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Causal maps and the evaluation of decision options—a review

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Causal maps are widely employed in problem-structuring interventions. They permit a rich representation of ideas, through the modelling of complex chains of argument as networks. The last stage of a problem-structuring intervention is often to identify and agree to a set of potential strategic options. In some circumstances the preferred direction may emerge naturally from a process of negotiation; in others further, more-or-less formal, analysis to evaluate the options and to understand their impacts on the goals could be helpful. Such analysis may help to bring closure to the process. The main aim of this paper is to review systematically the approaches for evaluating options following from the use of a causal map for problem structuring; some directly using the map structure, others working with concepts extracted from, or an external model derived from, the map. Following a proposed taxonomy, each approach is presented, and its advantages and disadvantages are discussed.

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Introduction

Causal maps have been widely used in problem-structuring interventions (Rosenhead and Mingers, 2004), in particular in the SODA (see chapter 2 of Rosenhead and Mingers, 2001)/Journey Making (Eden and Ackermann, 1998) methodologies (but see Axelrod (1976), Bryson *et al* (2004) and also Huff and Jenkins (2002) for other uses of causal maps). Such maps permit a rich representation of ideas, through the modelling of complex chains of argument, and are suitable for several types of analysis.

From a topological perspective, a causal map is a network of inter-linked concepts (ideas) which tries to represent the discourse of a person (but see Eden (1992) for details on the cognitive implications of this model). When employed in supporting decision-making, this discourse often assumes a means–ends structure, whereby decision options are means of achieving the decision-makers' goals.

When a facilitator is using a causal map as a problem-structuring tool, the preferred direction may emerge naturally from a process of negotiation. In some circumstances, however, further, more-or-less formal, analysis to evaluate the options and to understand their impacts on the goals could be helpful (Eden and Ackermann, 1998).

It is important to establish how we will use the terms 'decision option' and 'evaluation'. A decision option is one of a number of possible courses of action which the decision-makers wish to assess in terms of their goals. An option may be represented by a single concept in the map (a simple option) or it may be a compound option defined by a synthesis of several concepts (each in their turn representing a simple option or some aspect of the aggregate activity). In some of the approaches we will discuss, options feature as tails (concepts with only out-arrows) in the cause–effect map; and in others, they may be elaborated by concepts providing additional descriptive detail; and in others, the options may be external to the map (although they may have been generated by reference to it).

The evaluation may take different forms corresponding to a 'problematique' of *choice* of one or a small set of alternatives, *ranking* of alternatives, *classification* of alternatives into categories, or *description* of the consequences of alternatives in a systematic way (Roy, 1996). The specific purpose of the evaluation is significant for the degree of discrimination sought between options.

The main aim of the paper is to review approaches for evaluating options following on from the use of a causal map for problem structuring; some directly using the map structure, others working with concepts extracted from, or an external model derived from, the map.

The existing literature discussing the analysis of causal maps is not extensive and is also quite disperse; furthermore, there is little of this which is focused on the analysis of decision options. Eden *et al* (1992) and Eden (2004) present comprehensive reviews of potential analyses of this type of model, covering the broader topic of structuring issues; other

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authors (Axelrod, 1976; Wellman, 1994; Marchant, 1999) provide interesting insights on the analysis of causal maps, but again they are not focused on the problem of evaluating options. Eden and Ackermann (1998) present a thoughtful discussion on closure of decision processes supported by causal maps, and present some tools for evaluating strategic options; but their main emphasis is on the social process of supporting strategic decision-making rather than analysis of the map.

In reviewing the different approaches that have been presented for the analysis of decision options in conjunction with the use of causal maps, we aim to propose a coherent taxonomy, a systematic analysis of their main features, and a discussion of the advantages and disadvantages of each. We hope it may make the subject more accessible to facilitators of problem-structuring interventions and may help to extend their toolkit of analytical methods. It could provide, also, a framework within which researchers interested in the topic may undertake further analysis and development of these methods.

The paper starts with a brief presentation of the process of causal inference in causal maps, which sets the scene for a discussion of the evaluation of options with a causal map. We then review approaches that seek to evaluate decision options using the map structure. Next, we present methods that do not use the map structure to evaluate options but employ, instead, concepts extracted from the map, or external models for such evaluation. We conclude the paper with a discussion of some general issues relevant to the approaches reviewed here.

Causal inference in causal maps

Causal maps have been widely employed to represent subjective knowledge about a phenomenon, that is, a discourse about perceived causes and effects and about the perceived links between those causes and effects (for details see Eden, 1992). In this section we present briefly the topology of this type of model, and the concepts that underlie causal inference analysis. We also discuss the issues of indistinction and indetermination of decision options, which need to be addressed by any approach for evaluating alternatives.

The topology of a causal map

Topologically a causal map is a network, where each node represents a concept (an idea) and a link between two nodes represents causality/influence/implication (Axelrod, 1976; Wellman, 1994; Marchant, 1999; Eden, 2004). Thus, the map has a structure of causes and effects (or means and ends). In some approaches to mapping (like the one employed in the Journey Making methodology, described in Eden and Ackermann, 1998) concepts are bi-polar entities, the opposite pole (which may or may not be explicitly stated) elaborating the intended interpretation of the concept.

This network is a signed diagraph (Axelrod, 1976), where the links are arrows with a positive or negative sign. A positive sign indicates a positive perceived causal connection, whereby an increase in a cause generates an increase in the linked effect (eg 'more sales lead to more profit'). A negative sign denotes a negative connection, an increase in the cause leads to an increase in the opposite pole of the linked effect (for example, 'more sales lead to less spare production capacity'). Information about the strength of each link may also be displayed in the map (ie the perceived strength of each causal connection).

Causal inference

Causal inference in a causal map is concerned with determining the effect of a given cause concept on a given effect concept (Axelrod, 1976). For example, assume that the network in Figure 1a represents a causal map (where each concept is a numbered node). In this example, the decision-makers want to know the influence of causes ① and ② on the effect ⑤.

The analysis is performed along paths, where a path is defined as a sequence of distinct concepts that are connected by arrows from the first (cause) concept until the last (ultimate effect) concept. For example, in Figure 1a, there are two paths between ① and ⑤: ① → ③ → ⑤ and ① → ④ → ⑤. There are also two paths between ② and ⑤: ② → ③ → ⑤ and ② → ④ → ⑤.

In order to identify the total effect of each cause concept on the ultimate effect concept it is necessary to calculate two indices:

- *Partial effect* (PE) of a path: this index is obtained by multiplying the signs along the path. For example, in Figure 1a, between ① and ⑤ there is one positive and one negative path, while between ② and ⑤ there are two positive paths.
- *Total effect* (TE) of the initial concept on the last concept: this index is positive if all paths between those two concepts have a positive partial effect; it is negative if all paths have a negative partial effect; and it is undetermined otherwise. For example, in Figure 1a, ② has a positive effect on ⑤, but ① has an undetermined total effect on ⑤.

From this point we will focus our discussion on causal maps with a means/ends structure, as we are interested in causal maps for supporting decision-making (which usually generates a discourse with means–ends chains of argument, see Montibeller *et al*, 2005a). So instead of displaying a cause–effect structure, maps with means–ends arguments have decision makers' ends/goals at the top (nodes with only in-arrows) and decision options/means at the bottom (nodes with only out-arrows), as shown in Figure 2 (where each node represents a concept).

Indetermination and indistinction

The process of causal inference raises two types of issue in generating recommendations about which options are more influential/attractive. We will refer to these as *indetermination* and *indistinction*. Figure 1a represents a case of

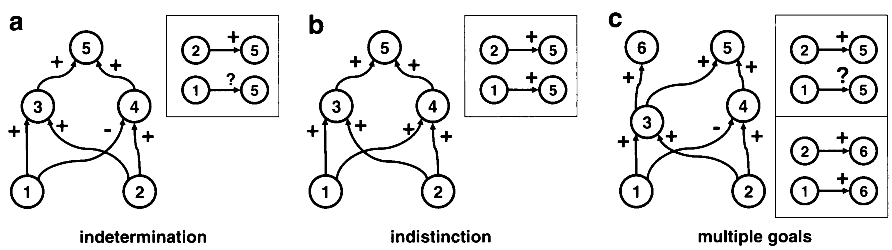

Figure 1 Indetermination and indistinction in causal maps.

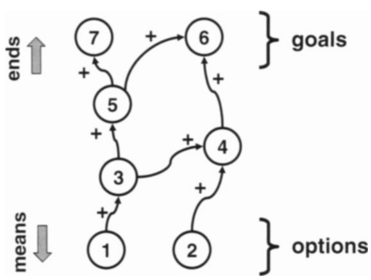

Figure 2 Goals and options in a causal map.

indetermination of the effect of option ① on the goal ⑤, as its total effect is undetermined (TE(① → ⑤)=?). This situation is also referred to as a dilemma (Eden *et al*, 1992), as node ① has both positive and negative influences on node ⑤. The other issue that may arise in this sort of analysis is that of indistinction, when there is not enough information to differentiate the effect of different means on a given end. This is exemplified in the causal map shown in Figure 1b, where both options ① and ② have a total positive effect on ⑤ (TE(① → ⑤) = + and TE(② → ⑤) = +). If we were seeking to chose between these options this analysis does not provide us with the information to do so.

The two networks displayed in Figure 1 have only one goal (node ⑤). In practice we would expect maps with several goals, in which case, the analysis we show should be performed for every goal and we may wish to consider the impact of the options on the overall goal system. For example, if a second goal ⑥ is included in network 1a, as seen in Figure 1c, with the associated positive link ③ → ⑥, then: TE(① → ⑥)=+ and TE(② → ⑥)=+. In this case, there is indistinction of these two options (① and ②) with respect to goal ⑥ but not indetermination. The assessment of the overall effect of the options on the goal system may be achieved by considering each of the individual goals to be linked to an overall supra-goal and extending the analysis described.

When a causal map is used in a real-world problem-solving process, it tends to be large (sometimes with hundreds of nodes, as described by Eden, 2004) and therefore we may expect to see many instances of indetermination, given the generally conflicting nature of goals. However, even if there are no undetermined total effects, the issue of lack of distinction remains and in such cases, it may be difficult to make recommendations about which options are more influential (Axelrod, 1976; Kosko, 1986; Montibeller *et al*, 2005a). For this reason, several ways of increasing the power of causal inference in causal maps have been proposed; these are reviewed in the next section.

Approaches employing the map structure

There are three main methods that employ the map structure for evaluating options: the use of the topological characteristics of a causal map; the assessment and analysis of strength of its links; and a multi-dimensional assessment of options' performances across the network. The two first methods assume an option is defined as a concept in the map, while the third method introduces options as external entities. These approaches are presented in this section.

Topological analysis

A common way of providing some information about which options are more influential on decision-makers' goals is by performing a topological analysis of the causal map. Some of the topological characteristics which have been proposed are:

- *Potency*: The potency of an option is determined by the number of goals it influences (Eden *et al*, 1992; Eden, 2004). For example in Figure 2, option ① is more potent than option ② (as ① influences goals ⑥ and ⑦, while ② influences only goal ⑥). The rationale here is that options that impact on the achievement of more goals are more potent.
- *Shortest path*: In this case, the option with the shortest path to the goals is considered to be the most influential one (Hall, 2002). For example, in Figure 2 option ② is more influential than option ①, as it has a shorter path (② → ④ → ⑥ compared to ① → ③ → ⑤ → ⑦, ① → ③ → ⑤ → ⑥ or ① → ③ → ④ → ⑥). The underlying principle here is that the shortest path represents the simplest argument in favour of an option.

In outlining the above topological analyses we discuss only how they could help with the issue of indistinction. The measurement of potency could also be employed to resolve indetermination, as through consideration of the number of positive and negative goals influenced by an option and/or the number of positive and negative paths between an option and the goals (thus determining a measure of +ve and −ve potency). The shortest path method employs a different strategy for dealing with indetermination, which will be presented when we review the *preference elicitation* approaches further on in the paper.

The main advantage of the rules using topological analysis is that they do not require any extra preference information. They are also simple to explain to decision-makers. This type of analysis can be performed using software available for analysing causal maps, such as Decision Explorer (www.banxia.com).

On the other hand, because of the lack of extra preference information, these approaches provide a low level of causal inference. In particular they struggle to cope with issues of indetermination. The next section presents methods that try to overcome this limitation, extending the power of inference in causal maps.

Analysis based on strength of links

The key idea behind the approaches that utilize the strength of links is that, by eliciting information on strength of causality (influence) between each pair of cause–effect (means–end) concepts, it is possible to provide richer recommendations than is possible using only topological analysis. Some of these methods are described below:

- *Qualitative assessments of strength*: In the method proposed by Kosko (1986), assessments of the strengths of causality/influence are elicited from the decision-makers using an ordinal scale (ordered qualitative labels). Information is aggregated for each option across the map using partial and total effect operators suited to this type of scale (he suggested using the Minimum for partial effect, and Maximum for total effect).

  For example, assume that a group of decision-makers has provided the assessments of strengths shown in Figure 3a.

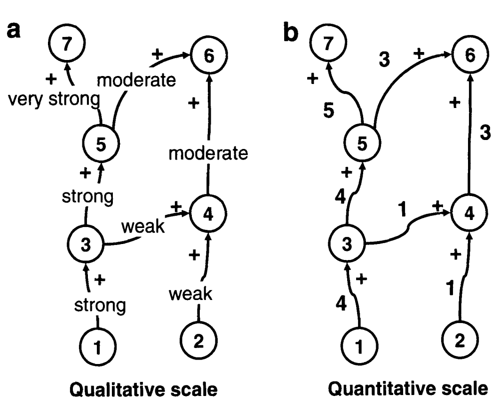

Figure 3 Elicitation of strengths of preference in causal maps.

  Then the partial effect ① → ⑦ is

$$PE(① \to ③ \to ⑤ \to ⑦) = \text{Min[strong, strong, very strong]} = \text{strong}$$

  In the same way: PE(① → ③ → ④ → ⑥) = weak; PE(① → ③ → ⑤ → ⑥) = moderate; and PE(② → ④ → ⑥) = weak.
  Total effect of option ① on goal ⑥ is given by

$$TE(① \to ⑥) = \text{Max}[PE(① \to ③ \to ④ \to ⑥), PE(① \to ③ \to ⑤ \to ⑥)] = \text{Max [weak, moderate]} = \text{moderate}$$

  In a similar way: TE(① → ⑦) = strong; and TE(② → ⑥) = weak.

  Thus, in this example, option ① has more positive influence on goals (moderate on ⑥ and strong on ⑦) than option ② (weak influence on ⑥).

  Kosko (1986) called this model a 'fuzzy cognitive map', suggesting that the qualitative labels could be fuzzified (ie represented by fuzzy functions) in conjunction with the use of appropriate fuzzy aggregation operators. More recently he redefined this type of model as a quantitative dynamic neural network (Kosko, 1992) and several extensions of this later model have been suggested, for example Khan and Quaddus (2004). However, this more recent model is concerned with inferring the dynamic behaviour of a system, rather than evaluating options, and for this reason will not be reviewed here.
- *Quantitative assessment of strengths*: Roberts (1976) proposed a method where a 'weight' is elicited for each link, as a measurement of intensity of strength. Partial effects are calculated by multiplying the strengths along a path. Total effects are calculated by adding up the partial effects.

  For example, assume that a group of decision makers has provided the strengths displayed in Figure 3b. Then the partial effect ① → ⑦ is given by

$$PE(① \to ③ \to ⑤ \to ⑦) = 4 \times 4 \times 5 = 80$$

  In a similar way: PE(① → ③ → ④ → ⑥) = 12; PE(① → ③ → ⑤ → ⑥) = 48; and PE(② → ④ → ⑥) = 1 × 3 = 3.
  The total effects for each option are given by: TE(① → ⑥) = 12 + 48 = 60; TE(① → ⑦) = 80; TE(② → ⑥) = 3. Thus, in this example, option ① is clearly more influential on goals (60 on ⑥ and 80 on ⑦) than option ② (3 on ⑥).
- *Probabilistic methods*: More complex quantitative methods have also been proposed for extending the power of inference in causal maps, using probabilistic information. Two of these frameworks allow the evaluation of options.

  In the first one, a causal map has been modelled as a Bayesian network (Nadkarni and Shenoy, 2001, 2004) where each node of the network is represented by a variable with a set of possible states (each state with probabilities defined by the decision-makers). Links in the map are represented as conditional probabilities. A table of conditional probabilities should be defined for each concept (that takes into account the probability of every outcome, given the combinations of the states associated with its means concepts). Decision options can then be evaluated by defining the actual states of each variable associated with tail concepts, and then propagating this information across the network.

Another quantitative framework represents a causal map as a qualitative probabilistic network (QPN, proposed by Wellman, 1994). A random variable is associated with each concept, and links denote probabilistic dependence. A positive link from a variable v_i (associated with a means concept) to a variable v_j (associated with an end concept) indicates that the larger the value of v_i, the higher the probability that the value of v_j is large as well. A negative link between v_i and v_j indicates that the larger the value of v_i, the lower the probability that v_j is large (see also Marchant, 1999). Decision-makers can then identify the probability that a given decision option would have a large value on the goal concepts, given its performance on tail concepts. The framework also proposes definitions of synergy between partial effects that can solve indetermination. (The full description of these two methods, Bayesian networks and QPN, is beyond the scope of this paper, and the reader is referred to the original articles for details.)

The method proposed by Roberts (*quantitative strengths*) resolves both the issue of indistinction (as exemplified above) and of indetermination (multiplications and summations carry the +ve or −ve signs, so if a partial effect is, for example, +80 and another one is −40, the total effect would be 40 = +80 − 40). The probabilistic methods also solve completely the indistinction and indetermination issues. Kosko's (1986) fuzzy cognitive map (*qualitative strengths*) just considers +ve links, so it does not cope with the issue of indetermination, but provides some support with the issue of indistinction, as presented in the example above.

Thus, the main advantage of the approaches that rely on the strength of links, when compared with the topological analysis, is that they increase significantly the power of inference in causal maps. Generally speaking, the more quantitative information is elicited, the greater the power of inference provided by the model.

On the other hand, one of the drawbacks of these methods is precisely the need to elicit quantitative information about the strength of links and, in some methods, to associate a variable with each concept (the only exception being Kosko's method based on *qualitative strengths*, which elicits only qualitative information). Another issue is the debate about the meaning of these measurements, and, indeed, if they are meaningful at all (Wellman, 1994; Marchant, 1999). Finally, there are few reports about real-world interventions using these methods, so it is hard to appraise how successful they are in supporting decision-making (one exception is Nadkarni and Shenoy, 2004, who describe a practical application, but still there is no discussion about the interaction between model and decision-makers).

The next section presents a tool that is also based on the idea of eliciting information about strengths of links, but seeks to address some of the drawbacks just raised.

Reasoning maps

Recently we have proposed a decision support tool called a reasoning map (Montibeller *et al*, 2005a) which enables a multi-criteria evaluation of decision options using a causal map structure. The evaluation is made wholly in qualitative terms: employing qualitative labels to describe strength of links and performance of options, and qualitative operators for aggregating performances across the network.

A reasoning map is a particular type of causal map, with a means–ends structure. This structure is composed by attribute concepts at its bottom, which lead to consequence concepts, and to final values at its top. For example, suppose hat the network displayed in Figure 4a is a reasoning map. The decision-makers are then required to associate a variable to each concept (eg for the concept 'increase our profits' the variable may be 'level of profits') and to map this onto a common qualitative scale (specified by the decision-makers) as seen in Figure 4b. Information about the strength of influence of each link is then elicited from decision-makers, using the same qualitative labels, anchoring their judgements in terms of the range from the lowest limit to the highest limit in each attribute concept (for example the strength e_{16} between concepts ① → ⑥ was judged as strong in Figure 4c). The performance of a decision alternative is evaluated in terms of its qualitative performance on each attribute (for example, as seen in Figure 4d, a given alternative a is **s**trong on v_1, **m**oderate on v_2, and **s**trong on v_3).

Operators for partial and total effects (inputting and outputting ordinal data) are defined according to the decision-makers' preferences. For example suppose that, in the example, they chose Minimum for PE. Then the partial effects impacting on node ④ are (as shown Figure 4e):

$$\begin{aligned}&\mathrm{PE}_{①\rightarrow④}(a)\\&\quad=\mathrm{Min}[v_1(a), e_{14}]\\&\quad=\mathrm{Min}[\text{strong}, \textbf{m}\text{oderate}]=\textbf{m}\text{oderate}\end{aligned}$$

$$\begin{aligned}&\mathrm{PE}_{②\rightarrow④}(a)\\&\quad=\mathrm{Min}[v_2(a), e_{24}]=\mathrm{Min}[\textbf{m}\text{oderate}, \textbf{w}\text{eak}]=\textbf{w}\text{eak}\end{aligned}$$

Suppose now, again referring to the example, that the decision-makers define Maximum for TE. Thus the total effect on node ④, given the PE calculated above, is (as shown in Figure 4f)

$$\begin{aligned}\mathrm{TE}_{④}(a)&=\mathrm{Max}[\mathrm{PE}(①\rightarrow④), \mathrm{PE}(②\rightarrow④)]\\&=\mathrm{Max}[\textbf{m}\text{oderate}, \textbf{w}\text{eak}]=\textbf{m}\text{oderate}\end{aligned}$$

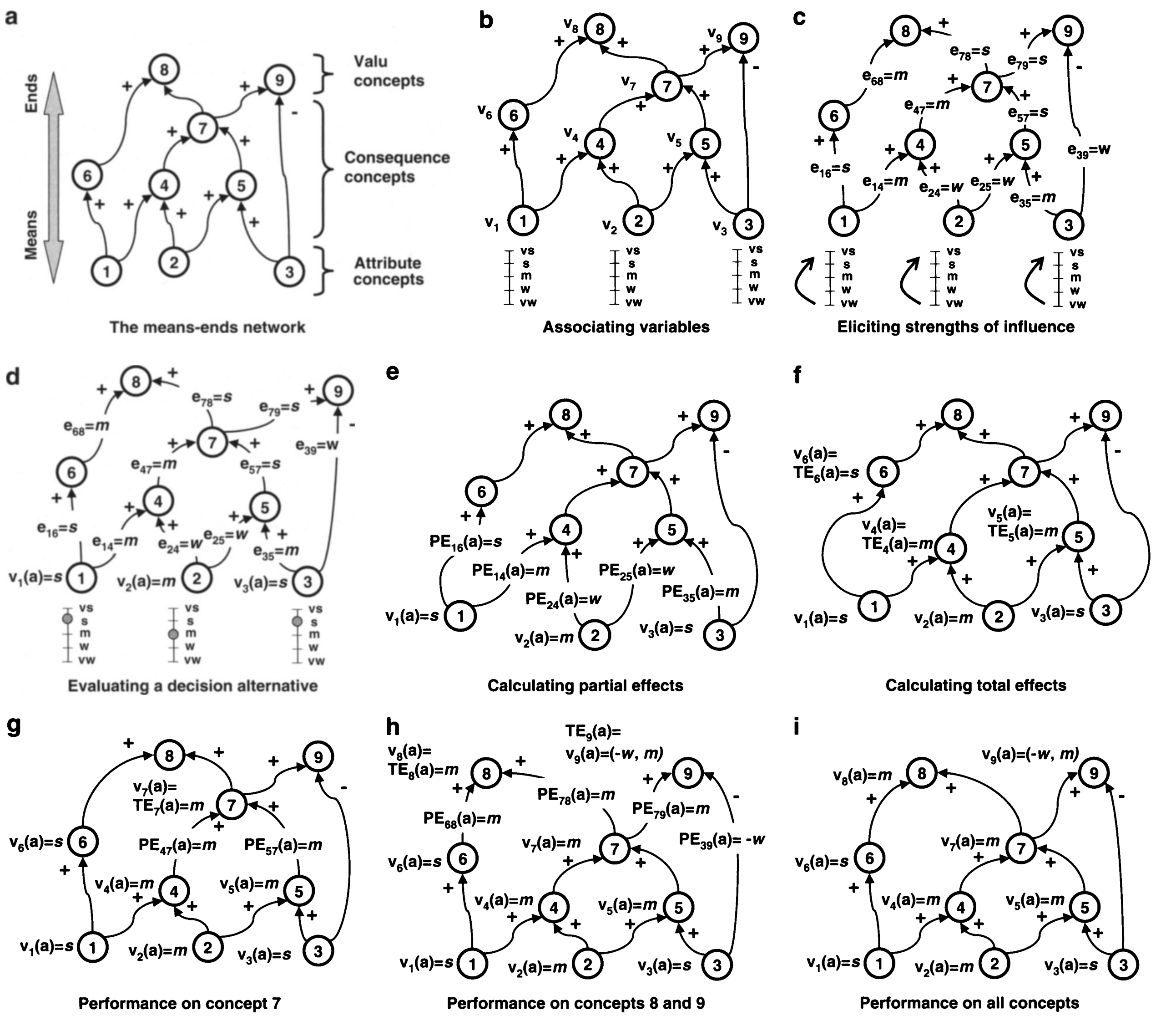

Figure 4 Evaluating decision options with a reasoning map (vs = very strong, s = strong, m = moderate, w = weak, vw = very weak).

Using these operators alternately, it is possible to aggregate performances across the map, as Figure 4g–i illustrates. Negative and positive performances are kept apart in this modelling, so if there were negative links, each alternative would have a negative and a positive effect on each node. For example, the performance of alternative a on node ⑨ has a negative component (Figure 4h): $\mathrm{TE}_{⑨}(a) =$ (−**w**eak, **m**oderate); that is, a weak negative influence and a moderate positive influence.

Reasoning maps cope to some extent with both the issues of indetermination and indistinction. As illustrated in the above example, the performance of each option is evaluated on each node using the specified qualitative scale, thus permitting distinction of positive and/or negative contribution of options (to a certain degree, given the limited granularity of a qualitative scale). In terms of indetermination, information about positive and negative strength of performance is helpful, although it does not completely resolve the issue (for example, in the example above, the positive impact of alternative a on goal ⑨ is stronger than the negative one).

While reasoning maps share the use of qualitative strengths of links and of qualitative operators with Kosko's (1986) method, they differ primarily in the use of variables (mapped onto a common qualitative scale) to describe the performance of the options with respect to attributes and in allowing positive and negative links. This means that the decision options are not concepts embedded in the causal map, rather they are external entities whose connection to the map is different to a standard means/end link. Also, they allow a flexible choice of operator for the calculation of partial and total effects (although this flexibility could be incorporated in the Kosko model). In common with Kosko's method all reasoning is done in qualitative terms, avoiding the cognitive burden involved in eliciting quantitative information (Larichev, 1992) that is a concern with the majority of methods using *strength of links*. In reasoning maps the elicitation of the strengths of links is anchored on attribute levels, with the aim of achieving an operationally well-defined and psychologically valid meaning.

As with other methods that elicit *strength of links*, reasoning maps extend the power of inference of causal maps by the introduction of extra information on decision-makers' preferences. For this reason, they provide richer results than the *topological analysis*. However, they also present some of the same drawbacks, in particular, the need to specify variables and assessing strengths of influence (albeit qualitatively) and the additional need to select the operators for partial and total effect. The method is still in a developmental phase, however, initial results from real-world applications (see Montibeller *et al*, 2005a, b) are encouraging.

Thus far all the methods presented in this paper, for analysing the impact of decision options on decision-maker's goals, have employed the causal map structure as an evaluation tool. The next section reviews approaches that do not directly employ the causal map structure for this evaluation. Instead, they evaluate the options, which may or may not be derived from concepts in the map, either using concepts extracted directly from the map or using an external model, the structure of which is derived from or informed by the map.

Approaches employing extracted concepts or external models

As indicated above, the approaches described in this section are informed by and in part based on concepts from the causal map resulting from a problem-structuring process, but do not make direct use of the structure of the map. We consider methods that are based on the elicitation of some form of holistic preference information, performance measurement approaches and multicriteria analysis. While the first method assumes an option is defined as a concept in the map, the other two introduce options as external entities. These approaches are discussed in this section.

Preference elicitation

The first approach that extracts concepts from the map and uses these concepts in an external evaluation is preference elicitation. It requires that decision-makers either vote in favour of or against an option; or decide for a given option-goal path. Three methods are based on this idea:

- *Preferencing*: This is a voting method, described in Eden and Ackermann (1998) and Bryson *et al* (2004), which asks decision-makers to indicate their preferences for selected options which feature in the map. Each decision-maker performs a holistic judgement, informed by the map as a whole and their learning from the problem-structuring process. Typically, each decision-maker is provided with a number of votes (in practice these may be physical or electronic 'sticky dots') which they allocate to the options according to their positive and negative preferences. At the end of this process, the total number of positive and negative votes assigned to each option is determined (for example, in Figure 1b, option ① could receive 10 +ve and 5 −ve votes; while option ② could receive 10 +ve and 15 −ve votes).
- *Shortest path*: In the analysis suggested by Hall (2002), once the positive and the negative shortest paths are identified via a topological analysis, decision-makers are asked to choose whether it is the negative or the positive link that better reflects the impact of a given option on a goal (for example, in Figure 1a, they could say that the path ① → ③ → ⑤ reflects the impact of option ① on goal ⑤ better than ① → ④ → ⑤).
- *Impact of paths*: In this method, proposed by Chaib-draa (2002), once all the positive and negative paths from a given option to goals are determined, the decision-makers identify which paths are more valuable. It is similar to the previous one, except that the focus is not only on the shortest paths.

The *shortest path* and *impact of paths* methods resolve the issue of indetermination by asking the decision-makers to choose their focus on the positive or negative impact of an option on a goal. They were not concerned about the issue of indistinction.

The *preferencing* method provides some support for the issue of indetermination, as the decision-makers may compare the number of positive and negative votes for each option. It is designed to help with the issue of indistinction, but the issue remains of how to aggregate positive and negative votes; options may be ranked according to the number of positive votes with negative votes having only a veto function, or they may be ranked according to the net positive votes (obtained by subtracting negative votes from positive).

These methods also elicit extra preference information from decision-makers. However, in contrast to the methods reviewed in the last section (*strength of links* and *reasoning maps*) this information does not increase the specification of the causal map itself. Instead, these methods seek to directly resolve issues of indetermination and indistinction by presenting these dilemmas to the decision-makers and seeking their holistic evaluation.

The main advantage of these approaches is their simplicity. Their main weakness is that they do not use the rich map structure to perform the evaluation of options. For the *path* approaches, the selection of only one positive *or* negative path may be too simplistic, as consideration of indetermination usually plays an important role in decision-making (each option typically has positive *and* negative effects and a

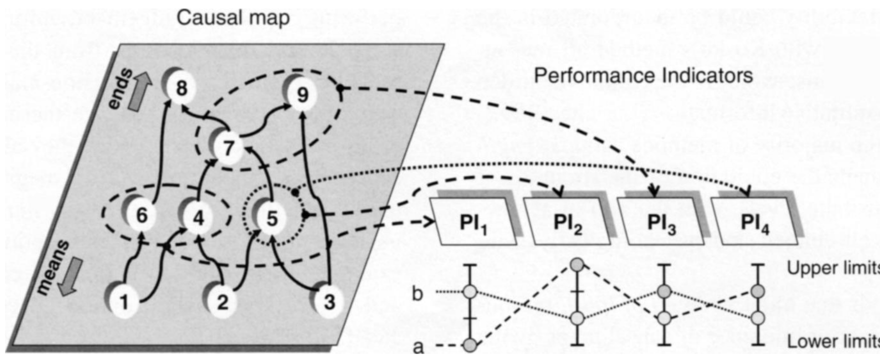

Figure 5 Deriving performance indicators from a causal map.

key aspect of the decision-making is to balance these against each other). For the *preferencing* approach, there is a risk that the holistic evaluation does not take into account the full multi-dimensional complexity of all options, but relies instead on well-recognised simplifying heuristics (see Goodwin and Wright (2004), for an introductory presentation of these heuristics).

Performance indicators

The second approach that extracts concepts from the map in order to perform evaluations is the use of performance indicators as suggested by Eden and Ackermann (1998) and also Suwignjo *et al* (2000). In this method, the structure and content of a causal map informs the definition of performance indicators, in an *ad hoc* way.

For example, assume that the network displayed in the left-hand side of Figure 5 represents a causal map. The group of decision-makers may define performance measurements from a single concept, like node ⑤, which generates performance indicators PI_2 and PI_4 (for instance, the concept 'increase sales' may be measured by 'level of sales in the domestic market' and 'level of sales in the international market'). A group of concepts may generate a single indicator, like ⑥ and ④ forming PI_1 (eg the concerns 'invest more in R&D' and 'extend our portfolio of products' may be appraised by 'number of new products released per year'). A group of concepts that suggest an indicator may be also placed in different hierarchical levels, like ⑦ and ⑨ generating PI_3 (for example 'more revenue would lead to more profit', may be measured by 'level of profits').

Once the indicators are derived from the map structure and content, they can be employed as the basis for measuring the performance of options, which can be depicted using simple visual displays that highlight strengths and weaknesses, as illustrated in Figure 5 for alternatives *a* and *b*. The issue of indetermination with respect to each measure is resolved through the use of direct measurement, but there is no attempt to aggregate negative and positive indicators. Similarly, the process does not necessarily seek to resolve the issue of indistinction directly (ie it does not provide guidance about which option is preferred).

The main advantage of using performance indicators is their simplicity: they are easy to explain and the visual display of performance of decision alternatives on each indicator may be quite useful in promoting discussion about the pro/con of each option. It is also a good way of creating a follow up monitoring system, once an option is selected and implemented.

There are a number of limitations to the determination and use of performance indicators in this way. Firstly, as they do not use the map structure to perform the evaluation, the rich information contained in the causal map (multiple +ve and −ve paths, complex paths of arguments) may not be taken fully into consideration in the measurement. Also, the definition of the performance indicators, from the causal map, may be a difficult task, as they have to be 'translated' from both the map structure and content (and therefore it would be hard to automate this transition).

As already indicated, this simple use of performance indicators does not resolve issues of indistinction. However, it is a simple step to build a multicriteria model based on performance measures. Multicriteria models also incorporate preference information on acceptable trade-offs between performances on different dimensions, and thus solve both issues of indetermination and indistinction, as described in the next section.

Multicriteria decision analysis

The last approach to be outlined in this paper is the joint use of causal maps and Multicriteria Decision Analysis (MCDA). In particular, multi-attribute value analysis (a simple and well-founded type of MCDA method; for details see Belton and Stewart (2002), Goodwin and Wright (2004), and the classic text of Keeney and Raiffa (1993)) has been employed for the evaluation of options, following an initial phase in which causal maps were used to support problem structuring (Belton *et al*, 1997; Bana e Costa *et al*, 1999; Ensslin *et al*, 2000). As with *performance indicators*, this approach does not use the causal map structure directly to evaluate options.

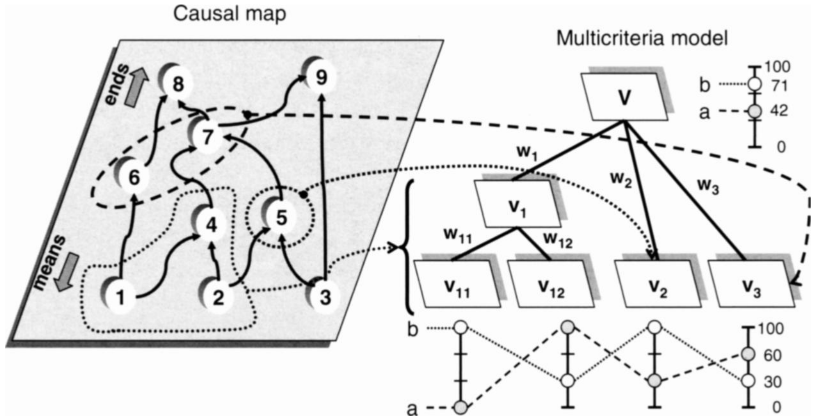

Figure 6 Structuring a Multicriteria model from a causal map.

A multi-attribute value model decomposes decision-makers' strategic objectives into levels of increasing specification and structures these as a value tree, as illustrated in the right-hand side of Figure 6 (the strategic objective V is decomposed into sub-objectives v_1, v_2 and v_3; and v_1 is further decomposed into v_{11} and v_{12}). At the lowest level of the value tree these objectives are translated into attributes, with each one of them evaluating a given characteristic of the decision options (for example, the objective 'increase our sales' may be measured by the attribute '% increase in level of sales'). Thus, in Figure 6, there would be attributes for v_{11}, v_{12}, v_2 and v_3, for which well-defined scales are constructed. The performance of each decision option against each attribute is determined and weights reflecting acceptable trade-offs of performance among objectives are elicited from the decision-makers.

Figure 6 exemplifies the process of evaluation of two alternatives a and b. A global performance of each option then can be calculated, using the performances of each alternative on each attribute and the weights. For example in the same figure, assume that $w_{11}=60\%$ and $w_{12}=40\%$; also that $w_1=30\%$, $w_2=40\%$ and $w_3=30\%$. Then, given the performances on each attribute displayed in the same figure (gauges below each attribute), the global value V of option a is

$$
\begin{aligned}
V(a) &= w_1 v_1(a) + w_2 v_2(a) + w_3 v_3(a)\\
&= w_1[w_{11} v_{11}(a) + w_{12} v_{12}(a)]\\
&\quad + w_2 v_2(a) + w_3 v_3(a)\\
&= 0.3[0.6 \times 0 + 0.4 \times 100]\\
&\quad + 0.4 \times 30 + 0.3 \times 60 = 42
\end{aligned}
$$

In the same way, the global value of option b is: $V(b) = 70.6 \approx 71$.

This evaluation model is based on several assumptions about the decision-makers' structure of preferences; see Belton and Stewart (2002) and also Keeney and Raiffa (1993) for a complete discussion of multi-attribute value models and their properties.

When used in conjunction with a causal-map, the structure and content of the map informs the building of the multi-attribute value model, in an *ad hoc* translation. Similarly to what was described for *performance indicators*, the causal map may be used to elicit attributes and objectives (eg v_2 and v_3 in Figure 6). It also informs the structure of the value tree, which may be derived from the causal map's means–ends structure (as exemplified in the formation of v_1 and its sub-objectives v_{11} and v_{12} from the causal map's concepts ④, ① and ②).

The use of an MCDA, method like multi-attribute value analysis, resolves both the issue of indetermination and indistinction. (As with *performance indicators* negative impacts in the map are reversed in the attributes, so the best level is always on the top and the worst always at the bottom.) As the example in Figure 6 showed, the initial indistinction of options a and b on the attributes (neither was a dominating alternative) was resolved using quantitative weights. The problem of indetermination is resolved through the model structure, whereby all options are evaluated with respect to the hypothetical worst case scenario characterized by a zero score on all attributes (hence all evaluations represent added value with respect to this).

The main advantage of using a multicriteria method is the richness of results it provides. It generates not only a ranking of decision options, but also the relative global performance of every alternative (the gauge on the right-hand side of objective V in Figure 6). As with any model based on decision-makers' preferences, these results should be employed with caution, as preferences are constructed along the process of decision support, rather than simply mirrored by the model (Roy, 1996; Belton and Stewart, 2002).

Multi-attribute value analysis is a well-researched and well-founded methodology, and a relatively simple MCDA method. Software is widely available for supporting this type of multicriteria analysis, such as V•I•S•A (www.simul8.com) or Hiview (www.catalyze.co.uk). Some of the limitations of *performance indicators*, discussed in the previous section, can also be eliminated using MCDA, as Santos *et al* (2001) proposed.

However, the price of this richness is the need to build the value tree and to elicit quantitative information about performances and weights, which may be cognitively demanding (Larichev, 1992). It also requires a facilitator with knowledge and experience in the use of both causal maps, and MCDA (or two facilitators with these distinct expertises, as suggested Belton *et al*, 1997). The transition from a causal map to a multicriteria model also may be challenging as the two methods are based on distinct modelling rules (Montibeller *et al*, 2005a). Finally, as an MCDA model does not use the map itself for evaluating options, it may not fully capture some of the complex relationships displayed in the map.

We now conclude the paper with some general observations about the approaches that just have been described.

Conclusions

This paper has reviewed several approaches that may be used for the evaluation of options following on from the use of a causal map for problem structuring. An overview of this analysis is presented in Table 1.

We believe that this is the first attempt to compare and contrast these different approaches to analysis and would like it to be seen as the initiation of a discussion rather than a conclusive assessment. Our evaluation is based on our personal experiences and perspectives and we recognize that others may perceive different advantages and disadvantages of each approach.

We have presented these approaches in a complete and fairly 'clinical' manner, not seeking to explore in any depth the way in which they might be used in action with a group of decision-makers. However, it is important to remember that we see the principal aim of analysis as furthering understanding and promoting discussion of a problem, not for providing a numerical solution (Roy, 1996; Belton and Stewart, 2002). The ultimate test of any of these approaches is the extent to which a facilitator can utilize them in this way, a factor that is dependent in part on the facilitator's style and specific skills, in part on the availability of easy to use supporting software, in part on the particular context and on the decision-making group.

We conclude with some general comments on the approaches we have described and their potential use in practice.

Intent of intervention

The extent to which a particular approach to the analysis of options within, or in conjunction with the use of, a causal map is appropriate will depend on the original intent of the intervention and the manner in which it evolves. In some circumstances, the need to incorporate a detailed evaluation of options within a broader exploration of an issue may be clear from the start. In such circumstances it may be worthwhile designing the intervention with the intent of incorporating a framework to allow such a detailed evaluation, as described by Belton *et al* (1997). This particular intervention used a multicriteria model derived from the causal map, but it is also possible to consider one of the forms of analysis described here directly using the map structure. In other situations, the need for the evaluation may emerge during the process, or may not be a central focus of it; in this case it may be more appropriate to first use some of the simpler topological analyses.

Extent of the map

If the intervention is focused from the start on evaluating options then the resultant map could be such that it contains little additional information and thus provides a compact model for this evaluation. If the intervention is more broadly focused and the need for a detailed analysis of options emerges, then it may be appropriate to collapse the map onto the relevant concepts (options and goals) and the paths which link these. The collapsed map may then be used as the basis for one of the analyses based on *strength of links* or *reasoning maps*.

Considerations in choice of approach

The decision on which approach to adopt for the evaluation of options needs to take particular cognisance of the following factors:

- *Qualitative versus quantitative modelling*: As discussed throughout the paper, usually the more quantitative information is elicited, the higher the power of inference of the evaluation tool, but the higher the cognitive demands placed on the decision-makers (Larichev, 1992; Montibeller *et al*, 2005a). Thus, the decision to employ a more quantitative approach must balance these factors in arriving at a judgement about whether the additional efforts (cognitive and temporal) merit the additional insights and auditability which may be achieved.
- *Preference elicitation and groups*: Frequently causal maps are employed with groups, which can make the elicitation of preferences more onerous for those approaches that require it. The facilitator would have to decide if it is appropriate to elicit the preferences of the group (which may disclose different opinions and raise conflicts, but also generate new insights) and if so, how (for example, whether a 'sharing' or 'comparing' mode is more suitable, see Belton and Pictet, 1997). Or, rather, is it better to use methods based on topological information that do not require preference elicitation (making the analysis quicker and less burdensome, but also less challenging for the group).
- *Direct or indirect use of the causal map*: Some of the approaches described (MCDA and use of performance indicators) require a transition from the map to an external model. This is an *ad-hoc* process which relies heavily on the expertise of the facilitator. It may be time consuming and could be difficult to explain and justify the process to

Table 1 Approaches for evaluating options in causal map-based interventions

Approach	*Strategy*	*Pro*	*Con*
Topological analysis	Employs topological information from the causal map (eg number of paths, goals, length of paths)	• Does not require any extra preference information and are simple to explain • Analysis is supported by existing software.	• Power of inference is quite limited
Strengths of links analysis	Elicits extra information from the decision-makers about perceived strength of each causal link	• Extends the power of inference of causal maps • Uses the model as the evaluation tool (thus avoids a transition phase)	• Requires elicitation of strength of preference • Raises further issues on the meaning of causation • Lack of reports on their use in real practice
Reasoning maps	Uses the causal map to perform a multi-criteria evaluation of options, eliciting qualitative information about strengths of influence and performances of options	• Extends the power of inference of causal maps • Uses the model as evaluation tool • Permits to understand the impact of decision alternatives on goals along complex paths	• Requires elicitation of qualitative strength of preference • Requires definition of operators for partial and total effect • Still lacks user-friendly software to support the analysis
Preference elicitation	Decision-makers are required either to vote in favour/against an option; or to decide for a given option-goal path	• Simple to use and understand • Provide a display of pro/con of each option • Supporting software is available	• Does not use the rich map structure to perform the evaluation of options • Does not use a multi-dimensional evaluation of options (preferencing approach) • Focus on a single path may be too simplistic (path approaches)
Performance indicators	Derives, from a causal map, performance measurements, which are then employed to evaluate decision options	• Simple to use and understand • Provides a visual display of pro/con of each option	• Requires the translation of map concepts into performance indicators • Does not use the rich map structure to perform the evaluation of options • Does not model trade-offs between indicators
Multicriteria decision analysis (MCDA)	Derives, from a causal map, a value tree structure, which then is employed to perform a multi-criteria evaluation of decision options	• Represents performances and trade-offs, providing rich results (ranking of options) • Well-researched and well-founded method • Supporting software available	• Requires the translation of map concepts into a multi-criteria model • Does not use the rich map structure to perform the evaluation of options • Requires elicitation of quantitative performances and weights

decision-makers (as well as calling for additional cognitive effort, Montibeller *et al*, 2005a). However, the process may bring new insights and the use of the new ‘condensed’ model as the basis for a detailed evaluation of options may be more straightforward than an analysis which needs to incorporate the more detailed specification of the map (Belton *et al*, 1997). If this latter direction is taken we would strongly recommend that the map and the new model continue to be used in tandem: the former continuing to provide the context for the latter.

- *Type of evaluation*: Different types of evaluation may also guide the selection of a given approach. For example, if the ‘problematique’ is of *choice* of a single option, then both issues of indetermination and indistinction have to be resolved, thus leading to approaches that deal with both. On the other hand, if the ‘problematique’ is of *classification* into two categories (eg dividing alternatives with positive and alternatives with negative impact) then only the resolution of indetermination may be needed, which enlarges the spectrum of choice of approaches.

- *Creation of new options*: Often, in practice, the evaluation is not focused only on selecting the best alternative(s), but also on creating new (and better) options (Keeney, 1992). If that is the case, approaches that provide detailed information about the impacts of each alternative on concepts/criteria (such as MCDA, fuzzy cognitive maps or Reasoning Maps) could be suitable. Such detailed information may help the decision-makers to think about ways of improving an option (eg in Figure 6, how could alternative b be improved on criterion v_{12} and v_3?) and also about new options with better impacts on those concepts/criteria (eg in Figure 4d, is there a new option that could perform better than a on attributes v_1, v_2 and v_3?).
- *Measurement of influence*: It should be noted that the selection of the means to measure the propagation of influence through the map or in a derived model, whether it be a simple mechanism or a complex rule of inference, is an intrinsic part of the evaluation process. This choice should be guided by beliefs and preferences with regard to appropriate axiomatic foundations or psychological/cognitive frameworks. Different operators are likely to lead to different results. We suggest that, rather than looking for the 'right' set of rules, the selection of an inference process should be seen as a working hypothesis (Roy, 1993) with the aim of promoting further learning about the problem and the consequences of adopting a particular option.
- *Structure of the map*: It is often the case that a causal map developed during a problem-structuring intervention contains loops (Eden *et al*, 1992; Eden, 2004); indeed, these are seen as important characteristics of the problem. Whilst approaches that do not make direct use of the map are able to handle this in the translation to an external model, several of the analyses described here require the map to be acyclic (for a discussion see Wellman, 1994). The presence of loops usually indicates dynamic characteristics of an issue; these are important in the evaluation of options if they highlight distinctive features of those options. We suggest that there are two possible ways to proceed. The first is to ignore the dynamic effects in the analysis of options, restructuring the map to remove the loops (using, for example, one of the approaches suggested by Eden (2004) or by Nadkarni and Shenoy (2004)) and proceeding with the causal inference analysis. A second approach is to independently perform a dynamic analysis (for example, using system dynamics as described by Eden (1994), or the dynamic version of fuzzy cognitive maps proposed by Kosko (1992)) which could informally inform the analysis of options. Another version of this second approach is the one described by Santos *et al* (2004), which uses a causal map, a system dynamics model and a multi-attribute value analysis in the context of performance measurement.

Further to the above considerations in assessing suitability of approaches for different types of interventions, which all merit empirical exploration, we would like to note some generic directions for further research in this field. A key fundamental one, which is needed to facilitate any significant empirical investigation, is the design and development of software to support analysis using many of the approaches described in the literature. This will permit appraisal of their value in practice by making them more available for decision-makers and facilitators. A second area that merits more research is the choice of aggregation operators (taking into account the cognitive burden of preference elicitation, the type of results they provide, as well as their impact on decision-making) and the elicitation of preferences in causal maps. Effective software would also be helpful to facilitate study of these aspects.

To conclude finally, this paper is an attempt to present and review, in an accessible, but rigorous way, several approaches for evaluation of options following on from the use of a causal map for problem structuring. We believe this should be of interest to problem-structuring facilitators who employ causal maps in their practice and hope that the categorisation and evaluation of proposed methods may stimulate further discussion and research on this topic by the Problem Structuring Methods community.

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References

Axelrod R (ed) (1976). *Structure of Decision: The Cognitive Maps of Political Elites*. Princeton University Press: Princeton.

Bana e Costa CA, Ensslin L, Corrêa EC and Vansnick JC (1999). Decision Support Systems in action: integrated application in a multi-criteria decision aid process. *Eur J Opl Res* **113**: 315–335.

Belton V, Ackermann F and Shepherd I (1997). Integrated support from problem structuring through to alternative evaluation using COPE and V•I•S•A. *J Multi-Criteria Dec Anal* **6**: 115–130.

Belton V and Pictet J (1997). A framework for group decision using a MCDA model: Sharing, aggregating or comparing. *J Decis Syst* **6**: 283–303.

Belton V and Stewart T (2002). *Multiple Criteria Decision Analysis: An Integrated Approach*. Kluwer: Dordrecht.

Bryson JM, Ackermann F, Eden C and Finn CB (2004). *Visible Thinking*. Wiley: Chichester.

Chaib-draa B (2002). Causal maps: theory, implementation, and practical applications in multi-agent environments. *IEEE Trans Knowledge Data Eng* **14**: 1201–1207.

Eden C (1992). On the nature of cognitive maps. *J Mngt Studies* **29**: 261–265.

Eden C (1994). Cognitive mapping and problem structuring for system dynamics model building. *Syst Dynam Rev* **10**: 257–276.

Eden C (2004). Analyzing cognitive maps to help structure issues or problems. *Eur J Opl Res* **159**: 673–686.

Eden C and Ackermann F (1998). *Making Strategy—The Journey of Strategic Management*. Sage: London.

Eden C, Ackermann F and Cropper S (1992). The analysis of cause maps. *J Mngt Studies* **29**: 309–324.

Ensslin L, Montibeller G and Lima MVA (2000). Constructing and implementing a DSS to help evaluate perceived risk of accounts receivable. In: Haimes YY and Steuer RE (eds). *Research and Practice in Multiple Criteria Decision Making*. Springer, Berlin, pp 248–259.

Goodwin P and Wright G (2004). *Decision Analysis for Management Judgement*, 3rd edn. Wiley: Chichester.

Hall RI (2002). Gaining understanding in a complex cause–effect policy domain. In: Huff AS and Jenkins M (eds). *Mapping Strategic Knowledge*. Sage, London, pp 89–111.

Huff AS and Jenkins M (eds) (2002). *Mapping Strategic Knowledge*. Sage: London.

Keeney RL (1992). *Value-Focused Thinking: A Path to Creative Decision-Making*. Harvard University Press: Cambridge.

Keeney RL and Raiffa H (1993). *Decisions with Multiple Objectives. Preferences and Value Tradeoffs*, 2nd edn. Cambridge University Press: New York.

Khan MS and Quaddus M (2004). Group Decision Support Using Fuzzy Cognitive Maps for Causal Reasoning. *Group Decis Negot* **13**: 463–480.

Kosko B (1986). Fuzzy cognitive maps. *Int J Man-Machines Studies* **24**: 65–75.

Kosko B (1992). *Neural Networks and Fuzzy Sets*. Prentice-Hall: Englewood Cliffs.

Larichev OI (1992). Cognitive validity in design of decision-aiding techniques. *J Multi-Criteria Decis Anal* **1**: 127–138.

Marchant T (1999). Cognitive maps and fuzzy implications. *Eur J Opl Res* **114**: 626–637.

Montibeller G, Belton V, Ackermann F and Ensslin L (2005a). *Reasoning maps for decision aid: an integrated approach for problem structuring and multi-criteria evaluation*. Working Paper 2005/11, Department of Management Science, University of Strathclyde (available at: (http://www.managementscience.org/research/ab0511.asp).

Montibeller G, Belton V and Lima MV (2005b). Supporting factoring transactions in Brazil using reasoning maps: a language-based DSS for evaluating accounts receivable. *Decis Support Syst* (forthcoming, available at http://www.sciencedirect.com).

Nadkarni S and Shenoy PP (2001). A Bayesian network approach to making inferences in causal maps. *Eur J Opl Res* **128**: 479–498.

Nadkarni S and Shenoy PP (2004). A causal mapping approach to constructing Bayesian networks. *Decis Support Syst* **38**: 259–281.

Roberts FS (1976). The questionnaire method. In: Axelrod R (ed). *Structure of Decision: The Cognitive Maps of Political Elites*. Princeton University Press, Princeton, pp 333–342.

Rosenhead J and Mingers J (2004). Problem structuring methods in action. *Eur J Opl Res* **152**: 530–554.

Rosenhead J and Mingers J (eds) (2001). *Rational Analysis for a Problematic World Revisited*. Wiley: Chichester.

Roy B (1993). Decision science or decision-aid science? *Eur J Opl Res* **66**: 184–203.

Roy B (1996). *Multicriteria Methodology for Decision Aiding*. Kluwer: Dordrecht.

Santos S, Belton V and Howick S (2001). Adding value to performance measurement by using system dynamics and multicriteria analysis. *Int J Opns Product Mngt* **22**: 1246–1272.

Santos S, Belton V and Howick S (2004). Using system dynamics and multicriteria analysis for performance measurement: a case study. In: Neely A, Kennerly M and Walters A (eds). *Performance Measurement and Management—Public and Private*. Performance Measurement Association, Cranfield, pp 1197–1204.

Suwignjo P, Bititci US and Carrie AS (2000). Quantitative models for performance measurement system. *Int J Product Econ* **64**: 231–241.

Wellman MP (1994). Inference in cognitive maps. *Math Comput Simulation* **36**: 137–148.

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