Bayesian Belief Networks, a cross-cutting methodology in OpenNESS: Briefing Note

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Version/Date: OpenNESS_BBN_BriefingV1_11092013

This document reflects early ideas on the use of BBN as a cross-cutting methodology, and will be revised as the project progresses and applications are developed. It was prepared as an input for the BBN HUGIN Training Workshop, Nottingham 16th-18th September 2013.

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Note:

This is an early reflection on the background to the use of BBNs in OpenNESS, and has been prepared for the purpose of discussion within the OpenNESS consortium only. Do not circulate it outside.

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Haines-Young, R., Barton, D.N., Smith, R. and Madsen, A. (2013) Bayesian Belief Networks, a cross-cutting methodology in OpenNESS: Briefing Note, September 2013.

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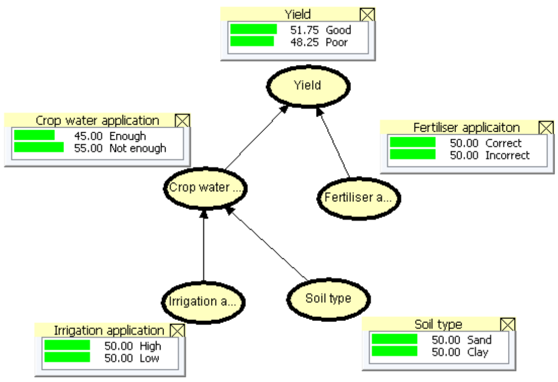
1. Introduction: What is a BBN?

Bayesian Belief Networks (BBNs) have been identified as one of the cross-cutting themes within OpenNESS. The purpose of this briefing note is to introduce the concept and the kinds of analysis it can support within the Project, and to stimulate discussion and collaboration across the work packages. More detailed material can be found in Kjærulff and Madsen (2013) and Cain (2001).

Cain (2001) defines a Bayesian Belief Network as a 'graphical tool for building decision support systems to help make decisions under uncertain conditions'. The key phrase to focus on in this definition is 'uncertain conditions'. As Cain points out, BBNs were originally developed to allow the impact of uncertainty about management systems to be accounted for, so that decision makers could balance the desirability of an outcome against the chance that the management option selected might fail. The representation of a system in terms of a set of relationships that have probabilities associated with them is at the heart of the Bayesian approach.

Figure 1: Example BBN to predict yield given management inputs (modified from Cain, 2001)



An example of a simple model that might form the basis of a BBN is shown in Figure 1. If we think about the sorts of things that might influence agricultural yield, for example, then these might include water supply and fertiliser applications. The amount of water applied to the crop might, in turn, be influenced by such factors as soil type and the level of irrigation. Figure 1 shows this diagrammatically, in what is technically called a 'Directed Acyclic Graph' (DAG). Constructing such a graph is usually one of the first steps in building a BBN.

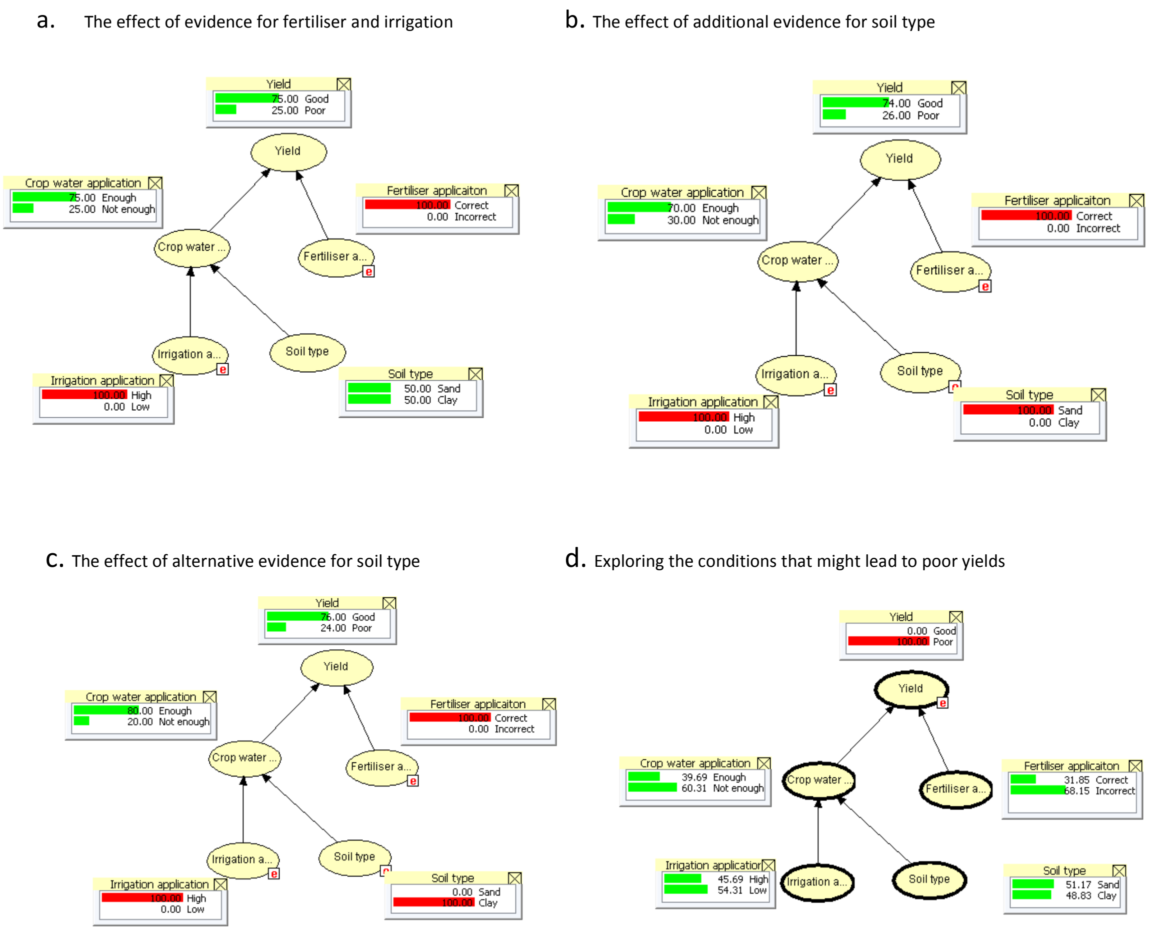
The variables in the DAG shown in Figure 1 are also called '**nodes'**; the term 'variable' and 'node' mean the same thing. The relationships between the variables are shown as a set of arrows or **links**. These simply set out the connections between the variables; they show what influences what. The direction of the arrows describes what we think the probabilistic relationships are within the system.

In Figure 1 each of the nodes are shown as being able to take various **states**. In the HUGIN software used to construct this network, the states can be seen in the associated **'monitor windows'.** This network is obviously a very basic one. Thus yield is simply represented as 'good' or 'poor', or soil type can be 'sandy' or 'clay'. The monitor windows show the state of each node as a 'belief bar', which shows the probability that the variable (node) is in a particular state. What the BBN allows us to do through the links, is to assign conditional probabilities to the states of the different nodes,

OpenNESS Grant Agreement no: 308428 - http://www.openness-project.eu/

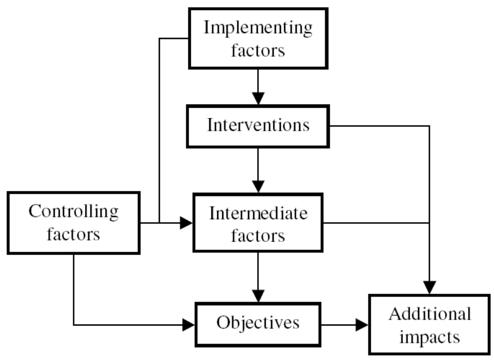
showing their dependencies on the nodes that feed into them. These probabilities are held in Conditional Probability Tables (CPTs) that underlie each node. In the example the Tables that define the response of yield and crop water application are shown in Figure 2. The effect of assigning these probabilities on these two nodes is shown in Figure 3. If we have evidence, for example, that the correct amount of fertiliser was used and the irrigation application was high then the BBN shows the probability of a good yield to have increased to 0.75 (Figure 3a). If on the other hand we know the soil type, and this extra evidence would propagate through the network to change the outcome (Figure 3 b & c). On sand the probability would be 0.74, while for clay it is 0.76. The red bars in Figure 3 show that evidence has been added – and we are certain that a node is in the state shown, compared to the situation in Figure 1. One of the other interesting features of a BBN is that we can look at the kinds of condition that would lead to a particular outcome. This in Figure 3d, we have selected 'poor yield' and the network can help us identify what kinds of condition might lead to such a result.

Figure 3: Exploring the impact of evidence using the simple yield model



Cain (2001) suggests that when building BBNs it is often easier to start off by putting the variables that you are dealing with into different categories (see Figure 4). Not all categories have to be present in every DAG – you have to tailor the network to the problem you are dealing with. However, usually there is a set of nodes that represent outcomes of some type and another set of inputs. To help you recognize the different types of node you can look at the relationships defined by the arrows in a BBN. The arrow is said to run from a **'parent'** node to a **'child'** node. The nodes that are only 'parents' (i.e. only have arrows leaving them) are usually controlling factors or interventions. By contrast, those nodes that are 'children' only have arrows leading into them; these are often objectives. The intermediate factors have both parent and child relationships.

Figure 4: Types of node in a BBN (after Cain, 2001)



2. BBNs in OpenNESS

BBNs have been used widely in the natural and social sciences to model various phenomena, and more recently to model ecosystem services (see for example, Barton et al 2012; Haines-Young, 2011; Kuikka et al. 1999; and Landuyt et al. 2013; McCann et al, 2006).

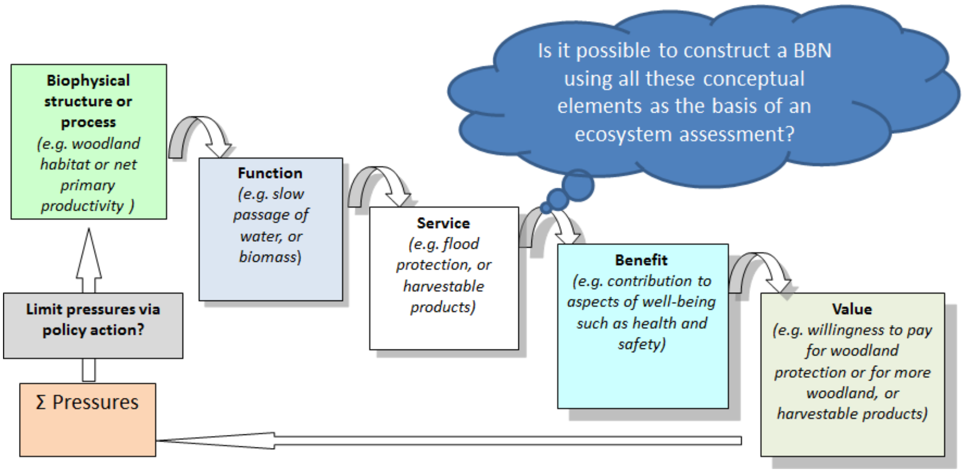
Some advantages to using BBNs for modelling scientific and local knowledge include:

- promoting social learning processes between scientists and local resource managers through joint building of causal networks to describe a decision problem;
- integration of different types of information on causal links and conditional probability tables and distributions, based on observations, model simulation or expert judgments and beliefs;
- use of a causal network as a 'meta-modelling tool' to link sub-models from different biophysical and social knowledge domains (for example driver-pressure-state-impact-responses model chains);
- explicitly acknowledging uncertainty by modelling all links between models as conditional probability distributions; and,
- providing a tool for decision analysis under uncertainty, including cost-benefit and cost-effectiveness analysis.

In OpenNESS we will explore these and other advantages:

- **In WP1:** BBNs will be used to explore and operationalize different sorts of conceptual models that can help people address the four challenges that are the focus of OpenNESS (well-being, regulatory frameworks, sustainable management of ecosystems and competitiveness). For example, it might be one way of operationalizing the cascade model. The challenge would be to build a network for a particular application that included representations of all the conceptual elements shown in Figure 5. The work in WP1 will also provide some simple BBN tools to help people operationalize their thinking. Two initial applications are available on the OpenNESS-HUGIN website, dealing with classifying

Figure 4: The cascade model as a template for operationalising a BBN

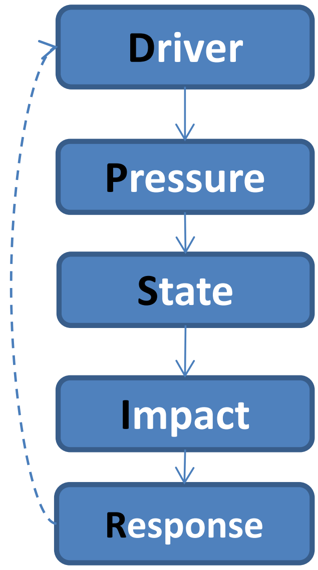


ecosystem services and modelling service outputs given the biophysical characteristics of different habitats[1].

- **In WP2:** BBNs could be used to help with the work on participatory scenario development, as well as the conceptualisation of regulatory frameworks. In particular it can help identify the kinds of policy information that is needed for input to the valuation method used in WP4. Examples of using BBNs for participatory scenario development are provided by Henriksen et al (2011) and Haines-Young (2011).

- **In WP3:** BBNs could be used to conceptualise and model the relationships between the biophysical characteristics of different ecosystems and their capacity to deliver different types of service, and how different drivers of change may impact on them (Figure 5). The BBNs could serve as a 'meta-model' integrating data from different sources, or for capturing the results of analyses and systematic reviews in ways that can be explored dynamically by the user. They could also help identify what biophysical mapping and modelling is required as input to the valuation method used in WP4. An example of BBNs as meta-modelling tool is provided by Barton et al (2008). Further examples (e.g. Smith et al,

Figure 5: BBNs have been used as a 'meta-modelling' tool for integrating a cascade of DPSIR models, familiar from integrated environmental assessments, and conceptually similar to ecosystem service cascades.

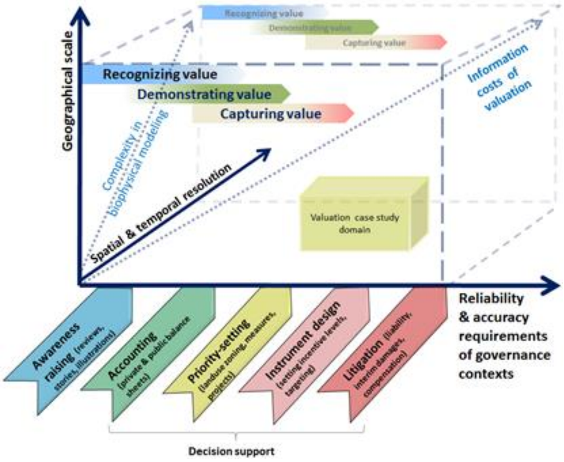


[1] See: http://openness.hugin.com/example/cices and http://openness.hugin.com/example/habitat

2012[2]) can be found on the OpenNESS-HUGIN website.

- **WP4:** The focus of the initial work in OpenNESS will be on operationalizing the conceptual framework that forms the basis of WP4 (see Figure 6). In terms of the four challenges the work with BBNs will attempt to:
    - identify how BBNs can integrate the different approaches to modelling human preferences in monetary valuation methods(e.g. choice experiments) versus non-monetary valuation methods (e.g. deliberative valuation in multi-criteria decision analysis);
    - explore how BBNs can be used as an "integrated" or "hybrid" valuation method that accounts for relationships between biodiversity and ecosystem function and how these affect valuation;
    - examine how the uncertainty in biophysical models and valuation methods can be modelled jointly in the evaluation of the cost-effectiveness and cost-benefit of policies;
    - explore how BBNs can be used with MCDA techniques to represent conflicting stakeholder interests in decision support; and,
    - understand the different roles BBNs can play in different valuation decision-support settings(scale, resolution, governance context) (Figure 6).

Figure 6: OpenNESS valuation framework



- **WP5:** The application of BBNs in the context of the case studies is open-ended, and we will be looking to find some 'real-world' situations where we can test ideas and explore the extent to which expertise and knowledge can be transferred between different areas. Some of the early work with WP1, for example, will be to try to use BBN to 'story-board' the issues being considered in the case studies in terms of the different influences and the ways they can be measured or characterised.

- **WP6:** One of the particular advantages of BBNs is that they can help transfer and operationalise knowledge, and so they will be especially interesting to WP6. The partnership will HUGIN will help ensure that many of the BBNs developed during the Project can be made available via the internet.

Visit the OpenNESS-HUGIN platform: http://openness.HUGIN.com/. HUGIN are using a development version of the software for OpenNESS, that can be used to design and test the new concepts and methods that will emerge from the Project. A particularly active area will be using BBNs as a mapping tool and for spatial analysis. A further topic will be to investigate how temporal processes

[2] See also: http://openness.HUGIN.com/example/smith_fig2

can be analysed, say using BBNs to represent different time slices. We anticipate that the OpenNESS case studies will present many complex problems and another area of interest will be to see how networks dealing with different issues can be linked as a series of sub-nets.

References

Barton, D.N. et al. (2008) Bayesian belief networks as a meta-modelling tool in integrated river basin management — Pros and cons in evaluating nutrient abatement decisions under uncertainty in a Norwegian river basin. *Ecological Economics*, 66, 91-104.

Barton, D. N., et al. (2012) Bayesian Networks in Environmental and Resource Management. *Integrated Environmental Assessment and Management* 8(3): 418–429.

Cain, J. (2001) *Planning improvements in natural resources management: Guidelines for using Bayesian networks to support the planning and management of development programmes in the water sector and beyond.* CEH, Wallingford.

Haines-Young, R. (2011): Exploring ecosystem service issues across diverse knowledge domains using Bayesian Belief Networks. *Progress in Physical Geography* 35(5): 681-700.

Henriksen, H.J. et al. (2011) Use of Bayesian Belief Networks for dealing with ambiguity in Integrated groundwater management. *Integrated Environmental Assessment and Management* , 8 (3), 430–444.

Kjærulff, U.B and Madsen, A.L. (2013) *Bayesian Networks and Influence Diagrams: A Guide to Construction and Analysis: A Guide to Construction and Analysis*. Second Edition. Springer. See: http://link.springer.com/book/10.1007/978-1-4614-5104-4/page/1

Kuikka, S., et al. (1999). Modeling environmentally driven uncertainties in Baltic cod (*Gadus morhua*) management by Bayesian influence diagrams*. Canadian Journal of Fisheries and Aquatic Sciences* 56(4): 629-641.

Landuyt, D., et al. (2013) A review of Bayesian belief networks in ecosystem service modelling, *Environmental Modelling & Software* http://dx.doi.org/10.1016/j.envsoft.2013.03.011

McCann, R., et al. (2006) Bayesian belief networks: applications in natural resource management. *Canadian Journal of Forest Research* 36: 3053-3062.

Smith, R., Dick, J., Trench, H., and van Oijen, M. (2012) Extending a Bayesian Belief Network for ecosystem evaluation. In: 2012 Berlin Conference of the Human Dimensions of Global Environmental Change on "Evidence for Sustainable Development", Berlin, Germany, 5-6 October 2012. See also: http://openness.HUGIN.com/example/smith_fig2