Dependency Modelling for Cultural Heritage

Joel Taylor, Nigel Blades and May Cassar

Centre for Sustainable Heritage, University College London, United Kingdom

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1 Introduction

Preventive conservation strategies have been developed to identify and monitor hazards to collections, through assessment of risk [1], environmental conditions [2] and condition of objects [3]. However, because the way in which we mitigate problems is often so varied, there is less published work on generalised techniques for mitigation. Valuable case studies on control methods and solutions to specific problems exist, but choosing the right approach can be difficult. Cost/Benefit Analysis [4, 5] is the only technique that addresses how to choose appropriate mitigation methods but it needs to draw upon existing, defined solutions in advance. However, risks to collections are dependent on the outcome of a chain of events which *can* be generalised. Like any process or chain, there are strong and weak links that will determine success or failure. It is the identification of critical points and pathways that leads to effective risk management.

The links in the chain are understood and monitored in a number of different ways (figure 1). These can be related to existing assessment methods that record different parts of the same 'chain'. What we assess is the impact, or potential impact, of this chain of event s on an object or collection. Modelling the process in such a way allows the conservator to think strategically about the most effective way of breaking the chain, which is essentially the goal of preventive conservation.

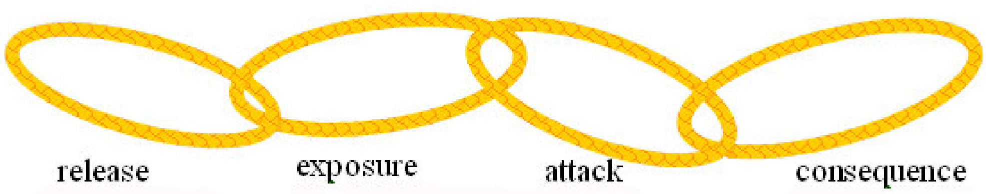


Figure 1: The risk chain: Various stages must be fulfilled before 'damage' occurs. Based on Covello and Merkhoffer[6].

Dependency modelling is a technique that develops this concept as a deductive 'top down' approach to analysing risks in systems. It involves specifying a 'top event', which is the outcome of a chain of events. This is followed by identifying everything that leads up to that event and all the ways in which that event can happen. Top events can be any identifiable outcome, positive or negative, as long as boundary conditions can be developed to model the process.

The technique was developed for cultural heritage as part of the MASTER project (Preventive Conservation Strategies for Protection of Organic Objects in Museums Historic Buildings and Archives) [7], as part of the preventive conservation strategy. Its integration with diagnostic monitoring and other data in preventive conservation will be discussed later.

2 The process of dependency modelling

The technique was originally devised by Bell Telephones in 1962 in connection with the minuteman missile launch system and developed by Boeing. It has since been used for applications as diverse as nuclear reactor safety [8] to reliability of broadcasting methods [9]. Assessing the vulnerability of a system can lead to a broad understanding of, not only the events preceding an outcome but their relationship. An advantage of dependency modelling for catastrophic risks is that it does not imply that catastrophes are single events that are not influenced by the context in which they occur. This has been a problem in analysing conservation issues before. Jigyasu points out that earthquake disasters are not simply one event but should be viewed with the context that surrounds them [10].

A very similar method, fault tree analysis which models failure of systems, is the logical inverse of dependency and also relevant to discussion. But for heritage conservation, dependency model is a more appropriate term since there is less value judgement about the outcome. It has been used elsewhere to find areas in a process that require strengthening or contingency. It is adapted here to identify ways to reduce risks to heritage collections.

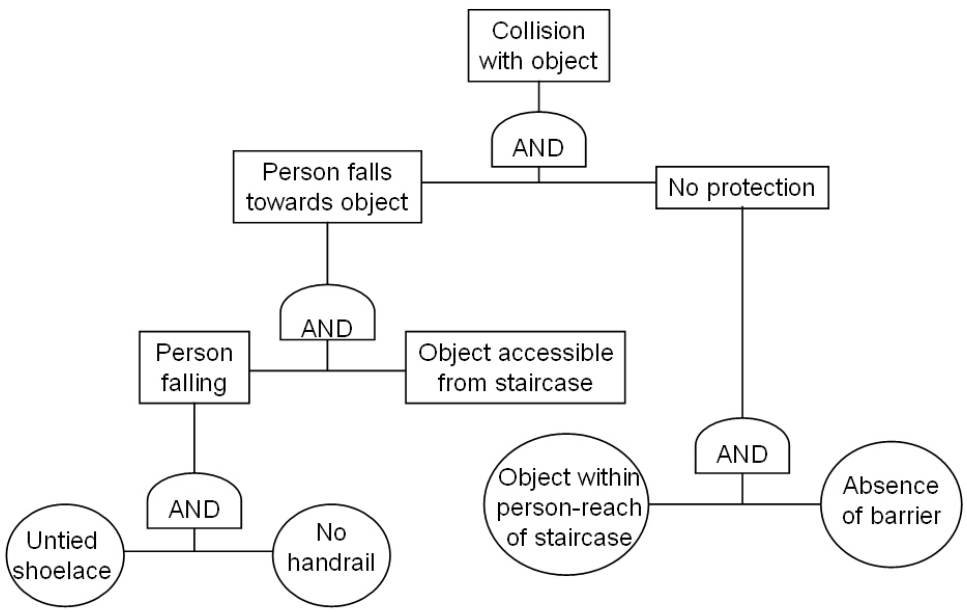


Figure 2: An example of a sudden event with preceding events.

Dependency models can be applied to any process of which the user has a working knowledge, and fleshed out with specific information. It has a logical structure that can go into as much detail as required. The simple example above (figure 2) illustrates the points at which events take place, and the relationships that lead to them.

In developing a dependency model of risks to collections, defining the top event is essential. Damage may occur in many different ways, with large or small impacts. In terms of deterioration, this may mean an acceptable level or rate of change. In these cases, the top event can be quantified. The conservator must declare the point at which the chain is ‘broken’ This can be based on technical information, such as a damaging level for a material present in the collection, or likelihood of catastrophe. It can be a more abstract concept, as long as there is an understanding of when the top event has occurred.

Definition of potential damage might require reference to a time period, so an acceptable rate or probability can be expressed. For example, Ashley-Smith et al. [11] defined levels of acceptability for lux levels in a year based on rate of change of different dyes and pigments. Concentrations or levels might be required to define problems with pollution or critical points of relative humidity for different materials.

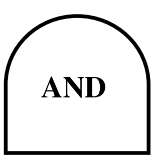
Framing a top event involves specifying the nature of the risk or system to a certain extent. By developing the processes involved for each risk, the specific factors relevant to an institution can be applied to the model. This can involve different kinds of information, sensitive to the context. The 'boundary conditions' of the model have to be defined in advance. The boundary conditions in the model are determined by the outcome. There may be many ways in which an event might occur, such as a statue breaking from earthquakes, vandalism or display conditions. The extent to which different events are modelled will depend on how far one wishes to examine. Equally, the level of resolution in the model can vary. Considerable detail of event causes may be required, and the preceding causes to be identified but this must be balanced with keeping the analysis on a manageable scale. This level of resolution will vary, depending on the reasons for the model and the situation.

2.1 Kinds of relationship

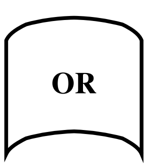
Dependency models are based on the notion that some links in the chain are easier to break than others. The strength of different links can be based on a number of factors and illustrates the novel approach of the model. The strength of a relationship depends on the number and influence of contributing factors. For an event to occur, the factors that contribute to it must take place at the same time. However, the contributing factors may come from a number of different sources. These issues build up the character of the model.

2.1.1 AND / OR dependencies

For the 'top event' to be successful, all of the lower events must be fulfilled. Figure one only shows one kind of relationship between events. However, there are two important types of relationship in a in a dependency model. These are defined as AND and OR relationships. If all factors are required for an outcome to occur, relationships are weak. Where alternative factors exist, relationships are strong. AND relationships are weak, since they are dependent on all of the contributing factors. OR relationships are strong because elimination of one contributing factor does not eliminate the relationship. Points at which elimination of an event might not mitigate the outcome can be identified by the presence of OR relationships. There may be any number of events leading to an OR relationship.



The output event occurs if all of the input events occur.



The output event occurs if at least one of the input events occur.

The point where these prior events meet, where the AND or OR symbol stands, is referred to as the *logic gate*. Causality never passes through an OR gate [12] – the input faults are never the causes of the output faults – they are identical to the output but more specific. For example, open windows, open doors and uncontrolled heating are all specific versions of uncontrolled relative humidity. AND gates *do* specify a causal relationship [12], for example unstable storage box and a high shelf lead to the output of an object falling to the floor.

There are variations on these gates which have been created to add sensitivity to the modelling. Some of them are useful to conservation. All of them are variations of the AND or OR gates.

- Priority AND - All take place in a sequence
- Inhibit - Conditional factors (AND + the condition). Deposition of pollution on some objects may be affected by RH levels, or pest infestations only take place in certain RH conditions. This is usually expressed as a hexagon.

2.2 Kinds of event

There are various different kinds of event, which are characterised to illustrate their role in the model. It is useful to distinguish between an initiating event, which requires no previous causal information and intermediate events, which are the consequence of earlier events occurring.

- Top event – the event that signifies that the process has reached a conclusion in terms of the system boundaries. The definition of a top event may require some indication of time or values to indicate what constitutes occurrence and what doesn't. The top event can be anything, tangible or intangible. It may be an object breaking from physical damage, or simply the impact of physical force on an object. It can be tangible or intangible, positive or negative as long as preceding events can be identified. These as usually represented as rectangles.

- Intermediate event – an event that occurs because of one or more antecedent causes acting through logic gates. These are most of the events that lead up to a top event. These are usually also represented as a rectangle.

- Initiating or basic event – a basic event requiring no more development under the model. An initiating event may be the source of a hazard, such as artificial light, or a point at which the institution has control over a hazard, such as daylight entering a museum. They require no further development for the model. These are usually represented as circles.

2.2.1 Other kinds of event

Other types of event have been developed to help illustrate the process in the model, which can include information on how activities occur. These are less common features of dependency models.

- Conditioning event – this is a modifying factor, which is usually used in connection with 'Inhibit' relationships mentioned above. It is used to record restrictions or limits that might apply to any relationships within the system. Environmental effects on reactions are examples of this kind of event. These are usually represented as ovals.

- Undeveloped event – an undeveloped event is an event that is not examined further because information is unavailable, or because the consequences are insignificant. As a result, the sources and definitions are not well defined. Improper installation of equipment is an example of this. These events are usually represented as diamonds.

- External event – this is an event that is usually constant, expected to occur and outside the control of the modeller. This is an event which is not necessarily a positive or negative factor but will influence the outcome of the events, such as relative humidity reaching dew point which could lead to interstitial condensation or condensing dehumidification. They are usually represented as a house shape.

External information about the process can be useful for a number of reasons. External events, such as the psychrometric changes in air are useful to understand and illustrate the process, and can also help assess the effects of possible mitigation methods, such as refrigerant dehumidification. An example is given in figure 3, below. By including technical information, and knowledge about the context, the model is supplemented with information that makes the model more sophisticated.

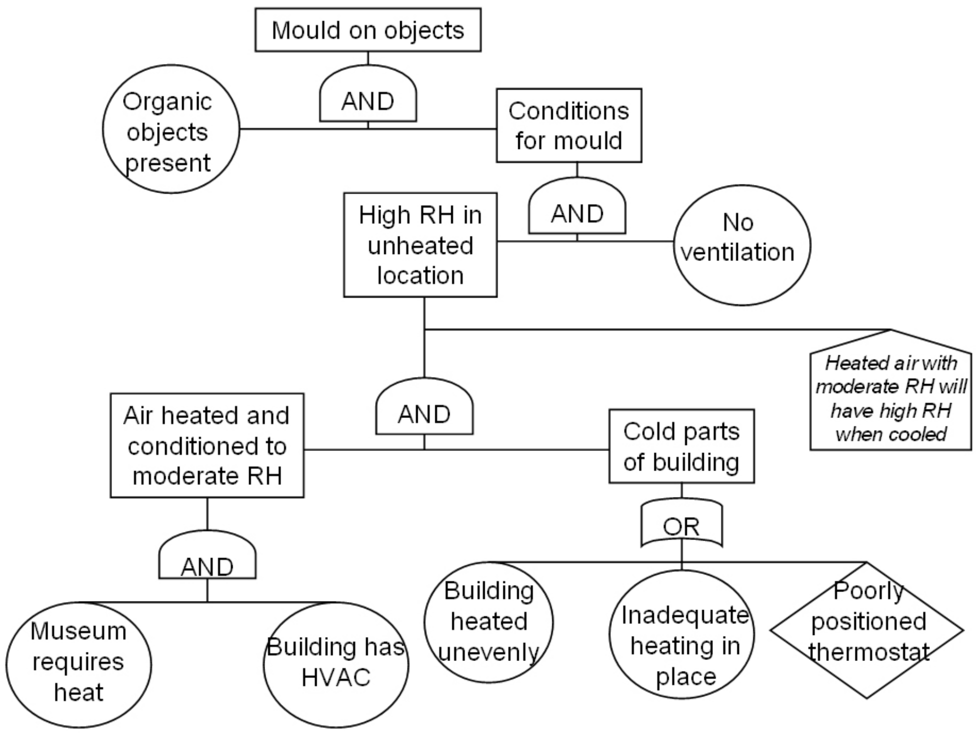


Figure 3: A dependency model with an external event helping illustrate the process being modelled.

3 Deterministic risks

The nature of the dependency model appears to be more suited to catastrophic risks, where events either happen or don't, rather than gradual or cumulative risks. There is no directly definable event for deterministic risks but the build up of damage over time. There is also the fact that the rate of these 'events' can be influenced indirectly. For example, the deposition rate of pollution can be influenced by temperature and RH. Their presence alone will not result in the success or failure of an event but a decrease in temperature and RH will reduce the reaction rate. As a result, both the event itself, and relevant relationships do not have Yes-No functions to suggest that the chain is intact or broken.

However, the levels of preservation to determine acceptable and unacceptable environments can be used to define the point at which the event is successful (i.e. damage takes place). By providing a quantitative description of acceptability, the top event can be given a point at which it is considered to have been reached. Determining a level of acceptability means one has the ability to define the event. This means that the deterministic qualities can be modelled. This kind of categorisation is common in risk management and preventive conservation.

Existing standards can be used to develop such steps, particularly where thresholds have been established. These should be related specifically to the materials and the risk being modelled.

3.1 A simple example based on a European museum

Taking a dependency model for NO_2 (figure 4), based on a European museum with a heating, ventilation and air conditioning (HVAC) system, one can see various points at which the risk can be mitigated. The weakest points in the model appear to be quite specific. As the tree gets lower down, from exposed surfaces of objects to ingress from external sources, the relationships are more general. As a result, there are more alternatives that are available to completion of those events. These general issues can be further broken down, such as defining different possibilities for natural ventilation. The level of detail can be defined by the institution. Currently, all of the lower level relationships are OR relationships, which are harder to break. Monitoring of a location can allow some of these events to be eliminated, so OR relationships become weaker AND relationships. As a result, there are clear points where mitigation can have a significant impact on the rate of level of NO_2, reducing it to an acceptable level

A level of 5ppb is given in the example, which is suggested as a level of acceptability for purpose built museum galleries in the MASTER project. The value was based on existing research into the effects of NO_2. Typical organic plant dyes on silk and cotton change within one year at this level, and natural organic colorants on paper change after five years [13, 14, 15].

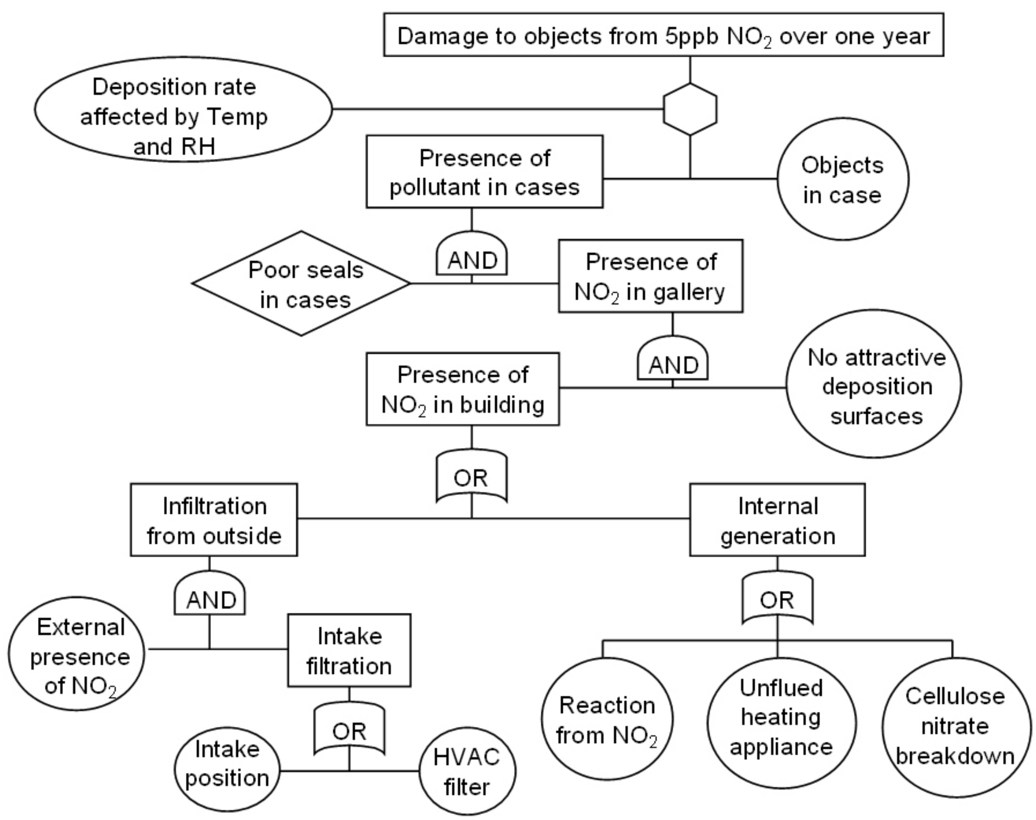


Figure 4: A model for exposure to nitrogen dioxide for a museum with an HVAC system, including an inhibiting relationship for the deposition on objects. Note the conditional AND relationship (hexagon) at the top of the diagram.

One can see various ways in which the chain can be broken, including reduction of the deposition rate by lowering temperature and RH, expressed as a condition in reaching damaging levels for objects. Factors such as deposition of pollutants on surfaces before they are exposed to objects can be taken into account also. The less likely internal generation of pollutants is also included in the model.

It can also be seen that the nearer to the top event one looks, the more localised the mitigation. Relationships, or links, near the top event might require manipulation of showcases with pollution scavengers or different seals but this will have to be carried out for all cases. Events lower down include broader issues, such as pollution infiltration which may be harder to manipulate.

4 Including data in the model

Preventive conservation information can be directly placed into the dependency model. Data from techniques such as diagnostic monitoring can reduce some of the options provided, and determine other critical points in the system. This can help determine probabilities and provide information about which events can be eliminated to simplify the model. If the 'top event' is quantitatively defined, monitoring can also determine when the risk has reached a level or rate that is acceptable to the institution.

Different kinds of context-sensitive information can refine a dependency model and help the institution to concentrate on the events that are affording deterioration. Events that are unlikely or irrelevant can be eliminated, and the weak points in the risk chain more easily identified. For example, the figure below is a general model of damage from NO_2 which has been reduced to make the model more specific to the context.

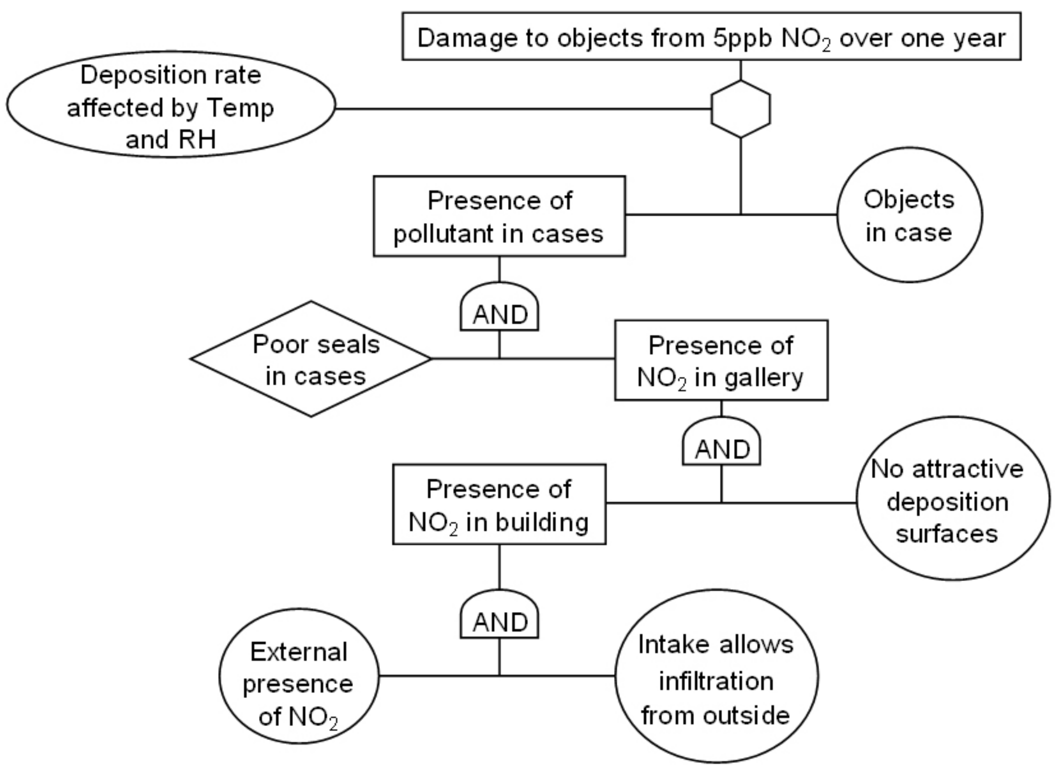


Figure 5: A reduced version of figure 4. The omission of some events is based on information from monitoring.

The figure above is based on figure 4 but certain elements have been removed to make it more specific to a context. Information about the context can inform which of those relationships exist. For example, if the way in which pollution was entering a museum had been determined through diagnostic monitoring an OR relationship can be removed from the system, and the weaker AND relationship can be concentrated upon. As a result, the mitigation is better informed and the weakest link can be identified.

Risk assessment data can be applied to the model quite easily. Since assessment of risk is really looking at the same process in terms of threat, rather than mitigation, the information about different scenarios can be applied to determine the most appropriate course of action.

5 Probability

Once the tree has been constructed, probabilities can be applied to each of the events. Including probabilities increases the effectiveness and representativeness of the model. Since the outcome of all risks, catastrophic and deterministic, will depend on chance or situation, this can provide insight into different routes that might lead to the top event, referred to as cut sets. Determining the most cost effective way to break the risk chain, or decide which lower events should be attended to may depend on the probability of that event occurring. This can be achieved with scientific information, collected data and information related to the context. The different routes by which an outcome can be reached can be charted this way and the most probable identified. Events may be infrequent or only take place at certain times, and therefore difficult to model, but the construction of the tree can be altered for different contexts.

Cognitively, probabilities are difficult to reflect upon [16], since probabilities are treated differently with different relationships. Because AND relationships require both prior events the calculation is multiplicative. Because any of the preceding events in an OR relationship can ensure the outcome, the calculation is additive. The example below shows that probabilities for events are significantly affected by the kind of relationship.

AND relationships	0.7 x 0.2 = 0.14
OR relationships	0.7 + 0.2 = 0.9

When connected, the whole model can have the effect of a Bayesian network from which one can infer causality, conditional probabilities, the most likely causes of an event, and modes and requisites for failure and success [17]. However, this is outside the scope of the paper.

6 Conclusion

Preventive conservation strategy has often provided useful, generalisable ways of determining the problems that conservators face. However, their mitigation has not received as much attention in terms of techniques that can be applied to different situations. The technique of dependency modelling offers a novel way of looking at how threats to collection preservation can be dealt with systematically and offers and approach to deciding on how identified problems might be mitigated.

Dependency modelling creates a deductive method for determining events, and a visual representation of the system. This can help understand and explain the appropriateness of different courses of action against risks to collections. Through the application of probabilities, a basis for quantitative analysis is provided. The technique identifies critical aspects of system behaviour and can be applied to any kind of system.

Development of a model tree does require a certain amount of expertise about the system but adaptable templates could feasibly be created for common situations. The process can also be time consuming but software has been developed to chart dependencies and calculate probabilities.

The model can be directly applied to European cultural heritage, and is intended to accommodate a wide range of applications. The illustrative examples are based on heritage institutions in Europe, but applications can be wider ranging. As well as modelling deterioration, one can use the same process to assess the reliability or effectiveness of mitigation. By making the aim of the mitigation the 'top event', the processes involved in the chosen method can be modelled as the prior events. 'Success' in the preservation of cultural heritage may be abstract to a certain extent, but dependency models have accommodated many abstract applications.

Because of its potential to be applied to any kind of heritage, and any kind of situation, dependency modelling has a great deal to offer conservation. The development of a method to select appropriate mitigation methods can lead to improved decision-making that is more transparent, and hence justifiable, and more cost-effective.

7 European Project Details

MASTER, EVK4-CT-2002-00093, Preventive Conservation Strategies for Protection of Organic Objects in Museums Historic Buildings and Archives, Elin Dahlin, Norwegian Institute of Air Research (NILU).

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