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Managing Information to Support the Decision Making Process

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Abstract. Decision-making is a crucial activity during the planning, design and operation of artefacts. To make a decision several alternatives must be evaluated and compared, which are tasks that require information, knowledge and expertise. A system that organises and manages the knowledge associated with every alternative and links ideas, arguments and issues can greatly improve and facilitate the decision making process. This paper presents how an Issue Based Information System (IBIS) implemented in Compendium (http://compendium.open.ac.uk) has been extended with new functionalities such as access to a toolkit of Multi-Criteria Decision Methods (MCDM), the ability to propagate values throughout the decision records and to perform sensitivity analysis of the recommended decisions with respect to a parameter. These additional functionalities enable the applicability of the system in the support of decisions that require not only argumentation, but also numerical evaluation of the properties of the alternatives such as those proposed during the design, planning and operation of engineering artefacts.

Keywords: Issue-based information systems; rationale; information management; decision support systems; knowledge representation.

1. Introduction

Information technology has changed the way in which we deal with knowledge. Nowadays information is stored electronically and people can meet virtually in collaborating working spaces to share this information. Information is crucial for decision making; to reach a decision, experts need to be consulted, several options and arguments must be carefully investigated and mathematical models evaluated. A system that keeps track of how a decision was made, i.e. the argumentation and information used to reach it (also known as the decision rationale), will greatly help to improve the communication between decision makers, explore the impact of changes on past decisions, and provide justification and documentation for the decision process.

The objective of the research described in this paper is the development of a system to support decision-making by integrating a qualitative representation of argumentation (represented in terms of issues, alternatives and criteria) with quantitative Multi-Criteria Decision Methods (MCDM) that relies on variables reflecting how well an alternative complies with the criteria. This new approach extends the functionality of Compendium, a software tool for the visualisation and management of information (Selvin *et al.*, 2001), and thus not only shows graphically the information related to the different alternatives in a user-friendly environment but also supports the decision making process by proactively evaluating the alternatives and recommending a possible solution. The resulting tool extends the scope of application of dialogue mapping techniques to decision problems that involve numerical data and the use of mathematical models, e.g., for simulation and optimisation.

The paper is organised as follows: Section 2 is a concise literature review of previous and current related work. A brief introduction to Compendium and how it can be used as a decision support system is presented in Sec. 3. Section 4 introduces the concept of design rationale and some MCDM are briefly described. Details about the extensions to Compendium are presented in Sec. 5. A case study and its results are described in Sec. 6, and finally the paper closes with our current work and ideas about future work.

2. Literature Review

The representation of the qualitative components of decision rationale is based on the Issue Based Information System (IBIS) methodology a pioneering methodology proposed by Kunz and Rittel (1970) to tackle wicked problems, i.e. problems that have incomplete, ambiguous and/or contradictory requirements.[1] Wicked problems have no right or wrong answer but rather a "satisfying" solution that is "good", "better" or "good enough". Decisions associated with wicked problems are made as a result of argumentative processes. Issues are raised and a number of positions (alternatives or options) are put forward as possible solutions to the issue, arguments are then presented for and against each of the positions. The IBIS representation can record all of these issues, positions and arguments so that the whole process is transparent to the people involved. As a result, dialogue can be presented in a way that allows the reasoning to be carefully analysed. Other offshoots of the IBIS representation have been proposed, e.g., QOC (MacLean *et al.*, 1991), PHI (McCall, 1991) and DRL (Lee and Lai, 1991).

When IBIS was initially proposed the decision process was recorded manually with a view to computerising the process in the future. The first such tool was gIBIS (Conklin and Begeman, 1988); there are several other software tools that aim to record the decision making process and that are based on the IBIS methodology such as Quest Map and Compendium as described in (Shum *et al.*, 2006). In particular, Compendium is a software tool aimed at facilitating dialogue mapping, which makes it applicable as a meeting facilitator and for capturing discussion. Other systems based on IBIS but focused on engineering design rationale are KBDS (Banares-Alcantara and King, 1997) (chemical process design), Design RAtionale MAnagement (DRAMA) (Brice *et al.*, 1998) (energy and water sectors), DRed (Bracewell *et al.*, 2009) (diagnosis and design problems in the civil aerospace sector) and a system for the design of next generation information appliances (Park, 2011).

More detail about the two technical strands of our work is provided in the next two sections. First, a more in-depth explanation of the functionality of Compendium as a tool to represent qualitative knowledge through the use of IBIS-like structures, and then an introduction to MCDM and how they are integrated in the system to extend the ability of Compendium to manage quantitative information.

3. Compendium as a Knowledge Mapping Tool

Compendium is a software tool that allows information and ideas to be linked together through a visual interface (Selvin *et al.*, 2001; Bachler, 2004). These concepts are expressed in the form of issues (question nodes), potential solutions (answer/position nodes) and arguments (pros and cons nodes). External references such as Word and Excel documents, websites and other types of files can be dragged and dropped into Compendium (see Fig. 1, where the most common types of Compendium nodes are depicted).

Compendium keeps graphical (qualitative) links between the alternatives and their supporting arguments but in a number of disciplines, such as Engineering, it is possible to quantify the degree of compliance of an option with respect to a criterion. In these cases it is desirable to evaluate and rank all the alternatives using a variety of MCDMs, see Sec. 4.

Compendium can be used to capture the rationale behind an argumentation, i.e. the reasoning that justifies why a decision was made. One of the key aspects of the problem is how to capture and record a discussion/decision process without disrupting that process. Anything that is recorded should have real and immediate value but not at the expense of the smooth running of the process that is being recorded (Shum *et al.*, 2006).

According to Conklin *et al.* (2003) and Shum *et al.* (2006) there are three main functionalities of Compendium:

- Hypermedia concept mapping — Compendium provides a visual view of issues, ideas and argumentations and the connections between them. A map can be populated with the issues being considered, their possible solutions and the pros and cons for each one. Nodes can be reused in a number of contexts to represent the same idea or question in a number of different settings. Any change that is made to one occurrence of the node results in all occurrences of the node being updated.
- Conceptual frameworks — IBIS was designed to model a discussion. Templates can be created in Compendium so that a specific approach can be prescribed when tackling a problem. A template can be based on a standard operating procedure, best practice or some other approach as required. Using a template to solve a new problem can be beneficial since the set of issues that need to be addressed can be seen by the user(s) from the outset. This should ensure that no aspects of the problem solving process are ignored.
- Meeting facilitation — This function of Compendium relates to recording a meeting. This is not just a case of taking minutes but capturing the essence of the meeting to see what was discussed, what arguments were put forward and what decisions were made in the process. This is known as Dialogue Mapping. A good example of how Dialogue Mapping can be used in a meeting is

[1] See Conklin (2006) for a more inclusive list of the characteristics of wicked problems.

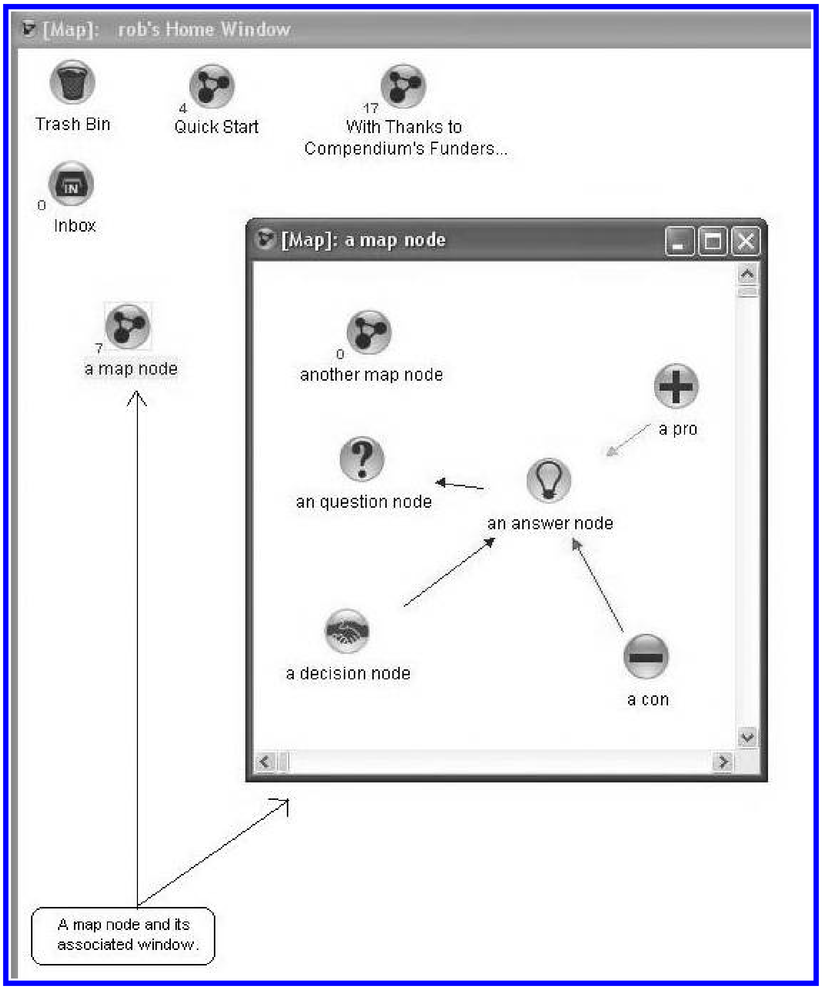


Fig. 1. A sample of Compendium nodes (taken from http://compendium.open.ac.uk).

presented by Conklin (2006). This approach to a meeting has a number of benefits associated with it: Meetings can become more focussed and productive; conflicts are depersonalised; and participants can see the progress of the meeting by following the display where the discussion is being mapped.

Compendium can also be used as a design process facilitator. We use Compendium mainly to record the process of design of artefacts.[2] This function is similar to the facilitation of meetings but without the need to record decision-making in real time. The length of a typical design process is on the order of months or years, involves dozens to hundreds of engineers, and makes use of several computer packages for simulation, optimisation and visualisation purposes.

This paper presents our approach to the development of a Decision Support and Management System that extends Compendium with Options versus Criteria matrix, and access to a library of MCDM and to numerical results, e.g., the results obtained from the simulation of mathematical models. This extension to Compendium can evaluate all the alternatives/options automatically and recommend the option that best satisfies all the criteria.

4. Design Rationale and Multi-Criteria Decision Methods

Design rationale deals with why decisions were made during the design process and the justifications for those decisions (Banares-Alcantara *et al.*, 1997; Brice *et al.*, 1998). One would expect that decisions made at various stages of a design are correct at the time of making them. However, certain factors such as those related to the environment, health and safety and cost estimations change over time. Therefore, it is possible that a decision that was made previously may no longer be correct when there is a change in the factors that were considered. When this type

[2] An artifact can be physical, such as a building or chemical plant, or immaterial, such as a policy or a piece of software.

of situation arises it is important to know how the original decision was made and also what effect a change in this decision would have on any subsequent decisions. The extent to which any change in the factors affect some decisions can only be fully considered if the decision processes have been recorded.

4.1. *Options versus criteria matrix to store the decision rationale*

Options versus Criteria matrix was used in a software tool called DRAMA (Brice *et al.*, 1998). DRAMA is a decision support tool that records decisions and their rationale during the design process. This tool was used in several academic and industrial applications, for example in the design of wastewater treatment plants (Vidal *et al.*, 2002). In this case, DRAMA was used to record the design objectives and the options considered for each of the issues, including the final choice and all the rejected options. For each issue a matrix was populated with all the options considered and the criteria against which they were evaluated. A weighting factor was added to each criterion to reflect its importance in the decision. For example, safety would have a large weighting in the context of aircraft design whereas cost may have a large weighting in the design of a watch. A normalised/scaled value between 0 and 1 is allocated to each option for each of the criteria in the matrix. The overall score for each of the options is then calculated, with the option having the highest score being the recommended choice. However, the final decision rests with the designers.

Based on the work developed in DRAMA we have extended Compendium by incorporating Options versus Criteria matrix, a value propagation function and a sensitivity analysis tool. The resulting extension to Compendium automatically evaluates each alternative and provides a recommendation using MCDM embedded in the matrix. The rejected options are recorded together with the justifications for their rejection and a mechanism to study how changes in the parameters affect the decision process has also been integrated into the extension of Compendium.

4.2. *Multi-Criteria decision methods (MCDM)*

While the aim of IBIS is only to represent the argumentation behind a decision, the purpose of MCDMs is to support decision makers in arriving at the "best" decision. As such, MCDMs analyse a finite set of options (aka alternatives) with respect to a set of criteria to produce an order of preference for the options.

Options versus Criteria matrix can be used to support the selection of the most suitable option to solve a particular problem (a question node in Compendium). Each option is measured against a set of criteria, and the degree of compliance is expressed as a value (either a constant or the result of evaluating a mathematical expression). Once all the options have been evaluated against the criteria a decision can be made about which is the most suitable option.

4.2.1. *The weighted sum method*

Figure 2 shows how Options versus Criteria matrix can be used to support a decision. In the simplified example there are two competing options that are compared in terms of their cost and the equipment they require (a total of two options and two criteria). The numbers in each cell represent values obtained after evaluating an option against a criterion (its score). For example, Option 1 requires 3 items of equipment and its total cost is Θ 500 (N.B. The values used in Fig. 2 were set only to explain the creation and functionality of the matrix). Each criterion has an associated weight that reflects its importance; a negative weight indicates that a high score is detrimental (in this case the values for both, "Cost" and "Equipment Required", should ideally be kept to a minimum, but the cost has priority over the number of items of equipment required). Note that the more expensive option, Option 1, is recommended due to a larger proportional difference in the scores for the "Equipment Required" and to the weights assigned to each criterion. The recommendation depends on how representative is the set of criteria and on the accuracy of the values in the matrix.

Criteria	Option 1	Option 2	Weight	Normalisation Factor
Cost	500	400	-10	0.002
Equipment Required	3	5	-7	0.2
Totals	-14.2	-15		
System Recommen...	Recommended			
Decision				

Fig. 2. Simplified Options versus Criteria matrix.

To avoid distorting the results due to the relative magnitude of the values associated to different criteria, all the values in the matrix are normalised (scaled) so that they are within the same range (a value between 1 and −1). This can be done using the formula

$$x_{\text{norm}} = \frac{x}{n_j} = \frac{x}{|x_{\text{max}}|},$$

where x is the value of a cell in the matrix, n_j is the normalisation factor associated to criterion j, and the subscripts norm and max refer to the normalised and maximum values in the row for that criterion, e.g. the normalisation brings the maximum cost value to 1.0 (for example in the case of the "Cost" of "Option 1", $500 \times 0.002 = 1.0$).

This method of normalising the values and multiplying by the corresponding weights is known as the Weighted Sum Method (WSM); it ensures that the recommendation made by the matrix is fair and gives each criterion the appropriate consideration in the decision.

The final equation used to evaluate an option is a simple weight sum of the criteria:

$$\text{Total score} = \sum_{x_{ij} \cdot w_j \cdot n_j},$$

where x_{ij} is the value of option i with respect to criterion j, and w_j is the weight factor associated to criterion j. In the case of "Option 1" its total score would be:

$$\begin{aligned}&\text{Total score of Option 1}\\ &\quad = (500)(-10)(0.002) + (3)(-7)(0.2)\\ &\quad = -14.2.\end{aligned}$$

The WSM is one of the simplest MCDMs and perhaps the most popular due to the relatively small amount of inputs it requires and its transparency for non-expert users. However, it has several limitations: It is strictly applicable only to single dimension problems, and its results may be unstable in the presence of small changes in the scores or with the introduction of a new option (Parlos, 2000), as will be exemplified in the case study. For this reason, we have also investigated more stable MCDM methods such as ELECTRE (Triantaphyllou, 2000). The ELECTRE family of MCDM methods is more complex and requires pair-wise comparisons between options for each criterion from which a set of Concordance and Discordance indices are calculated. These indices measure the likelihood of an option i outperforming or outranking another option j (Concordance (i,j)) or not (Discordance (i,j)) and are calculated for every pair of alternatives. The ELECTRE method was implemented within the system and results from its application can be found in Egrot (2008). The extended Compendium tool presented in this paper uses the WSM.

5. The Extended Compendium Software

Compendium is a software tool freely distributed with the Lesser General Public License (LGPL); its functionality can thus be easily extended by adding Java libraries to the existing source code.

Essentially, there are three new components that have been integrated into the existing Compendium system:

- the Options versus Criteria matrix,
- the Global Parameters table, and
- the Goals versus Criteria matrix.

All the extensions have been implemented in Java, the same programming language in which Compendium is written; the extensions have been added to the existing Compendium libraries and the data in the matrices and tables is stored in files.

Options versus Criteria matrix is created and linked to each one of the issue nodes in Compendium. The Options versus Criteria matrix relies on two ancillary tables/matrices to function. The first of these is the Global Parameters table which holds details of all the global variables available to a project (a project is a set of related decisions). The second is the Goals versus Criteria matrix which holds details of all the criteria that have been created and are available to a project.

These three components relate to Compendium and each other as shown in Fig. 3.

There is a node content dialog within Compendium that displays information about an individual node; the dialog appears as a window with three tabs: one for the node content, one for its properties and one for views. A fourth tab has been added to this window in the case of Issue nodes (see Fig. 9 where the new tab containing the Options versus Criteria matrix corresponding to the "Potential materials?" Issue node is depicted). Access to the Global Parameters table and to the Goals versus Criteria matrix is also provided from this tab.

5.1. *Flow of information between the key components in the extension*

Figure 4 summarises the information flow between Compendium and the three additional components. The extension accesses information from each Issue node to create automatically the columns of the matrix corresponding to the options to be considered (a column is

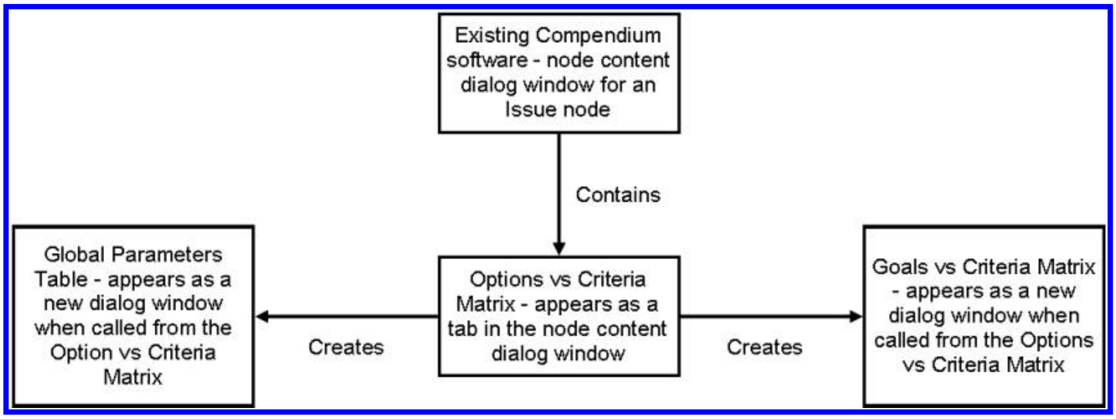


Fig. 3. Main components of the extended Compendium system.

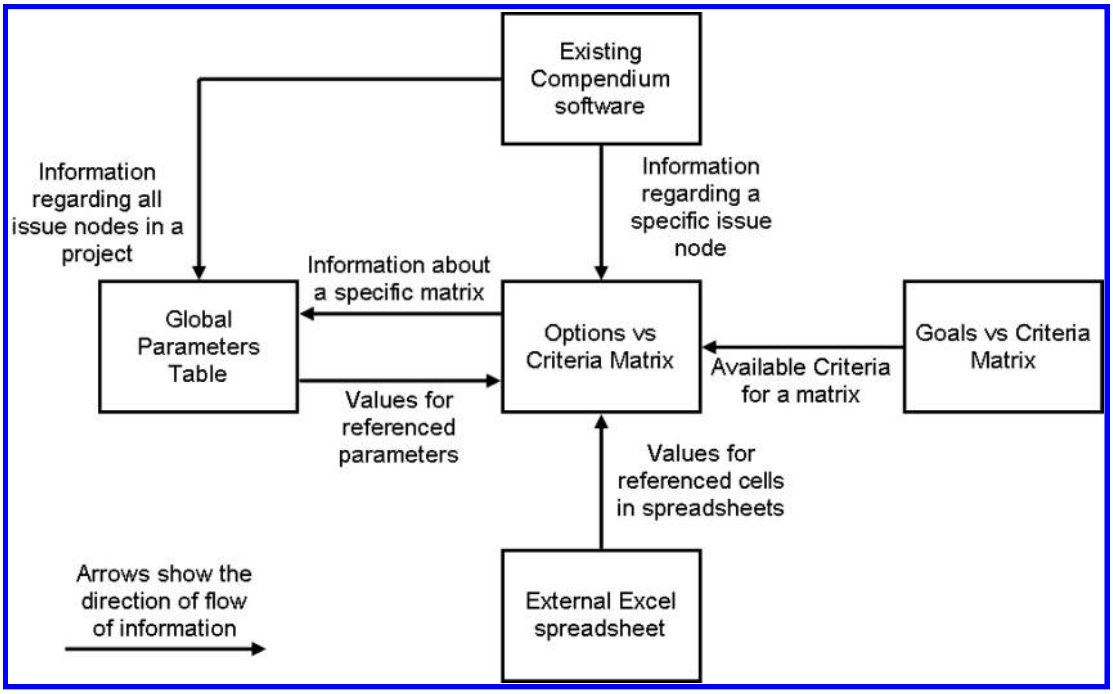


Fig. 4. Information flow across the extended Compendium system.

created for each Position/Alternative node that is linked to the Issue/Question node). The extension can also access information about the available criteria; the set of available criteria is obtained from the Goals versus Criteria matrix (a row is created for each criterion selected by the user). Once the matrix has been generated, the user must fill each cell with the value or expression to evaluate each criterion against an alternative. Values for the global variables referenced in the matrix can be retrieved from the Global Parameters table as well as from Excel spreadsheets.

The Global Parameters table stores the details of each parameter available in a project and its value is supplied to the Options versus Criteria matrix when a reference is made to that parameter. The Global Parameters table is also linked to the existing Compendium software to extract information about the Issue nodes in a project. This information is used to carry out either a propagation of values or a sensitivity analysis.

The extended Compendium software stores the details of all nodes and their link information in the same way as the original Compendium does (i.e. the version without the extension), but the core Compendium code cannot access the information in the Options versus Criteria matrix or any of its ancillary tables/matrices (see the direction of the arrows in Fig. 4).

5.2. *Propagation of values and sensitivity analysis*

The cell values in the Options versus Criteria matrix can be constants, variables or arbitrary functions of variables. Any variable used in the matrix must be pre-defined and given a value by the user; both of these actions are performed in the Global Parameters table (see Fig. 7). The main purpose of the table is to act as a repository of parameters that are going to be used in several decisions, for example the price of electricity may be used in several Issue nodes where the cost of operation is used as a criterion to compare between options.

Using a global variable maintains consistency throughout the decision records. Perhaps more important is that the value of any variable in the Global Parameter table can be changed at any point in time and this new value can then be propagated throughout the whole decision trail, this change spawns the re-calculation of scores in all the Options versus Criteria tables where the variable is present and may result in re-assessing the recommended option in some of them (because the total scores of the options may be re-ordered in terms of magnitude). As a result, it is possible to update the evaluation of options (and thus the recommendations) every time there is an external change over which the decision maker has no control, e.g., variations in prices and interest rates, or when there is a change due to a recalculation, e.g., when the designer decides to switch from a simple simulation model to a more detailed one.

The sensitivity analysis is another extension to Compendium that is used to gauge how sensitive the recorded decisions are with respect to variations in the values of selected variables in the system. This is a useful feature to check the robustness of decisions with respect to a parameter.

When a sensitivity analysis is performed a window appears which collects the following required information:

- The parameter to be varied during the analysis: e.g., cost of fuel.
- The range of variation in the value of the parameter (as a percentage): e.g., +/−50%.
- The number of steps in which the range is subdivided, e.g., 10.

In contrast to the propagate function the sensitivity analysis does not update the structure of the Options versus Criteria matrix files. In this case the matrix file associated with each Issue node is checked to see if it contains a reference to the global parameter that is the subject of the analysis. If it is then the reference to the matrix file, the label of the Issue node and the current system recommendation for that Issue node is added to an array. At every iteration step the total scores are recomputed and the resulting recommendation is compared with the original one, with any differences being reported to the user.

6. Case Study: Design of a Bio-Reactor

This section shows how the extension to Compendium can be used to support the design of an engineering artefact. The technical data is taken from a project to design a large-scale extraction process of plasmid DNA. A more detailed description of the decisions involved can be found in Middleton (2007) and Skrzypczak (2007). The design considered various issues such as the selection of cell culture, harvest and lysis methods, the choice of separation technology for the secondary recovery, and the selection of material of construction for the bioreactor as can be seen in Fig. 5 where the top level map view in Compendium is depicted. Every node in the figure represents one of the

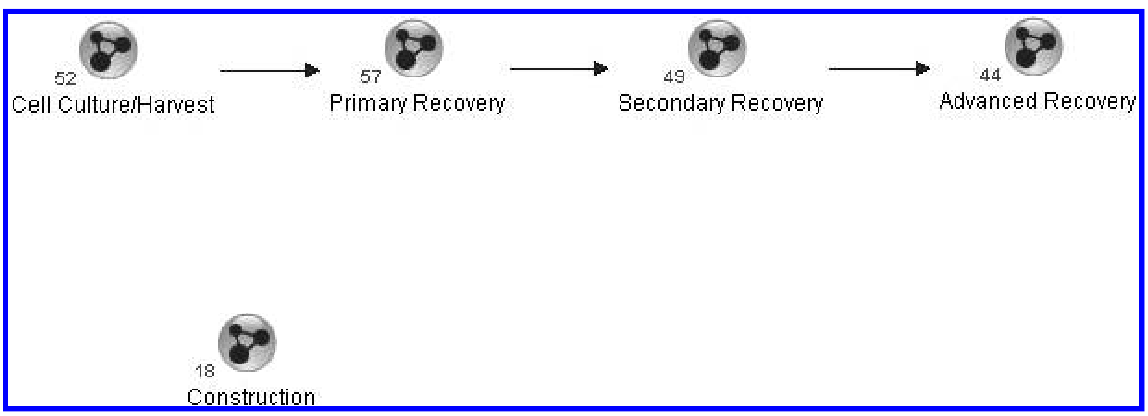
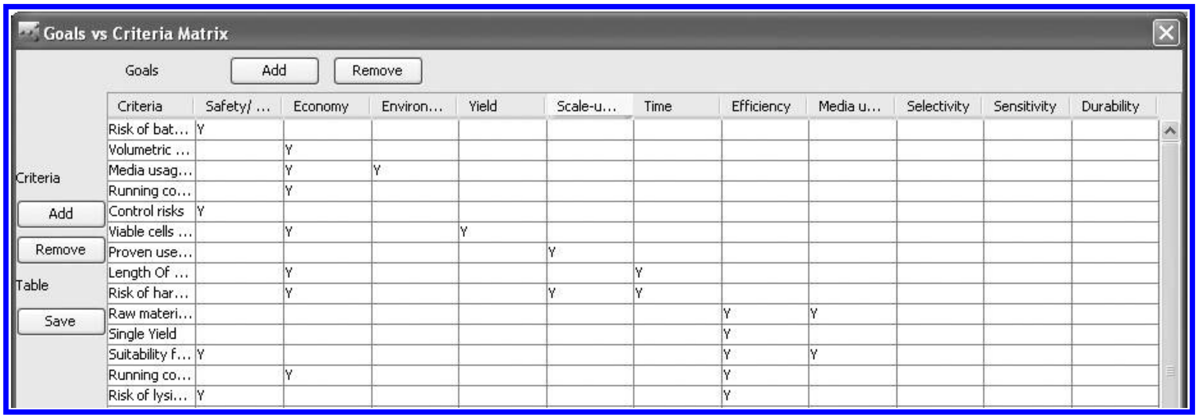


Fig. 5. Home map of the bioprocess design project in Compendium.



Criteria	Safety/ ...	Economy	Environ...	Yield	Scale-u...	Time	Efficiency	Media u...	Selectivity	Sensitivity	Durability
Risk of bat...	Y										
Volumetric ...		Y									
Media usag...		Y	Y								
Running co...		Y									
Control risks	Y										
Viable cells ...		Y		Y							
Proven use...					Y						
Length Of ...		Y				Y					
Risk of har...		Y			Y	Y					
Raw materi...							Y	Y			
Single Yield							Y				
Suitability f...	Y						Y	Y			
Running co...		Y					Y				
Risk of lysi...	Y						Y				

Fig. 6. Goals versus Criteria matrix embedded in Compendium.

top-level issues under consideration and each of them encapsulates a graphical representation of all the issues to be considered, the alternatives, arguments and chosen options.

Figure 6 is a snapshot of part of the Goals versus Criteria matrix containing the goals declared by the user (matrix columns) and the criteria used to test the compliance of an option with respect to a goal (matrix rows). This matrix is useful to check that every Goal has at least an associated Criterion and thus is testable, and that every Criterion is associated to at least a Goal thus ensuring that it tests a characteristic relevant to one of the goals of the project. For instance one of the goals in this case study is Safety and there are four criteria related to this: Risk of batch contamination, Control risks, Suitability for recycle, and Risks of lysis failure.

In turn, Fig. 7 show the list of global parameters used in the project; in this particular case all the parameters refer to the costs of materials (either reactants or materials of construction). These parameters can be dynamically updated and can also be linked to values extracted from specific web sites.

Figure 8 shows the Compendium-IBIS structure for the issue (question) related to the selection of the material of construction for the bioreactor. The map shows all the possible alternatives and the argumentation used for and against each one of them. The question node "Potential materials?" is linked to five alternative materials that must be evaluated to decide which one is the best. Each material appears as a column in the Options versus Criteria matrix associated with the question node (see Fig. 9).

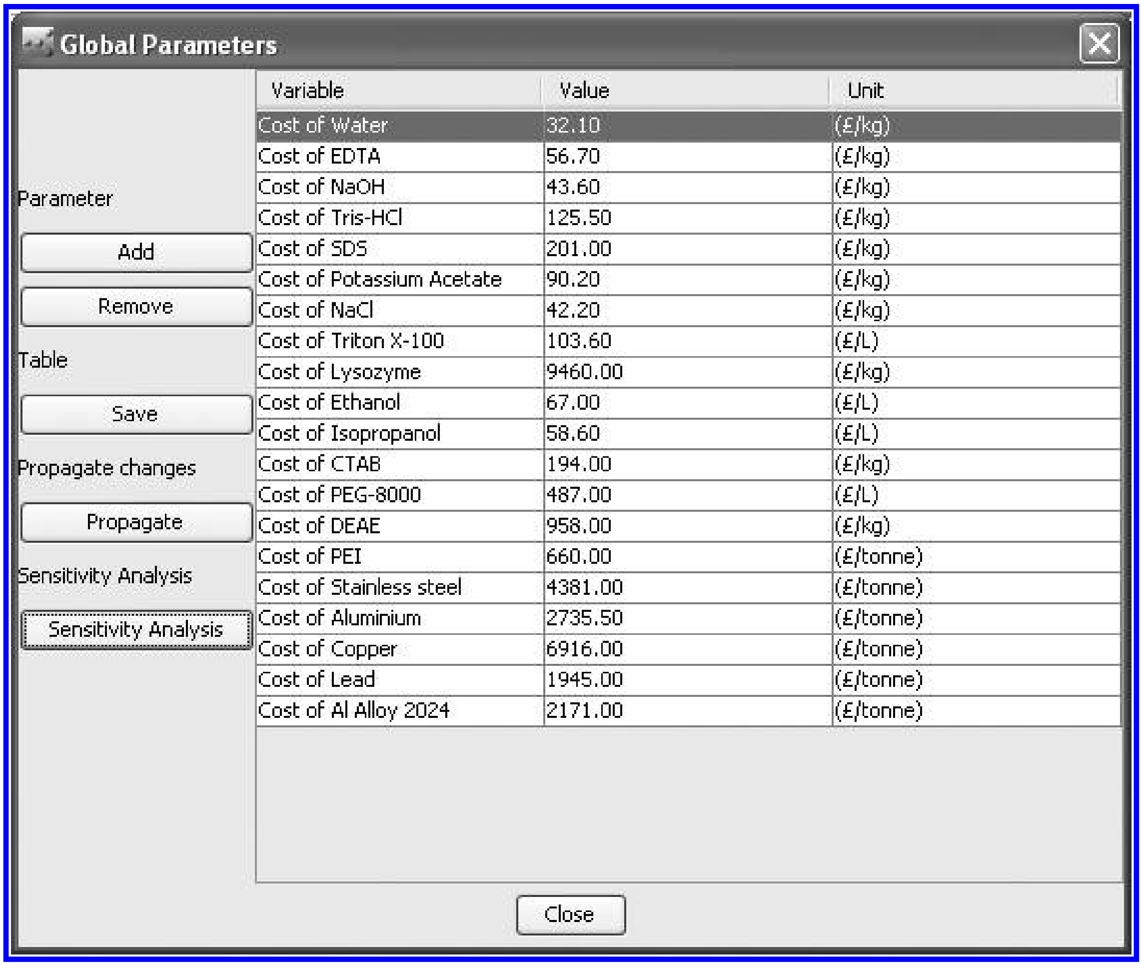
The other features added to Compendium, namely the Propagate function and the Sensitivity Analysis will be applied to the matrix to show how they enhance the functionality of Compendium.

6.1. *Construction materials for the reactor*

Figure 9 shows the Options versus Criteria matrix associated with the "Potential materials?" issue node in Compendium.

As explained before, a new tab has been added to every question node to display the Options versus Criteria matrix. The extended Compendium software automatically generates a column for each option considered in the IBIS structure (the five alternatives displayed in Fig. 8 are represented as five columns in the matrix attached to the "Potential materials?" issue node in Fig. 9). The user then needs to manually select the criteria used in the decision (rows in the matrix) and the evaluation of the alternatives with respect to the criteria (values inside the cells in the matrix; these values can be either a constant, a variable retrieved from the Global Parameter table or the result of evaluating an expression in terms of constants and/or variables). The criteria used in the decision must be selected from the table of Goals versus Criteria (Fig. 6). In the case of the bioreactor five possible materials (Lead, Copper, Aluminium, Aluminium Alloy 2024 and Stainless Steel) and three criteria (Cost, Young modulus[3] and the Ultimate Tensile Strength (UTS)[4]) are considered. The numbers in the cells come from the Global Parameter table (Fig. 7), which, in turn, were obtained from cost and physical properties tables. The extended version of Compendium evaluates all the options using the WSM described in Sec. 4.2 and, as a result, Stainless Steel is recommended as the material of construction for the bioreactor.

[3] A measure of how much a material expands under tension or shortens under compression.
[4] Maximum stress a material can endure before deformation.



Variable	Value	Unit
Cost of Water	32.10	(£/kg)
Cost of EDTA	56.70	(£/kg)
Cost of NaOH	43.60	(£/kg)
Cost of Tris-HCl	125.50	(£/kg)
Cost of SDS	201.00	(£/kg)
Cost of Potassium Acetate	90.20	(£/kg)
Cost of NaCl	42.20	(£/kg)
Cost of Triton X-100	103.60	(£/L)
Cost of Lysozyme	9460.00	(£/kg)
Cost of Ethanol	67.00	(£/L)
Cost of Isopropanol	58.60	(£/L)
Cost of CTAB	194.00	(£/kg)
Cost of PEG-8000	487.00	(£/L)
Cost of DEAE	958.00	(£/kg)
Cost of PEI	660.00	(£/tonne)
Cost of Stainless steel	4381.00	(£/tonne)
Cost of Aluminium	2735.50	(£/tonne)
Cost of Copper	6916.00	(£/tonne)
Cost of Lead	1945.00	(£/tonne)
Cost of Al Alloy 2024	2171.00	(£/tonne)

Fig. 7. Global Parameters table as seen in Compendium.

6.2. *Sensitivity analysis*

A sensitivity analysis was performed on the selection of material of construction for the bioreactor to see how the decision is affected by the cost of Stainless Steel. The analysis is carried out in 10 intervals from −70% to +70% of the cost of Stainless Steel (4381.00 £/tonne) and thus each interval corresponds to a change of 14% in the cost (around 613 £/tonne). The results of this analysis are shown in Fig. 10, where it is possible to see that

(a) The recommended decision remains the same up to an increment of 42% in the price of Stainless Steel, above which Aluminium Alloy 2024 becomes the new recommended option.
(b) The recommended decision does not change if the cost of Stainless Steel decreases.

A second sensitivity analysis shows that only an extreme decrease of −70% in the cost of Aluminium Alloy 2024 (i.e. from 2171.00 to 651.30 £/tonne) will affect the recommendation, at which point this material becomes the recommended option, see Fig. 11.

As we can see from the sensitivity analyses an increase of more than 42% in the cost of the Stainless Steel or a 70% decrease in the cost of the Aluminium Alloy would affect the recommendation. Thus, it can be concluded that the decision is not very sensitive to the cost of either material, although it is more sensitive to the cost of Stainless Steel.

6.3. *Propagate function*

The value propagation function enables to explore the impact associated with changes in some of the design parameters. For example, we can investigate the effect of a simultaneous decrease in the cost of Copper from 6916.00 to 5000.00 £/tonne (a decrease of −27.7%) and in the cost of Aluminium Alloy 2024 from 2171.00 to £ 1500.00 £/tonne (a decrease of −30.9%). Both of these changes were made and saved in the Global Parameters table and the

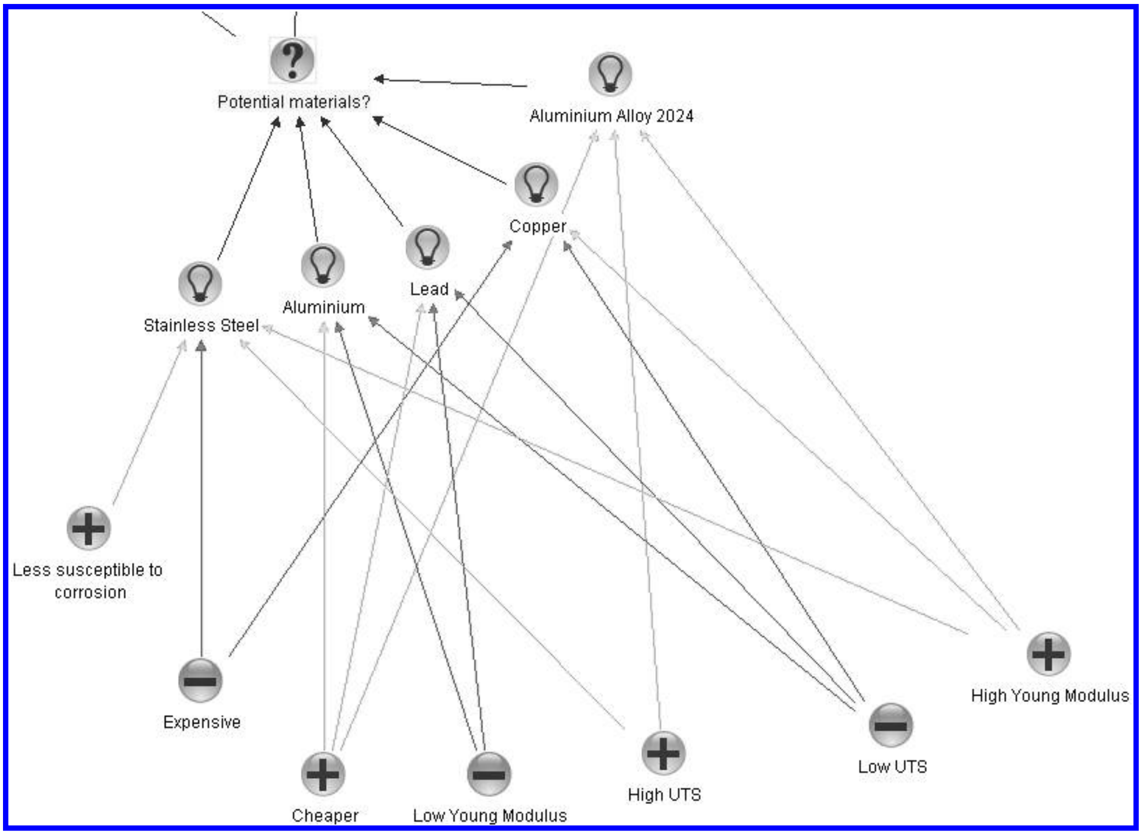


Fig. 8. IBIS structure used in the selection of the material of construction for the bioreactor in the process.

Potential materials?

Contents | Properties | Views | Options vs Criteria Matrix

Update ◉ Values ○ Formula

Criteria	Lead	Copper	Aluminium Alloy 2024	Aluminium	Stainless Steel	Weight	Normalisation Factor
Cost (per tonne)	1945	6916	2171	2735.5	4381	-1	0.0001
Young modulus (Gpa)	16	130	72	70	210	1	0.0048
UTS (Mpa)	12	210	480	45	450	2	0.0021
Totals	-0.16	0.49	2.03	0.13	2.24		
System Recommended					Recommended		
Decision							

Criteria

Add

Remove

Fig. 9. Example Options versus Criteria matrix.

Senstivity Analysis of Cost of Stainless steel varying by +/- 70.0%

Percentage	Node Label	Old Recommended Optio...	New Recommended Opti...
42.0%	Potential materials?	Stainless Steel	Aluminium Alloy 2024
56.0%	Potential materials?	Stainless Steel	Aluminium Alloy 2024
70.0%	Potential materials?	Stainless Steel	Aluminium Alloy 2024

Fig. 10. Results of sensitivity analysis for Stainless Steel.

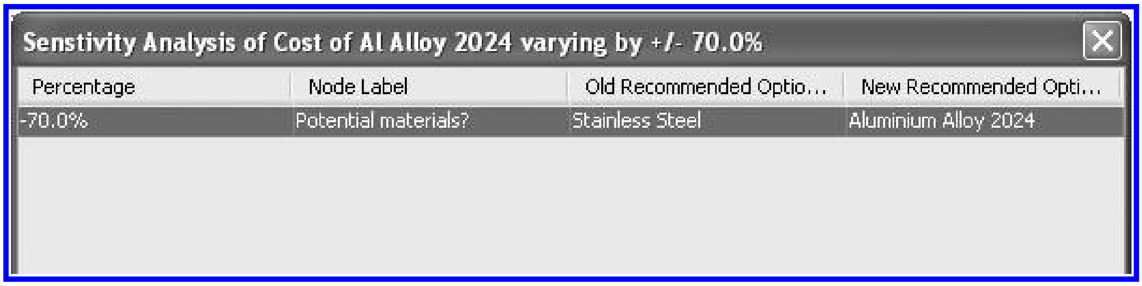


Fig. 11. Results of sensitivity analysis for Aluminium Alloy 2024.

Fig. 12. Results of the Propagate function.

Propagate function was executed (through the "Save" and "Propagate" buttons in Fig. 7). The results of the propagation are shown in Fig. 12, where it can be seen that the system recommendation for the choice of material of construction for the reactor has switched from Stainless Steel to Aluminium Alloy 2024.

Note the instability in the recommended option: Aluminium Alloy 2024 is recommended after a decrease in cost of only −30.9% instead of the −70% decrease that was required in the second sensitivity analysis (see Fig. 11). The reason is that the change in cost for Copper modified the normalisation factor of the Cost criterion from 1.45×10^{-4} to 2×10^{-4} changing, in turn, all the normalised scores for Cost and thus the total weighted sums; this is a well-known limitation of the WSM and the reason we have added other MCDM to the tool. The user will finally need to decide whether to follow the recommendation suggested by the tool or not. This decision can also be represented in Compendium together with the rationale behind it.

These simple tests show that the integration to Compendium of the Options versus Criteria matrix together with the value propagation and sensitivity analysis functions enable a wider exploration of the design space and the maintenance of decision rationale records in a format that the computer is able to manipulate.

7. Conclusions and Further Work

This paper presents how an IBIS implemented in Compendium, has been extended with new functionalities to support decision-making. These functionalities: (a) Options versus Criteria matrix with access to a toolkit of MCDM; (b) Sensitivity Analysis, and (c) Value Propagation, enable the applicability of the extended system in the support of decisions that require not only argumentation, but also a numerical evaluation of the alternatives. Thus, the contribution of the research is the broadening of the scope of application of dialogue mapping techniques to decision problems that involve numerical data and mathematical models. We believe that the integrated support of both of these features (argumentation and mathematical models) is necessary for problems arising during the design and operation of engineering artefacts; existing support systems address them separately. This new approach provides a graphical interface to the relevant information within a user-friendly environment and also facilitates the decision making process by evaluating the alternatives and recommending a possible solution.

Further application of the extended Compendium system has been very encouraging. Undergraduate students in Oxford have used the system to support their final year project. The tool has been used to select the ideal place for a CO_2 sequestration project (Yeoh, 2009), to integrate forecasting methods and algorithms during decision-making (Hanbury, 2010) and to determine the most appropriate solution to provide clean water access in poor countries (Evans, 2011). The extended version of Compendium was also incorporated as a part of a methodology for the identification of operational problems in a chemical process (Contreras-Valenzuela *et al.*, 2010). All these projects found the extensions to Compendium very helpful, particularly the Options versus Criteria matrix, as this matrix can encapsulate all the information required to make a decision.

The current version of the extended Compendium system has a number of limitations such as:

- The information stored in the system cannot be accessed by other applications nor is available in alternative formats (e.g., as a report). Some initial work regarding these additional functionalities has been completed.
- User entries are not validated by the system.
- There is not a satisfactory search facility to find all the nodes that are related to a topic, e.g., finding all nodes related to safety.

Further work on some of these additional functionalities is the focus of another PhD research (Hunt, 2009) which has not only incorporated the lessons learned in the case studies, but is also exploring new features to add such as the use of ontologies of the domain and of the decision making process to extract semantic information from the decision trail stored in Compendium, and to classify the criteria to prevent the user selecting an irrelevant criterion for a specific issue. Ontologies can also be used to develop an intelligent search engine so the user can look for all the nodes related to a specific subject.

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