
FUTURCST						3.0
AESTHET						

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more IMPORTANT than COLUMN element
unless enclosed in parenthesis.

LIFESFTY :Life Safety
BODYHLTH :Bodily Health
PROPPROT :Property protection
SYSPRICE :System Price
FUTURCST :Future costs
AESTHET :Aesthetics

0.391
LIFESFTY XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.281
BODYHLTH XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.126
PROPPROT XXXXXXXXXXXXXXXXXXXXXXXXX

0.120
SYSPRICE XXXXXXXXXXXXXXXXXXXXXXXX

0.054
FUTURCST XXXXXXXXXX

0.029
AESTHET XXXXX

INCONSISTENCY RATIO = 0.068

Exhibit K Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure, risk-averse attitude

Judgments and priorities determining risk exposure with respect to Life Safety - Level 2

JUDGMENTS AND PRIORITIES WITH RESPECT TO
LIFESFTY < GOAL

	AV-RISK	HI-RISK	LO-RISK
AV-RISK		(4.0)	5.0
HI-RISK			8.0
LO-RISK			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more LIKELY than COLUMN element
unless enclosed in parenthesis.

AV-RISK :Average risk of fire and death
HI-RISK :Higher-than average risk of fire and death
LO-RISK :Lower-than-average risk of fire and death

0.237
AV-RISK XXXXXXXXXXXXXXXXXXXXXXX

0.699
HI-RISK XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.064
LO-RISK XXXXXX

INCONSISTENCY RATIO = 0.081

Exhibit L Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure, risk-averse attitude

Judgments and priorities determining risk exposure with respect to Bodily Health - Level 2

JUDGMENTS AND PRIORITIES WITH RESPECT TO
BODYHLTH < GOAL

	AVRISK	HIRISK	LORISK
AVRISK		(5.0)	6.0
HIRISK			9.0
LORISK			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more LIKELY than COLUMN element
unless enclosed in parenthesis.

AVRISK :Average risk of fire and injury
HIRISK :Higher-than average risk of fire and injury
LORISK :Lower-than-average risk of fire and injury

0.218
AVRISK XXXXXXXXXXXXXXXXXXXXX

0.728
HIRISK XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.054
LORISK XXXXX

INCONSISTENCY RATIO = 0.141

Exhibit M Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure, risk-averse attitude

Judgments and priorities determining risk exposure with respect to Property Protection - Level 2

JUDGMENTS AND PRIORITIES WITH RESPECT TO
PROPPROT < GOAL

	AV-VALUE	HI-VALUE	LO-VALUE
AV-VALUE		(4.0)	4.0
HI-VALUE			6.0
LO-VALUE			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more LIKELY than COLUMN element
unless enclosed in parenthesis.

AV-VALUE :Average value of property
HI-VALUE :Higher-than-average value of property
LO-VALUE :Lower-than-average value of property

0.236
AV-VALUE XXXXXXXXXXXXXXXXXXXXXXXX

0.682
HI-VALUE XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.082
LO-VALUE XXXXXXXX

INCONSISTENCY RATIO = 0.093

EXHIBIT N Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure, risk-averse attitude

Judgments and priorities determining alternative with respect to higher-than-average risk to Life Safety - Level 3

JUDGMENTS AND PRIORITIES WITH RESPECT TO
HI-RISK < LIFESFTY < GOAL

	SMKDET	SPRINKLR	DET&SPR
SMKDET		(1.3)	(1.6)
SPRINKLR			(1.2)
DET&SPR			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more IMPORTANT than COLUMN element
unless enclosed in parenthesis.

SMKDET :Smoke detectors
SPRINKLR :Sprinkler system
DET&SPR :Combination of smoke detectors and sprinklers

0.257
SMKDET XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.336
SPRINKLR XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.407
DET&SPR XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.000

EXHIBIT O Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure, risk-averse attitude

Judgments and priorities determining alternative with respect to higher-than-average risk to Bodily Health - Level 3

JUDGMENTS AND PRIORITIES WITH RESPECT TO
HIRISK < BODYHLTH < GOAL

	SMKDET	SPRINKLR	DET&SPR
SMKDET		(9.2)	(9.2)
SPRINKLR			1.0
DET&SPR			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more IMPORTANT than COLUMN element
unless enclosed in parenthesis.

SMKDET :Smoke detectors
SPRINKLR :Sprinkler system
DET&SPR :Combination of smoke detectors and sprinklers

0.052
SMKDET XXXXXXXX

0.474
SPRINKLR XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.474
DET&SPR XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.000

EXHIBIT P Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure, risk-averse attitude

Judgments and priorities determining alternative with respect to higher-than-average value of Property Protection

---

JUDGMENTS AND PRIORITIES WITH RESPECT TO
HI-VALUE < PROPPROT < GOAL

	SMKDET	SPRINKLR	DET&SPR
SMKDET		(3.2)	(3.2)
SPRINKLR			1.0
DET&SPR			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more IMPORTANT than COLUMN element
unless enclosed in parenthesis.

SMKDET :Smoke detectors
SPRINKLR :Sprinkler system
DET&SPR :Combination of smoke detectors and sprinklers

```
0.135
SMKDET   XXXXXXXXXXXXXXXXXXXXXXXXX

0.432
SPRINKLR XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.432
DET&SPR  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

INCONSISTENCY RATIO = 0.000

EXHIBIT Q Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure, risk-averse attitude

Judgments and priorities determining alternative with respect to System Price - Level 2

JUDGMENTS AND PRIORITIES WITH RESPECT TO
SYSPRICE < GOAL

	SMKDET	SPRINKLR	DET&SPR
SMKDET		8.0	9.0
SPRINKLR			1.5
DET&SPR			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element
unless enclosed in parenthesis.

SMKDET :Smoke detectors
SPRINKLR :Sprinkler system
DET&SPR :Combination of smoke detectors and sprinklers

0.807
SMKDET XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.111
SPRINKLR XXXXXXXXX

0.082
DET&SPR XXXXXXX

INCONSISTENCY RATIO = 0.008

EXHIBIT R Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure, risk-averse attitude

Judgments and priorities determining alternative with respect to M&R costs - Level 3

JUDGMENTS AND PRIORITIES WITH RESPECT TO
M&R COST < FUTURCST < GOAL

	SMKDET	SPRINKLR	DET&SPR
SMKDET		2.8	3.8
SPRINKLR			1.4
DET&SPR			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element
unless enclosed in parenthesis.

SMKDET :Smoke detectors
SPRINKLR :Sprinkler system
DET&SPR :Combination of smoke detectors and sprinklers

0.617
SMKDET XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.223
SPRINKLR XXXXXXXXXXXXXXXXXXXXXXXXX

0.161
DET&SPR XXXXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.000

EXHIBIT S Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure, risk-averse attitude

Judgments and priorities determining alternative with respect to Property Tax - Level 3

JUDGMENTS AND PRIORITIES WITH RESPECT TO
PROPTAX < FUTURCST < GOAL

	SMKDET	SPRINKLR	DET&SPR
SMKDET		9.0	9.0
SPRINKLR			1.0
DET&SPR			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element
unless enclosed in parenthesis.

SMKDET :Smoke detectors
SPRINKLR :Sprinkler system
DET&SPR :Combination of smoke detectors and sprinklers

0.818
SMKDET XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.091
SPRINKLR XXXXXXXXX

0.091
DET&SPR XXXXXXXXX

INCONSISTENCY RATIO = 0.000

EXHIBIT T Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure, risk-averse attitude

Judgments and priorities determining alternative with respect to Aesthetics

---

JUDGMENTS AND PRIORITIES WITH RESPECT TO
AESTHET < GOAL

	SMKDET	SPRINKLR	DET&SPR
SMKDET		1.5	2.0
SPRINKLR			1.0
DET&SPR			

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element
unless enclosed in parenthesis.

SMKDET :Smoke detectors
SPRINKLR :Sprinkler system
DET&SPR :Combination of smoke detectors and sprinklers

0.464
SMKDET XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.281
SPRINKLR XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

0.255
DET&SPR XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

INCONSISTENCY RATIO = 0.008

EXHIBIT U Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure,
risk-averse attitude

Tally for synthesis of priorities for alternatives

```
                    SELECT BEST FIRE MITIGATION SYSTEM
         TALLY FOR SYNTHESIS OF LEAF NODES WITH RESPECT TO   GOAL

LEVEL 1            LEVEL 2            LEVEL 3            LEVEL 4            LEVEL 5
-------            -------            -------            -------            -------

LIFESFTY =0.391
.                  AV-RISK   =0.093
.                  .                  SMKDET    =0.024
.                  .                  SPRINKLR =0.031
.                  .                  DET&SPR   =0.038
.                  HI-RISK   =0.273
.                  .                  SMKDET    =0.070
.                  .                  SPRINKLR =0.092
.                  .                  DET&SPR   =0.111
.                  LO-RISK   =0.025
.                  .                  SMKDET    =0.006
.                  .                  SPRINKLR =0.008
.                  .                  DET&SPR   =0.010
BODYHLTH =0.281
.                  AVRISK    =0.061
.                  .                  SMKDET    =0.003
.                  .                  SPRINKLR =0.029
.                  .                  DET&SPR   =0.029
.                  HIRISK    =0.204
.                  .                  SMKDET    =0.011
.                  .                  SPRINKLR =0.097
.                  .                  DET&SPR   =0.097
.                  LORISK    =0.015
.                  .                  SMKDET   .78E-03
.                  .                  SPRINKLR =0.007
.                  .                  DET&SPR   =0.007
PROPPROT =0.126
.                  AV-VALUE =0.030
.                  .                  SMKDET    =0.004
.                  .                  SPRINKLR =0.013
.                  .                  DET&SPR   =0.013
.                  HI-VALUE =0.086
.                  .                  SMKDET    =0.012
.                  .                  SPRINKLR =0.037
.                  .                  DET&SPR   =0.037
.                  LO-VALUE =0.010
.                  .                  SMKDET    =0.006
.                  .                  SPRINKLR =0.002
.                  .                  DET&SPR   =0.002
SYSPRICE =0.120
.                  SMKDET    =0.096
.                  SPRINKLR =0.013
.                  DET&SPR   =0.010
FUTURCST =0.054
.                  M&R COST =0.024
.                  .                  SMKDET    =0.015
.                  .                  SPRINKLR =0.005
.                  .                  DET&SPR   =0.004
.                  PROPTAX   =0.006
.                  .                  SMKDET    =0.005
.                  .                  SPRINKLR.54E-03
.                  .                  DET&SPR  .54E-03
.                  INSURNCE =0.024
.                  .                  SMKDET    =0.002
.                  .                  SPRINKLR =0.010
.                  .                  DET&SPR   =0.013
AESTHET   =0.029
.                  SMKDET    =0.013
.                  SPRINKLR =0.008
.                  DET&SPR   =0.007
```

EXHIBIT V Expert Choice Sample Printout for Case II
Homeowner with higher-than-average risk exposure, risk-averse attitude

Ranking of decision alternatives with respect to selecting the best fire protection system

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SYNTHESIS OF LEAF NODES WITH RESPECT TO GOAL

OVERALL INCONSISTENCY INDEX = 0.06

```
SMKDET   0.267 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

SPRINKLR 0.354 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

DET&SPR  0.379 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

         =====
         1.000
```

DET&SPR --- Combination of smoke detectors and sprinklers
SMKDET --- Smoke detectors
SPRINKLR --- Sprinkler system

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Sieglinde K. Fuller

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The report demonstrates that the Analytic Hierarchy Process (AHP) is a promising decision tool for evaluating fire protection systems for homeowners. It lays the ground for development of specialized computer software for applying the AHP to decisions of individual homeowners. Unlike conventional methods of economic analysis, the AHP integrates quantifiable and qualitative variables. The study explores how to include in the decision-making process information on an individual's risk exposure and risk attitude, information which is generally difficult or impossible to quantify. By differentiating between risk exposure and risk attitude, this application goes beyond the AHP's conventional treatment of risk. The AHP is applied to the choice of purchasing smoke detectors, a sprinkler system, or a combination of the two. Two hypothetical cases are assumed, one in which the homeowner is risk-taking and has lower-than-average risk exposure, and one in which the homeowner is risk-averse and has higher-than-average risk exposure. Subjective probabilities of fire, death, injury, and property loss are merged with more easily quantifiable benefit and cost criteria. A method of pairwise comparisons provides the data to calculate priority vectors for the fire protection alternatives.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

analytic hierarchy process; building economics; decision support software; economic analysis; qualitative data; residential fire protection; risk analysis; risk attitude; risk exposure; sprinkler systems.

13. AVAILABILITY

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