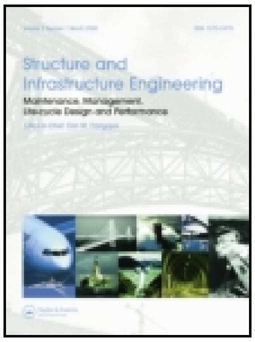

Taylor & Francis
Taylor & Francis Group

Structure and Infrastructure Engineering
Maintenance, Management, Life-Cycle Design and Performance

ISSN: 1573-2479 (Print) 1744-8980 (Online) Journal homepage: http://www.tandfonline.com/loi/nsie20

# Using real option methods as a tool to determine optimal building work programs

Miriam Esders, Bryan T. Adey & Nam Lethanh

**To cite this article:** Miriam Esders, Bryan T. Adey & Nam Lethanh (2016) Using real option methods as a tool to determine optimal building work programs, Structure and Infrastructure Engineering, 12:11, 1395-1410, DOI: 10.1080/15732479.2015.1131994

**To link to this article:** http://dx.doi.org/10.1080/15732479.2015.1131994

STRUCTURE AND INFRASTRUCTURE ENGINEERING, 2016
VOL. 12, NO. 11, 1395–1410
http://dx.doi.org/10.1080/15732479.2015.1131994

# Using real option methods as a tool to determine optimal building work programs

Miriam Esders, Bryan T. Adey and Nam Lethanh

Institute of Construction and Infrastructure Management, ETH, Zurich, Switzerland

**ABSTRACT**

Long-term management of a building requires consideration of costs and benefits of the building's operation that depend on interventions on the building elements. Each combination of interventions over time is a possible work program (WP), the one yielding the highest net benefits is the optimal WP. Much work has been done to evaluate WPs assuming that timing and type of interventions are known, whereas in reality, either timing or type might be unknown. A building manager planning an intervention in 10 years will certainly change her mind as that time approaches if new information suggests this change being beneficial. So-called real option methods (ROM) have been increasingly used to evaluate the possibility of single interventions on engineering systems considering this flexibility, and show potential to improve decision-making. Investigating the use of these ROM in the evaluation of WPs, four office building WPs with multiple interventions are evaluated with two ROM types, using a binomial tree, and a traditional method, with significant uncertainty associated with the operating costs. The results show that the ROM allow the building manager to determine better WPs than the TM, at least in some cases. Advantages and disadvantages of using ROM here are discussed.

**ARTICLE HISTORY**
Received 30 July 2015
Revised 2 October 2015
Accepted 19 October 2015

**KEYWORDS**
Strategic decision-making; flexibility; strategy evaluation; uncertainty; building intervention planning; infrastructure management; real options

## 1. Introduction

A building manager executes interventions[1] to ensure that a building provides an adequate level of service over a specified time period. It is in the building manager's interest to ensure that the interventions over the specified time period, i.e. work programs (WPs),[2] are executed to provide the maximum net benefits, e.g. rental income minus operation costs. The WP with the maximum net benefits is considered to be an optimal work program (OWP).

A traditional way of determining the OWP is to analyse all possible combinations of interventions at all possible times over the investigated time period and select the one with the highest expected net benefits. The expected net benefits are estimated considering the expected values of key parameters throughout the investigated time period. It is clear that there can be no certainty over longer time periods about the actual values of these key parameters, e.g. the condition or the remaining service life of a building element but also energy prices, construction times or specifications in standards. An example WP could be to execute an intervention in year 10 of a 20-year time period while ignoring the fact that a manager is not a static entity who may change her mind in year 9, based on new information about uncertain key parameters, ignoring the initial plan to execute an intervention in year 10. Thus, the decision to execute an intervention today depends on the decision to execute an intervention in the future, even though it may actually not happen! It would be better to consider the ability of the manager to change her mind. Correct evaluation of WPs requires explicit consideration of this uncertainty and managerial flexibility.

This is seemingly possible with, so called, real option methods (ROMs), which have increasingly been used in the field of civil engineering (Ford & Bhargav, 2006; Kalligeros & de Neufville, 2006; Santa-Cruz & Heredia-Zavoni, 2009). Using these types of methods, multiple researchers have discovered that, in specific cases, these methods lead to more accurate estimates of the benefits of decisions and hence, often result in different choices than the ones made with traditional methods (TM) (e.g. used in Boyles, Zhang, & Waller, 2010; Sarja et al., 2006; Zhang & Gao, 2010).

When using ROMs to determine OWPs it must be realised that all possible interventions in the future have a probability of occurrence, and it will only be known if one is executed when the time interval of the execution is reached. The OWPs developed using a ROM will, therefore, in general, consist of only the probable times and types of interventions at those times. In contrast, WPs investigated with a TM consist of the exact times and types of interventions to be executed.

For example, an OWP developed using a ROM would state that it is most probable that in 10 years, an intervention will be executed on the façade of a building and that that intervention will be the repair of the insulation. There will also, however, be a probability that either the replacement of the insulation, or the do nothing intervention will be executed in year 10 and a probability that the intervention will be done a year earlier or later. The timing and the type of intervention depends on the

**CONTACT** Miriam Esders esders@ibi.baug.ethz.ch

values of the key parameters at that time, and on the decisions made between time $t = 0$ and the time $t$ of the decision, e.g. if the insulation were already replaced, it will not be replaced again. An OWP developed using a TM would state that in 10 years, an intervention will be executed on the façade of a building and that that intervention will be the replacement of the insulation.

In this paper, the advantages and disadvantages of using two types of ROMs in the determination of optimal WPs for buildings are demonstrated. This is done by comparing the OWPs for an office building determined using the two types of ROMs and a TM. The possible interventions on the building are the replacement of the insulation or the windows or both. There is significant uncertainty associated with the future heating fuel price, which in turn affects the operation cost (e.g. heating during winter period), which is modelled stochastically.

The remainder of the article is structured as follows: Section 2 positions the work with respect to past developments in life-cycle cost analysis. In Section 3, the probabilistic model for the key parameter is described. Sections 4 and 5 contain descriptions of a TM and the two types of ROM investigated. In Section 6, the methods are used in an example. Sections 7 and 8 contain the discussion of the results and the conclusions, respectively.

## 2. Background

Economic methods used to determine the feasible construction and management of engineering projects, such as the determination of WPs, are often required whenever a new project is initiated. A vast number of literatures have been focused on types of life-cycle cost analysis such as benefit-cost or discounted cash flow analysis (Frangopol & Neves, 2008; Woodward, 1997). In principle, the benefit-cost ratio or the discounted cash flow of one project results in a value that is then compared against that of other projects or WPs. The one yielding the lowest costs, bringing the highest benefits, or having the highest benefit-cost ratio are considered as optimal.

The prediction of service life, the condition or, in general, the ability of an infrastructure and its elements to function as required, is one important component in life-cycle cost analysis. Considerable research has been conducted in the modelling of processes leading to a decrease of this ability, especially in the modelling of the deterioration of infrastructure elements (e.g. Alexander & Thomas, 2015; Baum & McElhinney, 2000; Moncmanová, 2007). Advanced statistical methods have been used to establish predictions of the service life (e.g. Chai, De Brito, Gaspar, & Silva, 2015; Shohet, 2003; Wang & Elhag, 2007) and the parameters used in adequate models (e.g. Chu & Durango-Cohen, 2008; Jongen et al., 2006; Mata, 2011).

Original life-cycle cost analyses were deterministic, i.e. the costs and benefits over the life cycle, and thus the key parameters they depend on, were assumed to be known with certainty (see for example Flores-Colen & de Brito, 2010; Mendes Silva & Falorca, 2009). Building on these original life-cycle cost analyses, a great number of researchers have proposed probabilistic modelling approaches instead of deterministic ones to address the uncertainties associated with engineering and construction projects, and to be used in any phase of the life cycle of the project (Kobayashi & Kuhn, 2007; Woodward, 1997). One example of using probabilistic methods in construction engineering and management is the use of the Monte Carlo method, e.g. to determine the distribution of the values of various risk factors occurring during the design and construction phases of a building project (Edwards & Bowen, 1998; Hui & Ng, 2008), the simulation of deterioration and the determination of the optimal times to execute maintenance interventions for bridges (Bocchini & Frangopol, 2011; Bucher & Frangopol, 2006), or the estimation of reliability, costs and revenues in maintenance planning for industrial plants (Marseguerra & Zio, 2000).

In the management of infrastructure objects such as roads, bridges, and tunnels, other probabilistic methods such as the use of Weibull, Poisson, and Markov models for the modelling of processes leading to the failure of infrastructure and the determination of optimal WPs have been widely used, e.g. a Weibull hazard function in (Lethanh & Adey, 2013) to model deterioration to optimise intervention strategies for a road link, a Markov model in (Lethanh, Adey, & Fernando, 2014 to determine optimal intervention strategies for multiple objects affected by uncorrelated manifest and latent processes, or a Poisson model in (Ching & Leu, 2009) to model the deterioration in components of civil infrastructure systems. Orcesi and Frangopol (2011) used an event tree to model uncertainties in the inspection process and the resulting intervention decision to find optimal intervention and monitoring strategies for bridges. The increasing use of probabilistic methods in infrastructure management can also be seen in their use in computerised infrastructure management systems (Fruguglietti, Pasqualato, & Spallarossa, 2012; Hajdin, 2001; Thompson, Small, Johnson, & Marshall, 1998).

In building and facilities management, probabilistic models have been used. For example, Kobayashi and Kaito (2010) developed a mixture Weibull model to be integrated into a hierarchical facilities management framework. Lounis and Vanier (2000) developed a maintenance management system for roofing systems with performance prediction based on a Markov model.

While the major body of methods used in optimisation of WPs in infrastructure management has been focused on the consideration of deterioration of materials, components and structures, efforts have been made to determine WPs explicitly under the consideration of changes in demand. In Allehaux and Tessier (2002), a systematic approach was presented for the assessment of functional obsolescence under criteria like compliance with user needs and flexibility, while not providing an explicit optimisation tool. In Khan and Haddara (2003), a methodology for risk-based decision processes was developed for determining OWPs using fault tree analysis. These methods rely on stakeholder expertise in the analysis of the system and choice of management strategies rather than analytic models and optimisation processes as for the maintenance management systems considering deterioration.

Recently, it has been shown that ROMs have the potential to be used in life-cycle cost analysis under demand uncertainty. ROMs belong to the set of probabilistic methods that were initially developed in the field of business investments (Nembhard & Aktan, 2009; Zhao, Sundararajan, & Tseng, 2004), and have been increasingly used in engineering fields (Pereira, Rodrigues, & Rocha Armada, 2006; Wang & de Neufville, 1996). Santa-Cruz and Heredia-Zavoni (2009) used a ROM to evaluate managerial flexibility regarding the maintenance of offshore oil platforms due to changing conditions as hydrocarbon prices or maintenance

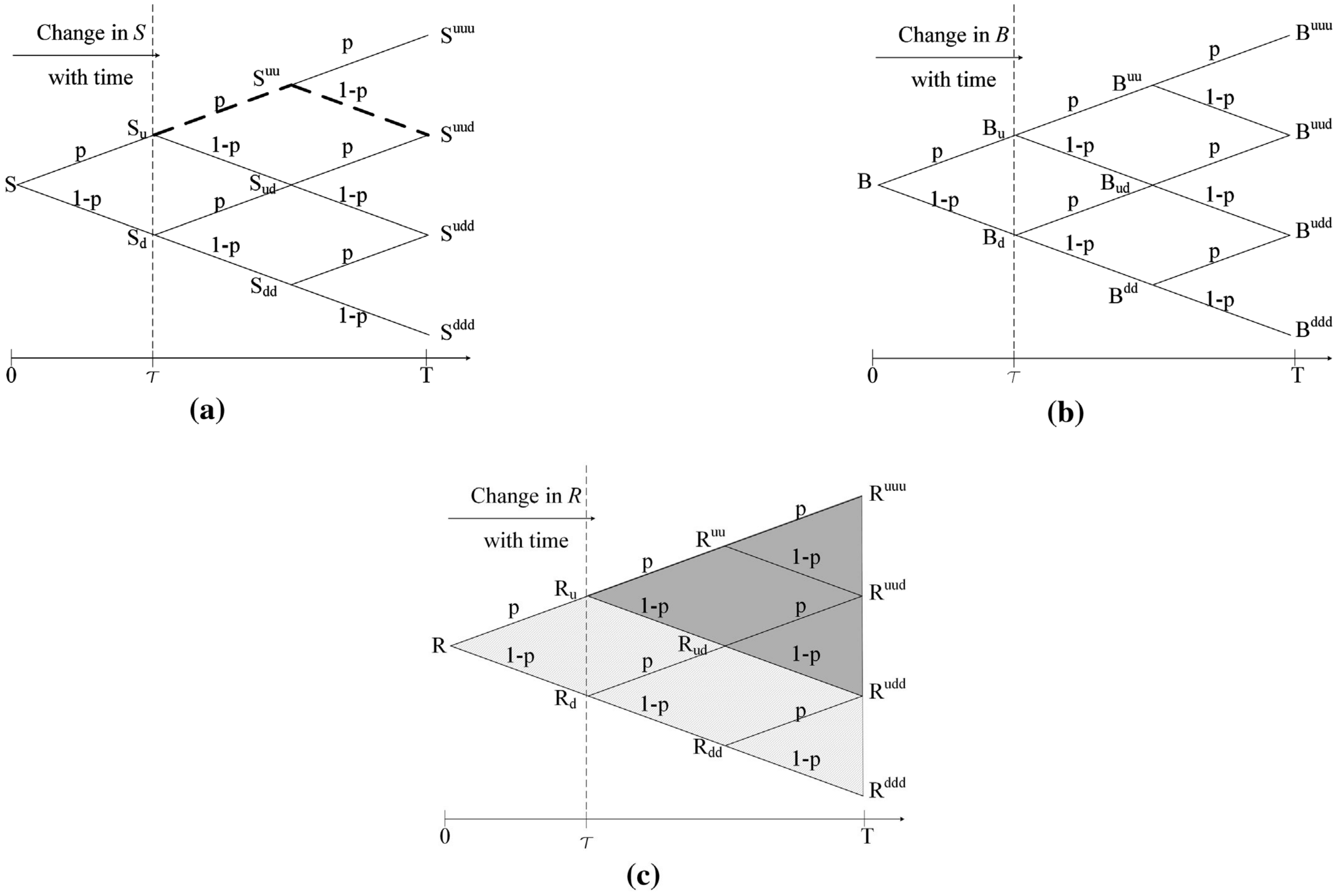

**Figure 1.** (a): Uncertain key parameter S, (b): Yearly benefits B, (c): Expected net benefits R in binomial tree (R is the sum of yearly benefits in the light-grey cone, Ru is the sum of yearly benefits in the dark-grey cone)

costs. In Jin, Li, and Ni (2009), a ROM was used to investigate the right time to execute preventive maintenance interventions depending on the condition state of the production line and product demand. Koide, Kaito, and Abe (2001) used a ROM to plan interventions on a steel girder bridge depending on the rate of deterioration of the different elements in the bridge. In Arboleda and Abraham (2006), a ROM was applied to the valuation of the operation and maintenance in infrastructure systems for public private partnership projects, considering uncertainties in the demand for the offered services of the systems. Lethanh and Adey (2014) used a ROM to determine optimal intervention windows for railway infrastructure.

Other sources used ROMs in the evaluation of retrofit projects. Ashuri, Kashani, and Lu (2011) investigate real options in form of energy retrofit interventions of existing buildings. In Menassa (2011), ROMs were applied to the evaluation for sustainable retrofits in existing building under uncertainty. In de Neufville, Scholtes, and Wang (2006), ROMs were employed to determine the foundation size for a parking garage structure that might have to adapt to new demand situations in the future. In Martins, Marques, and Cruz (2013), a comprehensive overview of the use of ROMs in infrastructure projects is given.

Keeping this in mind, the work presented in this paper has been conducted to investigate the potential of different types of ROMs to be used in the determination of WPs in building management systems. The particular challenge, which has not yet been addressed by any of the existing research, is to optimise work programs in building management under consideration of demand changes, using stochastic models for demand changes and systematic optimisation in decision-making in addition to stakeholder expertise.

## 3. Uncertainty modelling

In the construction of a static model of the system, it is necessary to make clear the entire range of possible scenarios to be analysed. This is done by identifying the range of possible values of the key parameters at each $t$ in the investigated time period, and determining how to divide these into a tractable number of scenarios. This usually means discretising the range of values within one unit of time.

One possible way to do this is to use a binomial tree, i.e. the values of the key parameters at each instant in time can be modelled as being located on one of a finite number of values at each point of time, and the number of possible values increases with the number of time units. The evolution of the value of a key parameter is then given by:

$$\mathrm{d}S/S = \mu_s \mathrm{d}t + \sigma_s \mathrm{d}z \tag{1}$$

where $S$ is the value of the key parameter at the beginning of the investigated time period, $\mu_s$ is the drift of the value of the key parameter, $\sigma_s$ is the volatility or standard deviation of the value of the key parameter, dt is an increment in time and dz is an increment of the standard Wiener process in dt that deviates around a mean of 0.

In a binomial tree, each value $S$ in time interval $t$ branches to two possible values in time interval $t + 1$, namely $S_t \cdot u$ and $S_t \cdot d$, where $u$ and $d$ represent the amount that the key parameter can increase in decrease in each unit of time, respectively. If the values of the upward and downward movements are equal over time, the binomial tree forms a recombining binomial lattice, as shown in Figure 1(a). For each time interval, the value of the key parameter goes up with the probability $p$ and down with the probability $(1 - p)$.

The evolution over time of the values of the key parameters can often be modelled as geometric Brownian processes where it can be assumed that the values at $t + 1$ depend only on the values at $t$ and that this can be modelled as random. In this case, the values of a key parameter going up and down can be determined by the following equations (Cox, Ross, & Rubinstein, 1979):

$$\begin{cases} u = e^{\sigma\sqrt{\mathrm{dt}}} \\ d = e^{-\sigma\sqrt{\mathrm{dt}}} \end{cases} \tag{2}$$

where $\sigma$ is the volatility or standard deviation of the key parameter and dt is the size of the time interval.

The risk-free probability of the value of $S$ going up and down is determined by the following equation (derivation e.g. in Dixit & Pindyck, 1993; Trigeorgis & Mason, 1987):

$$p = \frac{\exp(r \cdot \mathrm{dt}) - d}{u - d} \tag{3}$$

where $r$ is the risk-free interest rate. Using the risk-neutral probability instead of the real probability accounts for the underlying assumption that the building manager could also rent a different similar building and use this building for the same purposes as her own building (compare assumption in similar cases e.g. Greden & Glicksman, 2004; Menassa, 2011). Using the risk-neutral probability ensures that the results of the evaluation of the WPs have the same expected benefits as the renting opportunity; otherwise the building manager should simply rent a building from someone else.

Figure 1(a) shows the probabilistic model of one key parameter $S$ in a binomial tree, each node $n$ representing one possible value of $S$. As can be seen from Figure 1, future scenarios are the paths that immediately follow each node $n$, with a certain probability $q$. $B_{i_{n,t}}$ in Figure 1(b) are the yearly net benefits depending on the value of $S$. Therefore, the expected net benefits in Figure 1(c), $R_{n,\tau}$, that can be gained in the following years $t$ will be the sum of yearly benefits $B_{i_{n,t}}$ from all paths $i_{n,t}$ departing from node $n$ multiplied with their probabilities until the end of investigated time $T$, which can be represented by the following equation:

$$R_{n,\tau} = \sum_{t=\tau+1}^{T} \left\{ e^{-r(t-\tau)} \sum_{n=1}^{N_t} \sum_{i_{n,t}=1}^{I_{n,t}} \left( q_{i_{n,t}} \cdot B_{i_{n,t}} \right) \right\} \tag{4}$$

Here, the notation $\tau$ is referred to as the decision time interval, $r$ is the discount rate and $q$ is the joint probability leading to path $i_{n,t}$. For example, if considering in Figure 1(a) the node $n = S_u$ for the calculation of $R_{S_u,\tau}$, then the probability $q$ that leads to the path over node $S_{uu}$ to the node $n = S_{uud}$ (dashed path in Figure 1(a)) with $B_{uud}$ is $q = p \cdot (1 - p)$.

In addition to its computational tractability the use of a binomial tree gives an attractive representation of the possible values of the key parameters (Dixit & Pindyck, 1993), which helps to increase transparency in the decision-making process (Kalligeros, 2010).

## 4. A traditional method

With TMs of valuation of WPs it is assumed that all possible WPs are known at the decision time $t = 0$ and that the building manager chooses the OWP among all possible WPs at $t = 0$. Further, it is assumed that the yearly benefits considered for the evaluation of these WPs are subject to one uncertain key parameter.

### 4.1. Mathematical formulation

The mathematical model used in the TM in this paper is described with the following equations. The interventions to execute and when they should be executed are determined at $t = 0$, taking into consideration the probable values of one uncertain key parameter, i.e. their expected values, throughout the investigated time period, by discounting them back to $t = 0$ and summing them up (as described for example in Trigeorgis (1996)). The objective function is:

$$\arg\max_{\tau}\{X(\tau)\} \tag{5}$$

i.e. choose the time $\tau$ to execute an intervention type that results in the maximum expected net benefits. The value of $X(\tau)$ is the cumulative expected net present benefits for all yearly benefits estimated for the entire investigated period [0,T], and it can be described as follows:

$$X(\tau) = R_0 + e^{-r\cdot\tau} \left\{ \sum_{n=1}^{N_\tau} R^{+}_{n,\tau} - C_\tau \right\} \tag{6}$$

where $R_0$ are the reference expected net benefits for the entire period [0,T], i.e. for the case that no intervention is executed over the complete time period, and $\tau$ in this equation is referred to as the time to execute the intervention, $C_\tau$ is the cost of an intervention at time $\tau$. $N_\tau$ is the total number of nodes at time $\tau$ and $R^{+}_{n,\tau}$ are the additional expected net benefits that could be generated after any particular node due to the execution of the intervention. $R^{+}_{n,\tau}$ is calculated using Equation (4).

If considering multiple interventions, e.g. one type can be executed multiple times or two types of intervention can be executed sequentially, then $X(\tau)$ has to be calculated for each possible combination of intervention type and execution time $\tau$ in order to find the optimal.

### 4.2. Steps

The expected net benefits from a WP, determined with the TM, are determined by performing the steps shown in Table 1.

**Table 1.** TM steps.

| Step | Description |
|---|---|
| 1 | Determine the costs and benefits as a function of the values of the uncertain key parameters over the investigated time period (*T*) |
| 2 | Develop a static model of the system, i.e. determine the values of the key parameters to be considered possible over the investigated time period |
| 3 | Develop a dynamic model of the system, e.g. using a binomial lattice, where the values of the uncertain parameters move in equal units up and down after calculating the probabilities of having each of the values of each of the key parameters *S* at the beginning of each time interval (*p*) |
| 4 | Estimate the expected net benefits of a reference WP |
| 5 | Estimate the additional yearly net benefits for each *t* in which it is possible to execute an intervention |
| 6 | Calculate the expected net benefits over the investigated time period for each node *n* of each WP, under consideration of the probabilities of occurrence of each node *n*, discounted to and compared at *t* = 0 and chose the WP with the maximum expected net benefits |

## 5. Real options methods

Opposed to the TM, the ROMs explicitly take into consideration the ability of a facility manager to make decisions in the future based on new information, herein referred to as management's flexibility. The two types of ROMs investigated are:

1. ROM EO – where a decision is to be made at one specific point in time in the future, or at the last possible time interval, and
2. ROM AO – where decisions are to be made at multiple specific points in time in the future, or at the last possible time interval and in the intervals before.

Opposed to the TM, in both types of ROM, it is not assumed that the building manager chooses the OWP at *t* = 0, but merely the intervention at *t* = 0 that is most likely to be part of the OWP. In both ROMs, it assumed that decisions about interventions at times *t > 0* are made when the uncertainty related to the values the key parameters has decreased, i.e. when the building manager knows more about the actual value of the key parameter than she did at decision time *t*. The possible values of the key parameter are represented as nodes *n* in the binomial tree. It can be seen that in the ROMs, there is not one OWP at time *t* but an optimal set of WPs, and the intervention selected at *t* = 0 will belong to all WPs in that optimal set. As the key parameter develops probabilistically (compare Section 3), OWPs are selected with a certain probability. In this paper, the optimal set of WPs determined with a ROM is equally referred to as OWP.

### 5.1. Mathematical formulation

The mathematical model used in both ROMs is described in the following equations. This mathematical formulation applies for both ROM EO and ROM AO, while the decision in ROM EO can only be made at decision nodes in the last possible, i.e. only one, time interval, and in ROM AO is possible at decision nodes in selected time intervals before the last.

In the RO methods, the total expected net benefits at *t* = 0 can be calculated using following equation:

$$X_\tau(t) = R_0 + e^{-r\cdot t}\cdot\sum_{\bar{n}=1}^{\bar{N}_t} X_{\bar{n}}^{+}(t) \tag{7}$$

where, $\tau$ is the decision time interval and *t* is the time in [0, $\tau$] in which an intervention can be executed. The values of $X_{\bar{n}}^{+}(t)$ are determined by applying the following equation to the final nodes of last possible time interval at $\tau$ in both the ROM EO and ROM AO context (according to Kodukula & Papudesu, 2006; Menassa, 2011)

$$X_{\bar{n}}^{+}(\tau) = \mathrm{Max}\left[0, R_{\bar{n},\tau}^{+} - C_\tau\right] \tag{8}$$

In the European option (ROM EO) context, $X_{\bar{n}}^{+}(t)$ is determined only in the final nodes and then used in equation (7) to determine $X_\tau(t)$ at *t* = 0. In the American option (ROM AO) context, the decision is possible in the time intervals before the last and thus, $X_{\bar{n}}^{+}(t)$ can be determined (according to Kodukula & Papudesu, 2006; Menassa, 2011) in decision nodes before the last by applying

$$X_{\bar{n}}^{+}(t) = \mathrm{Max}\left[e^{-r\cdot \mathrm{dt}}\left[p\cdot X_{\bar{n},\mathrm{up}}^{+}(t+\mathrm{dt}) + (1-p)\cdot X_{\bar{n},\mathrm{down}}^{+}(t+\mathrm{dt})\right], R_{\bar{n},t}^{+} - C_t\right] \tag{9}$$

where $X_{\bar{n},\mathrm{up}}^{+}$ are the expected net benefits from executing an intervention in the time interval following *t* at the node with the increasing value of *S*, and thus *R* (up), and $X_{\bar{n},\mathrm{down}}^{+}$ are the expected net benefits from executing an intervention in the time interval following *t* at the node with the decreasing value of *S*, and thus *R* (down). $R_{\bar{n},t}^{+}$ are the additional expected benefits from executing an intervention only at the node $\bar{n}$; when an intervention is executed, positive benefits can be gained.

Applying equation (9) in recursive calculation from time *T* to 0, the expected net benefits at *t* = 0 can be expressed under the consideration of optimal decision-making at each decision node *n* in any *t*. It can be seen that the expected net benefits of the reference case, $R_0$, are not considered in the optimisation at each decision node described in equation (9), but finally in the total expected net benefits at *t* = 0 (Equation (7)). If considering multiple interventions, e.g. one type can be executed multiple times or two types of intervention can be executed sequentially, $X_{\bar{n}}^{+}(t)$ of each possible intervention after *t* and following node $\bar{n}$ has to be considered in the optimisation in Equations (8) and (9).

### 5.2. Steps

The expected net benefits from a WP, determined with the RO methods, is determined by performing the steps given in Table 2, which are similar to those used by others (Arnold & Crack, 2000; Kodukula & Papudesu, 2006).

## 6. Example

### 6.1. Overview

The effect of using a ROM to determine an OWP is demonstrated in this example by comparing the OWPs determined using the TMs and the ROMs shown in the previous sections. The goal of this example was to show that a case exists where management's

**Table 2.** ROM steps.

| Step | Description |
|---|---|
| 1 | Determine the costs and benefits as a function of the values of the uncertain key parameters over the investigated time period (*T*) |
| 2 | Develop a static model of the system, i.e. determine the values of the key parameters to be considered possible over the investigated time period |
| 3 | Develop a dynamic model of the system, e.g. using a binomial lattice, where the values of the uncertain parameters move in equal units up and down after calculating the probabilities of having each of the values of each of the key parameters *S* at the beginning of each time interval (*p*) |
| 4 | Estimate the expected net benefits of a reference WP |
| 5 | Estimate the additional yearly net benefits for each $\hat{t}$ in which it is possible to make a decision for each possible WP |
| 6 | *ROM EO*: Calculate the additional expected net benefits, i.e. additional to the one of the reference WP, of each possible WP for each possible node *n* in one time *t* in which decisions can be made and chose the one with the maximum expected net benefits for each node *n*; then discount this expected net benefits back to $t = 0$, considering the probabilities of occurrence of all possible node *n* with values of *S* at decision time *t*<br>*ROM AO*: Calculate the additional expected net benefits, i.e. additional to the one of the reference WP, of each possible WP for each possible node *n* for each possible time *t* in which decisions can be made. Then, starting with the latest possible decision time *t*, chose the WP with the maximum expected net benefits for each node *n* in that decision time *t*; then discount this expected net benefits back to $t - 1$ and again chose the WP with the highest expected net benefits for each possible node *n* at time $t - 1$, considering the probabilities of occurrence of all possible nodes *n* with values of *S* at decision time *t*, relative to $t - 1$. Repeat this backward calculation until time $t = 0$ |

**Table 3.** Characteristics of office building.

| Parameter | Description | Units | Value |
|---|---|---|---|
| $A_H$ | Heated area | $m^2$ | 12,000 |
| $A_F$ | Facade system surface area | $m^2$ | 7,000 |
| $f_d$ | Fuel demand of heating system | l/kWh | 0.1 |
| $c_r$ | Yearly rental income | €/a*$m^2$ $A_H$ | 300 |
| $d_0$ | Initial heating demand per area of building with old façade | kWh/a*$m^2$ $A_H$ | 75 |
| $c_f$ | Intervention costs for façade replacement per façade area | €/$m^2$ $A_F$ | 400 |

flexibility and its consideration with the ROMs result in higher expected net benefits and different WPs than with a TM. Further, the aim was to demonstrate the application of the ROMs and show the nature of the results possible with the application of the ROMs.

In this example, the building manager wants to determine if the expected net benefits from the operation of the building can be improved by renovating it. The manager receives rent from the tenants of the building and has costs for heating it. The heating costs depend on the price of heating fuel, with which there is substantial uncertainty, and the total amount of heating required, which can be changed by improving the façade system. Based on the past volatility in the price for heating fuel it is expected that they could either increase or decrease significantly over the next 50 years.

The façade can be improved by replacing the façade cladding, and thus the insulation, or by replacing the current insulation with improved ones. Improvement is here defined by the improvement of the heat transfer coefficient *U* of both insulation and windows, so that less heat is lost. The manager wants to determine what should be done at $t = 0$ and if no intervention is executed then, when it will most likely be that she should execute an intervention and what type of intervention that would be, i.e. the OWP.

### 6.2. Building

The building has 20 levels of about 3.5 m floor level and a rectangular footprint with a usable floor space of 600 $m^2$ per level (30 m × 20 m). This results in total usable floor space of 12,000 $m^2$ and a façade area of 7000 $m^2$. The façade system consists of façade cladding with the insulation, in the following referred to as insulation, and windows. The ratio of area of façade cladding to total façade area is 70% and the corresponding ratio of windows is 30%. The building characteristics are summarised in Table 3. The information required to enable the estimation of the expected net benefits are given in Table 4.

### 6.3. Decision situations

Three different decision situations were investigated (Table 5).

### 6.4. Interventions and WPs

The four possible interventions are (1) replace the insulation, (2) replace the windows, (3) replace the façade system, i.e. replace the wall insulation and the windows together, and (4) do nothing. These are summarised in Table 6. The investigated WPs are constructed from these interventions and the three possible WP types are explained in Table 7. The interventions are assumed to take effect immediately; costs are incurred immediately, benefits from operation are generated in the time interval following the decision, in this case over 5 years.

The multi-stage OWP using ROM EO was estimated by first determining the most beneficial time interval to have the ability to decide to replace the insulation (e.g. time interval 15), and then assuming that the insulation was replaced, determining the most beneficial subsequent time interval in which to have the ability to decide to replace the windows. This was done for all possible combinations (i.e. WPs) of execution of both stages. The WP with the highest expected net benefits was chosen as the optimal one.

The multi-stage OWP using ROM AO was estimated by first determining the OWPs and their expected additional net benefits of replacing the windows (stage 2) for each possible time interval when the insulation (stage 1) could have be executed and any possible outcome of the uncertain key parameter (e.g. if the insulation is replaced in time interval 5 at a fuel price of 1.96 €/l, then the recommended WP would suggest to replace the windows in time intervals 20, 30 and 40). Then, the beneficial time intervals

**Table 4.** Cost, benefits and time parameters for operation of office building.

| Parameter | Description | Units | Value |
|---|---|---|---|
| $B_{n,t}$ | Yearly net benefits $= I_t - O_t^{k_t} \cdot S_t$ | €/a | – |
| $I_t$ | Yearly rental income $= c_r \cdot A_H$ | €/a | – |
| $O_t^{k_t}$ | Yearly heating demand $= d_t^{k_t} \cdot A_H \cdot f_d$ | l/a | – |
| $S_o$ | Initial fuel price at $t = 0$ | €/l | 1 |
| $\sigma$ | Volatility of fuel price | – | 0.3 |
| $r$ | Interest rate per year | – | 0.02 |
| $f$ | Inflation rate per year | – | 0.02 |
| dt | Time steps of binomial tree model | Years | 5 |
| $T$ | Investigated time period for generation of yearly net benefits | Years | 50 |

**Table 5.** Decision situations.

| No. | Description | Decision times (years) |
|---|---|---|
| 1 | In this situation the building manager can decide to execute an intervention at the end of any 5-year time interval between now and one time step before the end of the 50-year time period (a decision in year 50 would lead to not executing the decision as no yearly benefits can be generated afterwards). This situation is one without constraints | 0, 5, 10, 15, 20, 25, 30, 35, 40, 45 |
| 2 | Here, the building manager can decide to execute an intervention at any time during the first 15 years of the 50-year time period but not afterwards. It is one where due to planned interventions on other nearby buildings nothing can be done beyond a specific point in time | 0, 5, 10, 15 |
| 3 | Here, the building manager can decide to execute an intervention now or in 15 years but at no other time. It is one where effort is being made to combine interventions on the building to reduce the impact on the users of the building | 0, 15 |

**Table 6.** Interventions.

| | | Heating demand per area | Yearly heating demand | Intervention costs per area façade |
|---|---|---|---|---|
| | | $d_0^{k_t}$ | $O_t^{k_t}$ | $c_t^{k_t}$ |
| Int | Description | (kWh/a*m² $A_H$) | (l/a) | (€/m² $A_F$) |
| 0 | Do nothing | 75 | 90,000 | 0 |
| 1 | Stage 1: Replace insulation only | 35 | 42,000 | 200 |
| 2 | Stage 2: Replace windows only additional to insulation | 17 | 20,400 | 200 |
| 3 | Replace complete façade system | 17 | 20,400 | 400 |

to have the ability to decide to replace the insulation (stage 1) were determined under consideration of the subsequent beneficial time intervals to be able to decide about the replacement of the windows determined before.

### 6.5. Results

The OWP of each type was found for each decision situation using each method. The results are shown in Table 8. For each decision situation and WP type, the expected net benefits are given along with the relevant times of the recommended WPs:

$\tau_{\text{TM}}$ for the TM, the optimal planned time of execution at $t = 0$.

$\tau_{\text{EO}}$ for the ROM EO, the best time to decide about the execution.

$\tau_{\text{AO}}$ for the ROM AO, the earliest time where the probability of execution is non-zero.

Table 8 shows the expected net benefits and probabilities of execution of the OWPs according to the mathematical formulation of Sections 3 and 5 for all situations, WP types and methods. The OWPs for each method and situation are the ones that yield the highest expected net benefits at $t = 0$. Table 9 shows the probabilities of execution for the multi-stage WP type for the evaluation with the ROM AO.

In Figure 2, for TM and ROM EO, the different expected net benefits at $t = 0$ are shown for each possible decision interval $t$ for decision situation 1. For the ROM AO, the decision can be made at each node of the binomial tree in each $t$ so that the representation in separate decision intervals $t$ is not possible; thus, only the maximum expected net benefits at $t = 0$ is shown for both WP types.

Table 8 shows the recommendation of the different methods for WPs that the building manager should adopt if she wants to maximise her expected net benefits. The expected net benefits of the do nothing OWP, 109.70 Mio. €, are the same determined with the TM and the ROMs, as no interventions are executed and the building manager has no flexibility to make decision in the future for this type of WP. Following the do nothing OWP yields the lowest expected net benefits at $t = 0$ of all OWPs. If the building manager has the possibility to execute an intervention in the future, i.e. WPs of all other types, it can be seen that the use of different methods to determine OWPs results in different OWPs (Tables 8 and 9).

For example, with decision situation 1, if the building manager

(1) investigates the single-stage WP type and uses
  (a) the TM to evaluate her possibilities she will replace the complete façade at $t = 0$ and will expect net

**Table 7.** Work program types.

| | | | | Number of possible WPs | | |
|---|---|---|---|---|---|---|
| | | | | Situation | | |
| No. | Name | Short description | Long description | 1 | 2 | 3 |
| 1 | Do nothing | Do nothing | No physical interventions are executed over the investigated time period | | 1 | |
| 2 | Single-stage | Replace complete facade system | All WPs that have only one intervention (additional to the do nothing intervention) with that intervention being the replacement of the façade system (they include the do nothing WP). This intervention is possible only once over the investigated time period | 10 | 4 | 2 |
| 3 | Multi-stage | Replace façade in stages (insulation and windows) | All WPs that have two interventions (additional to the do nothing intervention), where the first intervention is the replacement of the insulation and the second is the replacement of the windows (they include the WP with doing nothing at all and the WPs with only replacing the insulation). The second intervention is only possible after or at the same time as the first. Both interventions are possible only once over the investigated time period | 66 | 15 | 6 |

benefits of 110.36 Mio. €, i.e. additional expected net benefits of 0.66 Mio. € compared to the do nothing WP.

(b) the ROM EO to evaluate her possibilities, she will do nothing at $t = 0$ and wait to obtain more information in the future to determine whether or not she should execute the intervention. The expected net benefits are 111.00 Mio. €, i.e. additional expected net benefits of 1.30 Mio. € compared to the do nothing WP. The additional expected net benefits at $t = 0$, compared to the results from the TM, are 0.63 Mio. € (see Table 10). In this case, the best time to decide about the replacement of the system is year 15, and therefore the best time to have the ability to decide to execute an intervention is in year 15 where the probability is 0.37. The default intervention is to do nothing, i.e. with a probability of execution of 0.63, the façade would never be replaced.

(c) the ROM AO to evaluate her possibilities she will do nothing at $t = 0$ and wait to obtain more information in the future to determine whether or not she should execute the intervention. The expected net benefits are 111.22 Mio €, i.e. additional net benefits of 1.52 Mio. € compared to the do nothing WP. The additional expected net benefits at $t = 0$, compared to the results from the TM, are 0.86 Mio. €, compared to the ROM EO they are 0.22 Mio. € (see Table 10). The time intervals in which there is a non-zero probability of executing the window intervention, if given the chance, are year 10, 20, 30 and 40, with probabilities of 0.17, 0.08, 0.09 and 0.09, respectively. The default intervention is to do nothing, i.e. with a probability of 0.57, the façade would never be replaced.

(2) investigates the multi-stage WP type and uses

(a) the TM, she will decide to replace the insulation at $t = 0$ but then to not replace the windows at all. This yields an expected net benefits of 110.69 Mio €, i.e. additional net benefits of 0.99 Mio. € compared to the do nothing WP.

(b) the ROM EO, she will do nothing at $t = 0$ and wait to obtain more information future to determine whether or not she should execute the intervention. The expected net benefits are 111.06 Mio. €, i.e. additional net benefits of 1.36 Mio. € compared to the do nothing WP. The additional expected net benefits at $t = 0$, compared to the results from the TM, are 0.37 Mio. €. The best time to be able to decide to replace the insulation is in year 10, when the probability of doing so is 0.65. Assuming the insulation is replaced in year 10 the best time to decide to replace the windows is in year 20 when the probability of doing so is 0.19. The default intervention is to do nothing, i.e. with a probability of 0.35, the insulation would never be replaced, and with a probability of 0.81, the windows would never be replaced, even if the insulation were replaced.

(c) The ROM AO, she will do nothing at $t = 0$ and wait to obtain more information in the future to determine whether or not she should execute the intervention. The expected net benefits are 111.30 Mio. €, i.e. additional net benefits of 1.60 Mio. € compared to the do nothing WP. The additional expected net benefits at $t = 0$, compared to the results from the TM, are 0.61 Mio. €, compared to the ROM EO they are 0.24 Mio. €. The time intervals in which there is a non-zero probability of executing the insulation intervention if given the chance are years 5, 15, 25 and 40 with probabilities of 0.41, 0.10, 0.10 and 0.05, respectively. Assuming that they are executed at these times, the time intervals where there is a non-zero probability of executing the windows intervention if given the chance are shown in Table 8. They depend on the time when the insulation has been replaced and the energy price at that time. If, for example, the insulation has been replaced in year 5 at an energy price of 1.96 €/l fuel, the time intervals with non-zero probabilities for replacing the windows are years 15, 30 and 40, with probabilities of 0.069, 0.014 and 0.018, respectively. The default intervention is to do nothing, i.e. with a

**Table 8.** Results with net benefits and recommended WP.

| Situation | WP type | Evaluation method | τ | Recommended WP as probabilities of execution in interval | | | | | | | | | | Σ (Prob) | Expected net benefits in $10^6$ € | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Intervals in years | | | | | | | | | | | | |
| | | | | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | | Total | Differ. to WP 0 |
| **0** | Do nothing | All | | | | | | No execution | | | | | | | *109.70* | |
| **1** | Single-stage | TM | $\tau_{TM}$ | 1 | | | | | | | | | | 1 | *110.36* | 0.66 |
| | | ROM EO | $\tau_{EO}$ | | | | 0.37 | | | | | | | 0.37 | *111.00* | 1.30 |
| | | ROM AO | $\tau_{AO}$ | | | 0.17 | | 0.08 | | 0.09 | | 0.09 | | 0.43 | *111.22* | 1.52 |
| | Multi- stage | TM – insulation | $\tau_{TM}$ | 1 | | | | | | | | | | 1 | *110.69* | 0.99 |
| | | TM – windows | $\tau_{TM}$ | | | | | No execution | | | | | | 1 | | – |
| | | ROM EO – insulation | $\tau_{EO}$ | | | 0.65 | | | | | | | | 0.65 | *111.06* | 1.36 |
| | | ROM EO – windows | $\tau_{EO}$ | | | | | 0.19 | | | | | | 0.19 | | – |
| | | ROM AO – insulation | $\tau_{AO}$ | | 0.41 | | 0.10 | | 0.10 | | | 0.05 | | 0.66 | *111.30* | 1.60 |
| | | ROM AO – windows | $\tau_{AO}$ | | | | | See Table 9 | | | | | | 0.18 | | – |
| **2** | Single-stage | TM | $\tau_{TM}$ | 1 | | | | | | | | | | 1 | *110.36* | 0.66 |
| | | ROM EO | $\tau_{EO}$ | | | | 0.37 | | | | | | | 0.37 | *111.00* | 1.30 |
| | | ROM AO | $\tau_{AO}$ | | | 0.17 | 0.20 | | | | | | | 0.37 | *111.13* | 1.43 |
| | Multi-stage | TM – insulation | $\tau_{TM}$ | 1 | | | | | | | | | | 1 | *110.69* | 0.99 |
| | | TM – windows | $\tau_{TM}$ | | | No execution | | | | | | | | 1 | | – |
| | | ROM EO – insulation | $\tau_{EO}$ | | | 0.65 | | | | | | | | 0.65 | *111.03* | 1.33 |
| | | ROM EO – windows | $\tau_{EO}$ | | | 0.17 | | | | | | | | 0.17 | | – |
| | | ROM AO – insulation | $\tau_{AO}$ | | 0.41 | | 0.10 | | | | | | | 0.51 | *111.20* | 1.50 |
| | | ROM AO – windows | $\tau_{AO}$ | | | See Table 9 | | | | | | | | 0.07 | | – |
| **3** | Single-stage | TM | | 1 | | | | | | | | | | 1 | *110.36* | 0.66 |
| | | ROM EO | $\tau_{TM}$ | | | | 0.37 | | | | | | | 0.37 | *111.00* | 1.30 |
| | Multi-stage | TM – insulation | $\tau_{TM}$ | 1 | | | | | | | | | | 1 | *110.69* | 0.99 |
| | | TM – windows | $\tau_{TM}$ | | | | No Ex | | | | | | | 1 | | – |
| | | ROM EO – insulation | $\tau_{EO}$ | | | | 0.37 | | | | | | | 0.37 | *111.00* | 1.30 |
| | | ROM EO – windows | $\tau_{EO}$ | | | | 0.37 | | | | | | | 0.37 | – | – |

Notes:
$\tau_{TM}$ for the TM: the optimal planned time of execution at $t = 0$.
$\tau_{EO}$ for the ROM EO: the best time to decide about the execution.
$\tau_{AO}$ for the ROM AO: the earliest time where the probability of execution is non-zero.
WP Work program.
Bold values in the first column have been added to highlight the decision situation from which the results origin, and thus make the table more readable.
Italic values in the "Total" column have been added likewise to improve localization of total values as opposed to the probabilities (column to the left) and the differences in expected net benefits (column to the right)

**Table 9.** Probabilities of execution for staged WP of ROM AO – situation 1 and 2.

| Year of execution stage 1 | Energy price €/l | Probability of execution stage 1 (%) | Year of execution stage 2 | Energy price €/l | Probability of execution stage 2 (%) |
|---|---|---|---|---|---|
| *Decision situation* 1 | | | | | |
| 5 | 1.96 | 41.11 | 15 | 7.48 | 6.9 |
| 5 | 1.96 | 41.11 | 30 | 14.63 | 1.4 |
| 5 | 1.96 | 41.11 | 40 | 14.63 | 1.8 |
| 15 | 1.96 | 9.95 | 25 | 7.48 | 1.7 |
| 15 | 1.96 | 9.95 | 35 | 7.48 | 0.8 |
| 15 | 1.96 | 9.95 | 45 | 7.48 | 0.9 |
| 25 | 1.96 | 9.64 | 35 | 7.48 | 1.6 |
| 25 | 1.96 | 9.64 | 45 | 7.48 | 0.8 |
| 40 | 3.83 | 5.04 | 45 | 7.48 | 2.1 |
| *Decision situation* 2 | | | | | |
| 5 | 1.96 | 41.11% | 15 | 7.48 | 6.9% |
| 15 | 1.96 | 9.95% | – | – | – |

probability of 0.34, the insulation would never be replaced, and with a probability of 0.81 (compare Table 8), the windows would not be replaced, even if the insulation were. Table 9 shows that there are thresholds for the energy price above which the probability of execution is non-zero. For the first stage of the multi-stage WP type, these thresholds are 1.96 and 3.83 €/l, for the second stage, 7.48 and 14.63 €/l.

With decision situation 2, the results read the same as for decision situation 1, with the difference that the time period where decisions are possible is 15 years and not 45 years. With decision situation 3, the building manager can only decide about interventions in year $t = 0$ or $t = 15$. The evaluation with the

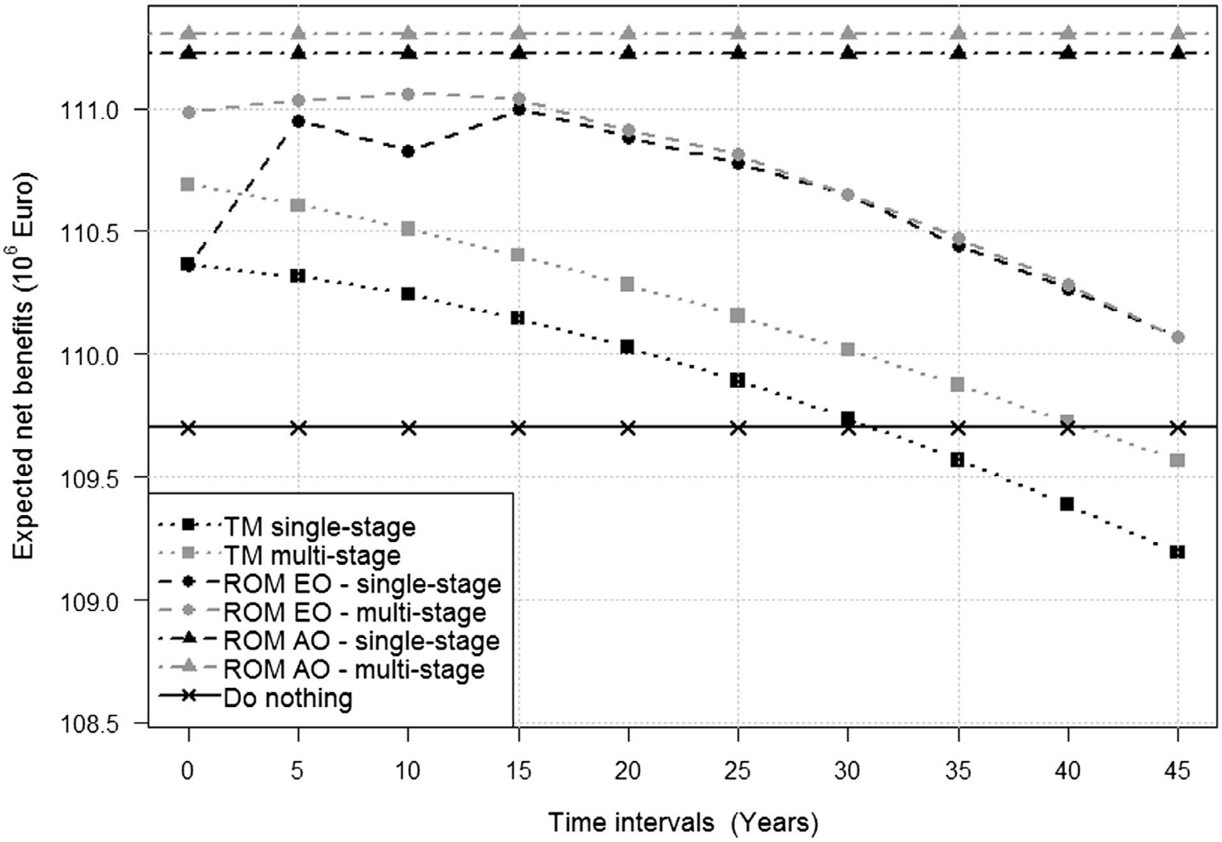

**Figure 2.** Expected net benefits for different $\tau_{TM}$, $\tau_{EO}$ and $\tau_{AO}$ for situation 1 (Decision in $t = [0, 45]$).

**Table 10.** Differences in expected net benefits for different methods, WP types and situations.

| | | | Difference of expected net benefits (in Mio. €) at $t = 0$ between | | | | |
|---|---|---|---|---|---|---|---|
| Situation | WP type | Method | ROM and TM | ROM AO and ROM EO | Single-stage and multi-stage type of WP | Sit. 2 & 3 and Sit. 1 | Sit. 3 and Sit. 2 |
| **0** | Do nothing | All | | | - | | |
| **1** | Single-stage | TM | | | | | |
| | | ROM EO | 0.63 | | | | |
| | | ROM AO | 0.86 | 0.22 | | | |
| | Multi-stage | TM – insulation | | | 0.32 | | |
| | | TM – windows | | | | | |
| | | ROM EO – insulation | 0.37 | | 0.06 | | |
| | | ROM EO – windows | | | | | |
| | | ROM AO – insulation | 0.61 | 0.24 | 0.08 | | |
| | | ROM AO – windows | | | | | |
| **2** | Single-stage | TM | | | | 0.00 | |
| | | ROM EO | 0.63 | | | 0.00 | |
| | | ROM AO | 0.76 | 0.13 | | –0.10 | |
| | Multi-stage | TM – insulation | | | 0.32 | 0.00 | |
| | | TM – windows | | | | | |
| | | ROM EO – insulation | 0.34 | | 0.04 | –0.03 | |
| | | ROM EO – windows | | | | | |
| | | ROM AO – insulation | 0.51 | 0.16 | 0.07 | –0.10 | |
| | | ROM AO – windows | | | | | |
| **3** | Single-stage | TM | | | | 0.00 | 0.00 |
| | | ROM EO | 0.63 | | | 0.00 | 0.00 |
| | Multi-stage | TM – insulation | | | 0.32 | 0.00 | 0.00 |
| | | TM – windows | | | | | |
| | | ROM EO – insulation | 0.31 | | 0.00 | –0.06 | –0.04 |
| | | ROM EO – windows | | | | | |

Note:
Bold values in the first column have been added to highlight the decision situation from which the results origin, and thus make the table more readable.

ROM AO is not applicable here, as with one decision interval (except $t = 0$), the results are identical to those from the ROM EO. If she investigates the single-stage WP type, and uses the TM, she will replace the complete façade at $t = 0$ and will expect net benefits of 110.36 Mio. €, i.e. additional net benefits of 0.66 Mio. € compared to the do nothing WP. If she uses the ROM EO, she will do nothing at $t = 0$ and wait to obtain more information in the future to determine whether or not she should execute the intervention. The expected net benefits are 111.00 Mio. €, i.e. additional net benefits of 1.30 Mio. € compared to the do nothing WP. The additional expected net benefits at $t = 0$, compared to the results from the TM, are 0.63 Mio. €. The best time to decide to replace the façade is in year 15, where there is a probability of 0.37 that it will be replaced if given the chance.

The comparison between the expected net benefits at $t = 0$ of the single-stage WP types and the multi-stage WP types in Table 10 shows that the multi-stage WP types yield higher expected net benefits than the single-stage WP types for all three situations, e.g. for situation 1, 0.32 Mio. € if comparing expected net benefits between the two types with the TM, 0.06 Mio. € if comparing expected net benefits between the two types with the ROM EO, and 0.08 Mio. € if comparing expected net benefits between the two types with the ROM AO.

Finally, comparing the expected net benefits at $t = 0$ for the different decision situations, the results for the situations 2 and 3 are lower than for situation 1. Comparing the expected net benefits at $t = 0$ for the situations 2 and 3, situation 3 shows lower or equal expected net benefits. This means, in this example, that using the ROMs results in different decisions of whether or not an intervention should be executed now and results in higher net benefits for a building manager.

### 6.6. Sensitivity analysis

Although it was found in the example that using the ROMs lead to different decisions at $t = 0$ and to different estimations of net benefits, it is not certain, based only on this information, to what extent their use makes a difference. This was investigated by varying the intervention costs (in ranges that can realistically be expected (Curschellas et al., 2011)) and volatility of the energy price (in a range from almost 0 (for the assumption of no uncertainty) to 0.5 (an increase if about 50% from 0.3)) to see the extent with which the use of the ROM results in different decisions and different expected net benefits. The ranges over which the values were varied are summarised in Table 11. The values were varied one at a time, e.g. the volatility was held constant at 0.3 and the expected net benefits were estimated for varying intervention costs and decision situation 1 using each method, as described above.

#### 6.6.1. Intervention costs

The extent that varying intervention costs change the expected net benefits, using each of the methods, can be seen in Figure 3. When the intervention costs are 0, the expected net benefits from ever executing an intervention are at their maximum, and the difference between the expected net benefits of executing an intervention at some point and doing nothing is high. The difference, however, with regard to the expected net benefits, between the methods is very small to almost 0 when the intervention costs are 0, i.e. all methods would recommend the same WP, in this case, to replace the complete façade at $t = 0$ (also compare Figure 4).

It can be seen in Figure 4 that for both the ROM AO and the TM, for intervention costs from 100 to 150 €/m$^2$, the recommended WP would be to execute the intervention in year $t = 0$, thus leading no difference between the expected net benefits from the different methods. With intervention costs between 150 and 450 €/m$^2$, the TM would recommend a WP with an execution in year $t = 0$ whereas the ROM AO would recommend a WP with waiting with the execution, first, to year $t = 5$, then even to year $t = 10$. Above intervention costs of 450 €/m$^2$, even the TM would give the recommendation of the WP with waiting with the execution.

#### 6.6.2. Volatility

With increasing volatility of the uncertain key parameter around the average scenario, the ROMs yield increasing expected net benefits for the preferred WPs while the expected net benefits with the TM remain the same (Figure 5). When the volatility is low, i.e. the key parameter can vary only close to the average scenario, the expected net benefits of all methods tend to the same value (while there remains a difference between the results of the single-stage and multi-stage WP type).

## 7. Discussion of results

The results of the analysis of the chosen example of the façade replacement show that the application of the two ROMs result in different OWPs with different expected net benefits than the application of a TM in specific cases such as this one. The differences between the expected net benefits are with about 1% very small and potentially lie in the margin of error of the input parameters; however, the goals to show how the proposed ROMs could be applied on a realistic example, and which results can be expected, were reached. The following points can be discussed for this particular example.

### 7.1. ROMs result in different estimates of expected net benefits than TMs

All three methods estimated that WPs that include an intervention are better than doing nothing over $T$, i.e. the OWP with interventions have higher expected net benefits than the doing nothing WP. The WPs determined with the two types of ROMs yield higher expected net benefits at $t = 0$ than the ones determined with TM; the reason for this is that the ROMs consider management flexibility in executing interventions in the future.

The WPs determined with the ROM AO yield higher expected net benefits than the ones determined with the ROM EO, because ROM AO considers a higher degree of management flexibility, i.e. more opportunities to exploit positive risk than ROM EO. The same argument applies to the fact that the multi-stage WP type yields a higher expected net benefits at $t = 0$ than the single-stage WPs. Situation 1 yields a higher expected net benefits at $t = 0$ than situation 2, and situation 2 a higher one than situation 3, because the manager has the least flexibility with decision situation 3, the most flexibility in decision situation 1.

**Table 11.** Values used in the sensitivity analysis.

| Varied | Minimum | Maximum | Increments | Figure |
|---|---|---|---|---|
| Intervention costs | 100 | 700 | 50 | Figure 3 |
| Intervention costs | 100 | 700 | 50 | Figure 4 |
| Volatility | 0.05 | 0.5 | 0.05 | Figure 5 |

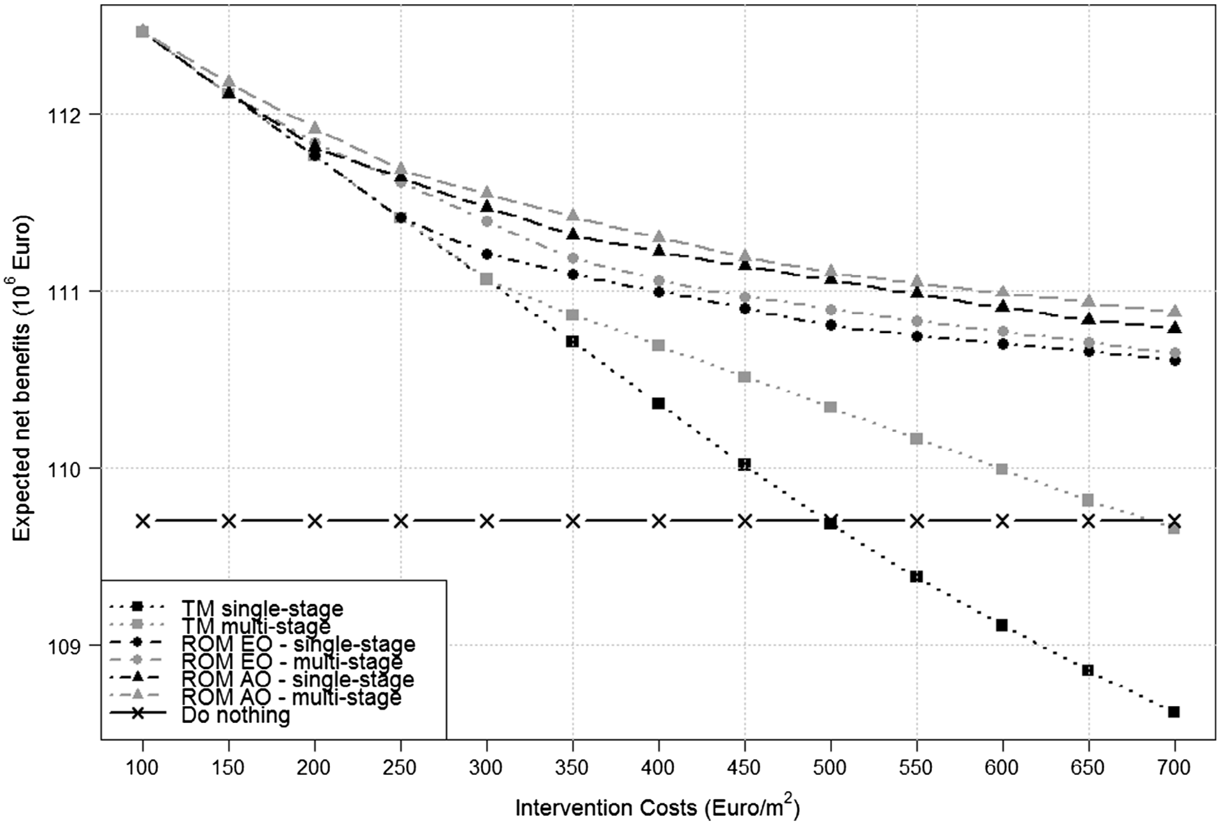

**Figure 3.** Decision situation 1: Expected net benefits at $t = 0$ as a function of intervention costs from 100 to 700 €/m$^2$.

The variation in the volatility of the key parameter (Figure 5) shows that as the volatility approaches 0, the expected net benefits determined with all three methods approach the same value when $t = 0$. The reason is that, with low volatility of the key parameter, i.e. low uncertainty of the key parameter around the average value, there are fewer situations where it is beneficial to wait and decide about the execution of an intervention in the future. In other words, the benefit of using a ROM over a TM is lower with decreased uncertainty.

As volatility increases, the expected net benefits determined with the TM and the OWP remain the same, whereas with the ROMs, the expected net benefits increase. This is due to the fact that the higher the assumed volatility, the bigger the expected range of values for the uncertain key parameter, in this case the energy price, with higher and lower benefits in case of replacement. In the determination of the expected net benefits with the TM, the high and low benefits cancel each other out whereas with the ROMs, there are increasingly better opportunities to exploit positive risk.

## 7.2. *ROMs are better or at least as good as TM*

The results from the sensitivity analysis for the intervention costs suggest that the use of the ROMs would always be better, or at least as good as, the TM, i.e. a building manager would always increase their expected net benefit at $t = 0$. The reason is that if there is one scenario where there is a possibility that a manager may change her mind about the execution of an intervention based on new information then there is information that cannot be captured appropriately in the TM.

Even if intervention costs are increased above a certain threshold, the expected net benefits for the ROMs are always higher than the ones for the TM. They are never lower. Also, as intervention costs increase, the expected net benefits from the TM decrease, whereas the latter can even fall below the expected net benefits of the do nothing WP, while the expected net benefits of the ROMs approach those of the do nothing WP.

That way, the ROM consider WPs that exploit even the smallest chance of additional benefits compared to do nothing WP, thus approaching the expected net benefit of the do nothing WP but

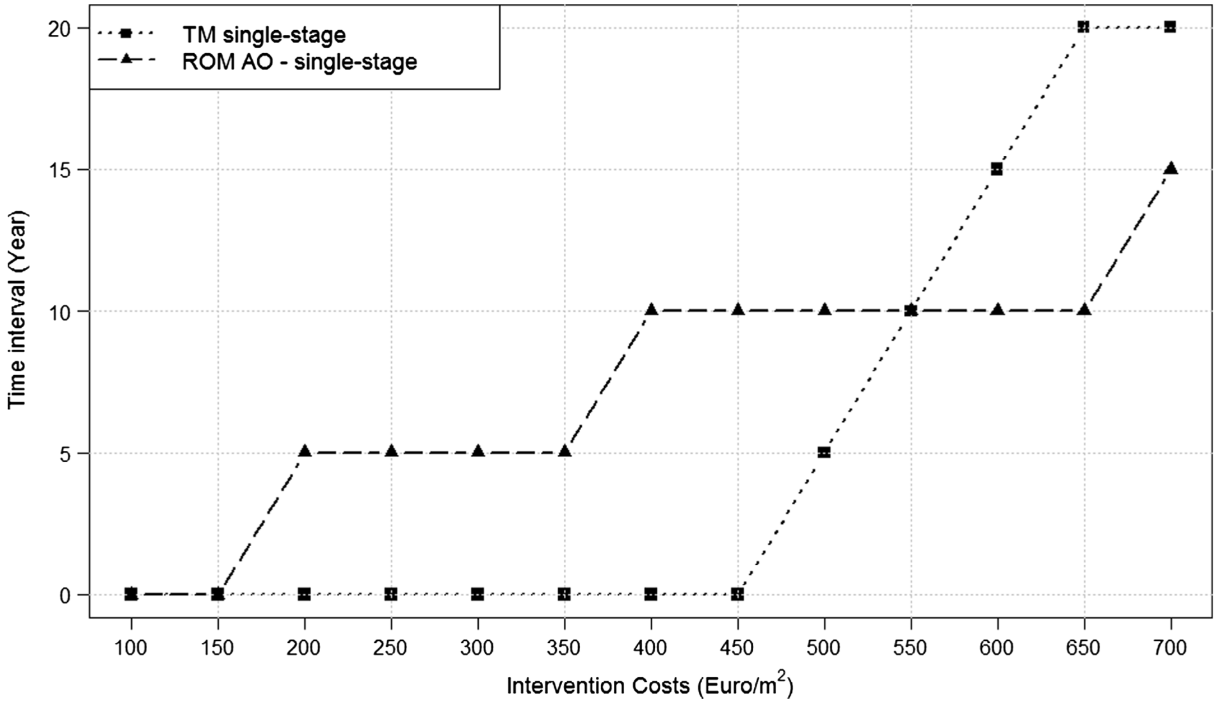

**Figure 4.** $\tau_{AO}$ for ROM AO and $\tau_{TM}$ for single-stage WP type in range of intervention costs from 100 to 700 €/m$^2$.

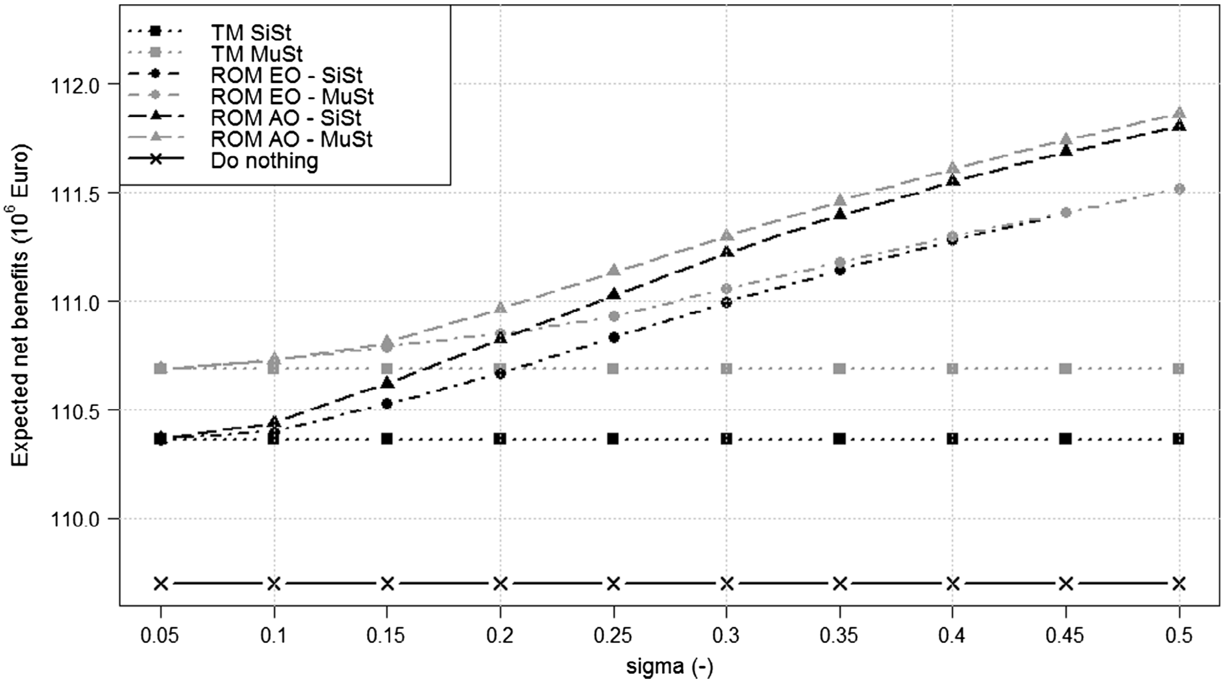

**Figure 5.** Expected net benefits at $t = 0$ applying the different methods of evaluation with increasing volatility of energy prices.

never going below. Even for high intervention costs, there might be situations where the key parameter has a value that results in benefits high enough to justify an intervention at a time $t > 0$.

### *7.3. ROM results in different WPs than TM*

As the expected net benefits from the methods are different so are the WPs. This means that if a building manager uses different methods to estimate net benefits she will arrive at different recommended WPs. As the use of the ROM in most cases is a better reflection of reality, i.e. a building manager normally has substantial flexibility, then the use of the TM will result in not only different WPs but less net benefit!

The variation in the key parameter's volatility (Figure 5) shows that above a certain volatility, the ROMs make better recommendations for the WP, as the recommendation of the TM 'destroys' the possibility of higher expected net benefits by executing the intervention today instead of waiting for better information. If the intervention costs exceed a certain value, the TM gives the same recommendation as the ROMs, i.e. to do nothing, which leaves the possibility open to reconsider the situation later. The ROMs, however, state clearly that the situation should be reconsidered later and even gives hints on when an optimal time might be to reconsider, whereas the results from the TM indicate that it is best to abandon the whole project.

## 8. Conclusions

In this paper, it has been stated that, due to the existence of uncertainty in key parameters, the determination of intervention of WPs requires the consideration of flexibility in decision-making by the building manager, so-called management flexibility. So far, this flexibility in decision-making has not been considered in existing methodologies for the determination of OWPs and is addressed in this paper by the application of ROMs.

ROMs can result in higher expected net benefits, and different WPs, than if a TM, as described in this article, is used. This occurs because the ROMs take into consideration the fact that a building manager will evaluate in the future whether or not it is beneficial to execute an intervention and will make a decision to intervene only if it is beneficial. As the flexibility of a manager increases so does the improvement of the estimate with ROMs, even if the OWP does not always change. In any case, the OWP determined using ROMs is never worse than the one determined using the TM.

The TM, which requires less computational effort, less effort for the estimation of scenarios, and no active reconsideration of WPs during the investigated time period and thus less management effort, is applicable in cases where

- it is clear that decision can only be made today,
- costs are low compared to benefit,
- the uncertainty of key parameters is low, or
- management flexibility is low.

The two types of ROMs require more computational effort, more effort for scenario estimation, active reconsideration of WPs, and thus more management effort over the investigated time period. The expected net benefits and OWPs determined with the ROMs, however, are closer to reality, and thus enable better budget planning. They should be used in cases where:

- management flexibility is a possibility,
- the uncertainty of key parameters is high, or
- the costs are high compared to the benefits, always taking into consideration that if the costs are so high that the TM would recommend to do nothing, technically, all methods would recommend the same thing at $t = 0$, i.e. to do nothing. The ROMs, however, will show that there are possible times in the future where is might be beneficial to execute an intervention. This can be seen as that the ROMs recommend to reconsider in the future, whereas the tradition method recommends simply to never execute an intervention.

The European option ROM should be used if there is only one decision interval (either $t = 0$ or $t > 0$), e.g. through time constraints; such constraints can occur through contractual arrangements or through the interaction with interventions in connected buildings or building elements, if, for example a building compound is refurbished successively where one of the buildings must always serve as a spare area to accommodate the people or equipment displaced from the building being renovated. The American option ROM should be used if there is more than one possible decision time, i.e. as soon as there are two time intervals of which one is $t > 0$, and it is possible to make the decision at either of these. It applies to single properties, on which interventions can be planned independently.

The use of ROMs to determine the time to intervene on buildings allows appropriate consideration of management flexibility and, therefore, will lead to an increased benefit for building managers. In addition, its use may even lead to the creation of more management flexibility and, therefore, further increased benefits. Examples of increased management flexibility are the allocation of additional budget today which might or might not be used for interventions in the future or even by changing the building physically to facilitate interventions in the future which might not be possible otherwise.

## Notes

1. An intervention includes all human activities executed at a time $t$ to help ensure that a building provides an adequate level of service.
2. A work program is a plan including the interventions to be executed on the building taking into consideration the specific conditions of the building. It is not to be confused with an intervention strategy, which is a plan that includes all interventions to be executed on a building taking into consideration all possible investigated conditions of the building.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## ORCID

*Nam Lethanh* http://orcid.org/0000-0002-0163-4529

## References

Alexander, M., & Thomas, M. (2015). Service life prediction and performance testing – Current developments and practical applications. *Cement and Concrete Research, 78*, 155–164. doi:10.1016/j.cemconres.2015.05.013

Allehaux, D., & Tessier, P. (2002). Evaluation of the functional obsolescence of building services in European office buildings. *Energy and Buildings, 34*, 127–133. Retrieved from http://www.sciencedirect.com/science/article/pii/S0378778801001049

Arboleda, C. A., & Abraham, D. M. (2006). Evaluation of flexibility in capital investments of infrastructure systems. *Engineering, Construction and Architectural Management, 13*(3), 254–274. citeulike-article-id:4252984. doi:10.1108/09699980610669688

Arnold, T. M., & Crack, T. F. (2000). *Option pricing in the real world: A generalized binomial model with applications to real options*. Otago. Retrieved from http://www.realoptions.org/papers2003/ArnoldSSRN_ID240554.pdf

Ashuri, B., Kashani, H., & Lu, J. (2011). An investment analysis framework for energy retrofit in existing buildings. In T. Sulbaran (Ed.),*47th ASC annual international conference* Omaha, NE: University of Nebraska-Lincoln.

Baum, A., & McElhinney, A. (2000). *The causes and effects of depreciation in office buildings: a ten year update. Working papers in land management & development*. Reading: University of Reading. Retrieved from http://centaur.reading.ac.uk/27211/

Bocchini, P., & Frangopol, D. M. (2011). A probabilistic computational framework for bridge network optimal maintenance scheduling. *Reliability Engineering & System Safety, 96*, 332–349. doi:10.1016/j.ress.2010.09.001

Boyles, S. D., Zhang, Z. M., & Waller, S. T. (2010). Optimal maintenance and repair policies under nonlinear preferences. *Journal of Infrastructure Systems, 16*, 11–20. doi:10.1061/(asce)1076-0342(2010)16:1(11)

Bucher, C., & Frangopol, D. M. (2006). Optimization of lifetime maintenance strategies for deteriorating structures considering probabilities of violating safety, condition, and cost thresholds. *Probabilistic Engineering Mechanics, 21*(1), 1–8. doi:10.1016/j.probengmech.2005.06.002

Chai, C., De Brito, J., Gaspar, P. L., & Silva, A. (2015). Statistical modelling of the service life prediction of painted surfaces. *International Journal of Strategic Property Management, 19*, 173–185. doi:10.3846/1648715X.2015.1031853

Ching, J., & Leu, S.-S. (2009). Bayesian updating of reliability of civil infrastructure facilities based on condition-state data and fault-tree model. *Reliability Engineering & System Safety, 94*, 1962–1974. doi:10.1016/j.ress.2009.07.002

Chu, C.-Y., & Durango-Cohen, P. L. (2008). Incorporating maintenance effectiveness in the estimation of dynamic infrastructure performance models. *Computer-Aided Civil and Infrastructure Engineering, 23*, 174–188. doi:10.1111/j.1467-8667.2008.00532.x

Cox, J. C., Ross, S. A., & Rubinstein, M. (1979). Option pricing: A simplified approach. *Journal of Financial Economics, 7*, 34. Retrieved from http://econpapers.repec.org/RePEc:eee:jfinec:v:7:y:1979:i:3:p:229-263

Curschellas, P., Bühlmann, R., Froese, R., Gebhard, R., Kühne, F., Rüdenauer, K., … Zöllig, S. (2011). *Element type catalogue EAK (Elementarten-Katalog) D/11 – Construction cost benchmarks (Kostenkennwerte)*. Zürich: CRB.

Dixit, A. K., & Pindyck, R. S. (1993). *Investment under uncertainty (II.)*. Princeton, NJ: Princeton University Press.

Edwards, P. J., & Bowen, P. A. (1998). Practices, barriers and benefits of risk management process in building services costs estimation: comment. *Construction Management and Economics*, 16, 105–108. Retrieved from http://doi.org/10.1080/014461998372646.

Flores-Colen, I., & de Brito, J. (2010). A systematic approach for maintenance budgeting of buildings façades based on predictive and preventive strategies. *Construction and Building Materials, 24*, 1718–1729. doi:10.1016/j.conbuildmat.2010.02.017

Ford, D. N., & Bhargav, S. (2006). Project management quality and the value of flexible strategies. *Engineering, Construction and Architectural Management, 13*, 275–289. doi:10.1108/09699980610669697

Frangopol, D. M., & Neves, L. A. C. (2008). Optimization of Life-Cycle Maintenance Strategies under Uncertainties: Role of Inspections. In B. H. V. Topping & M. Papadrakakis (Eds.), *Trends In Computational Structures Technology* (pp. 55–74). Stirlingshire: Saxe-Coburg Publications. http://doi.org/10.4203/csets.19.3

Fruguglietti, E., Pasqualato, G., & Spallarossa, E. (2012). Bridge management system implementation in Italy: Pontis® and other BMS application in Italy. In: F. Biondini & D. M. Frangopol (Eds.), *IABMAS 2012: 6th international conference on bridge maintenance, safety and management*. Stresa, Italy: Taylor & Francis.

Greden, L. V., & Glicksman, L. R. (2004). Options valuation of architectural flexibility: A case study of the option to convert to office space. *Real options 8th annual international conference*. Montreal, Canada.

Hajdin, R. (2001). KUBA-MS: The Swiss bridge management system. In P. C. Chang (Ed.), *Structures 2001: A Structural Engineering Odyssey*, (Vol. 109, p. 49). Washington, DC: ASCE. doi:10.1061/40558(2001)49

Hui, E. C. M., & Ng, I. M. H. (2008). A risk-based option pricing strategy for property valuation: an empirical study in Hong Kong. *Journal of Financial Management of Property and Construction, 13*, 48–59. doi:10.1108/13664380810882075

Jin, X., Li, L., & Ni, J. (2009). Option model for joint production and preventive maintenance system. *International Journal of Production Economics, 119*, 347–353. doi:10.1016/j.ijpe.2009.03.005

Jongen, R. A., Morshuis, P. H. F., Gulski, E., Smit, J. J., Maksymiuk, J., & Janssen, A. L. J. (2006). Application of statistical methods for making maintenance decisions within power utilities. *Electrical Insulation Magazine, IEEE*. doi:10.1109/MEI.2006.253418 Retrieved from: repository.tudelft.nl/assets/uuid:3c60e104-0f4b-4c10-b7c7-e48cfaa949ef/196298.pdf

Kalligeros, K. (2010). Real options in engineering systems design. In H. Black Nembhard & M. Aktan (Eds.), *Real options in engineering design, operations, and management* (pp. 123–149). Boca Raton, FL: CRC Press, Taylor and Francis Group.

Kalligeros, K., & de Neufville, R. (2006). *Platforms and real options in large-scale engineering and systems. Engineering systems division*. Cambridge: Massachusetts Institute of Technology.

Khan, F. I., & Haddara, M. M. (2003). Risk-based maintenance (RBM): A quantitative approach for maintenance/inspection scheduling and planning. *Journal of Loss Prevention in the Process Industries, 16*, 561–573. doi:10.1016/j.jlp.2003.08.011

Kobayashi, K., & Kaito, K. (2010). Random proportional Weibull Hazard model: Application to large-scale information systems. *Facilities, 29*(13/14), 1–21.

Kobayashi, K., & Kuhn, K. (2007). *Decentralized life-cycle cost evaluation and aggregated efficiency, in the book "the management and measurement of infrastructure: Performance, efficiency and innovation"*. Cheltenham: New Horizons in Regional Science.

Kodukula, P., & Papudesu, C. (2006). *Project valuation using real options: A practitioner's guide*. (2nd ed.). Ford Lauderdale, FL: J. Ross.

Koide, Y., Kaito, K., & Abe, M. (2001). Life cycle cost analysis of bridges where the real options are considered. In P. C. Das, D. M. Frangopol, & A. S. Nowak (Eds.), *Current and future trends in bridge design, construction and maintenance* 2 (pp. 387–394). London: Thomas Telford. http://doi.org/10.1680/caftibdcam2.30916.

Lethanh, N., & Adey, B. T. (2013). Investigation of the use of a Weibull model for the determination of optimal road link intervention strategies. *Structure and Infrastructure Engineering, 10*, 684–696. doi:10.1080/15732479.2012.758641

Lethanh, N., & Adey, B. T. (2014). A real option methodology to determine the optimal intervention windows for railway infrastructure. In C. A. Brebbia, N. Tomii, P. Tzieropoulos & J. M. Mera (Eds.), *Computers in railways XIV* (Vol. 135). WIT Transactions on the Built Environment.

Lethanh, N., Adey, B. T., & Fernando, D. N. (2014). Optimal intervention strategies for multiple objects affected by manifest and latent deterioration processes. *Structure and Infrastructure Engineering, 10*(5), 1–13, doi:10.1080/15732479.2014.889178

Lounis, Z., & Vanier, D. J. (2000). A multiobjective and stochastic system for building maintenance management. *Computer-Aided Civil and Infrastructure Engineering, 15*, 320–329. doi:10.1111/0885-9507.00196

Marseguerra, M., & Zio, E. (2000). Optimizing maintenance and repair policies via a combination of genetic algorithms and Monte Carlo simulation. *Reliability Engineering & System Safety, 68*, 69–83. doi:10.1016/s0951-8320(00)00007-7

Martins, J., Marques, R., & Cruz, C. (2013). Real options in infrastructure: Revisiting the literature. *Journal of Infrastructure Systems, 21*, 4014026. doi:10.1061/(ASCE)IS.1943-555X.0000188

Mata, J. (2011). Interpretation of concrete dam behaviour with artificial neural network and multiple linear regression models. *Engineering Structures, 33*, 903–910. doi:10.1016/j.engstruct.2010.12.011

Menassa, C. C. (2011). Evaluating sustainable retrofits in existing buildings under uncertainty. *Energy and Buildings, 43*, 3576–3583. doi:10.1016/j.enbuild.2011.09.030

Mendes Silva, J. A. R., & Falorca, J. (2009). A model plan for buildings maintenance with application in the performance analysis of a composite facade cover. *Construction and Building Materials, 23*, 3248–3257. doi:10.1016/j.conbuildmat.2009.05.008

Moncmanová, A. (2007). Environmental Deterioration of Materials. In S. Slovak Technical University (Ed.), *State-of-the-art in science and engineering* (Vol. 28). Southampton: WIT Press.

Nembhard, H. B., & Aktan, M. (2009). *Real options in engineering design, operations, and management*. CRC Press.

de Neufville, R., Scholtes, S., & Wang, T. (2006). Real options by spreadsheet: Parking garage case example. *Journal of Infrastructure Systems, 12*, 107–111. doi:10.1061/(ASCE)1076-0342(2006)12:2(107)

Orcesi, A. D., & Frangopol, D. M. (2011). A stakeholder probability-based optimization approach for cost-effective bridge management under financial constraints. *Engineering Structures, 33*, 1439–1449. doi:10.1016/j.engstruct.2010.12.035

Pereira, P., Rodrigues, A., & Rocha Armada, M.J. (2006). *The optimal timing for the construction of an International Airport: A real options approach with multiple stochastic factors and shocks*. Minho: University of Minho.

Santa-Cruz, S., & Heredia-Zavoni, E. (2009). Maintenance and decommissioning real options models for life-cycle cost-benefit analysis of offshore platforms. *Structure and Infrastructure Engineering, 7*, 733–745. doi:10.1080/15732470902842903

Sarja, A., Schiessl, P., Lay, S., Vesikari, E., Miller, J. B., & Söderqvist, M. K. 5 Life cycle management process. (2006). In A. Sarja (Ed.), *Predictive and optimised life cycle management – Buildings and infrastructure* (1st ed.). Abingdon: Taylor & Francis.

Shohet, I. M. (2003). Key performance indicators for maintenance of health-care facilities. *Facilities, 21*, 5–12.

Thompson, P. D., Small, E. P., Johnson, M., & Marshall, A. R. (1998). The Pontis bridge management system. *Structural Engineering International, 8*, 303–308. doi:10.2749/101686698780488758

Trigeorgis, L. (1996). *Real options – Managerial Flexibility and strategies in resource allocation*. (3rd ed.). Cambridge, MA: MIT Press.

Trigeorgis, L., & Mason, S. P. (2001). Valuing managerial flexibility. In E. S. Schwartz & L. Trigeorgis (Eds.), *Real Options and Investment under Uncertainty - Classical Readings and Recent Contributions* , (1st ed., pp. 47–60). Cambridge, MA: Massachusetts Institute of Technology.

Wang, T., & de Neufville, R. (1996). *Analysis of real options in hydropower construction projects – A case study in China. Engineering systems division*. Cambridge: Massachusetts Institute of Technology.

Wang, Y.-M., & Elhag, T. M. S. (2007). A comparison of neural network, evidential reasoning and multiple regression analysis in modelling bridge risks. *Expert Systems with Applications, 32*, 336–348. doi:10.1016/j.eswa.2005.11.029

Woodward, D. G. (1997). Life cycle costing – Theory, information acquisition and application. *International Journal of Project Management, 15*, 335–344. doi:10.1016/S0263-7863(96)00089-0

Zhang, X. Q., & Gao, H. (2010). Optimal performance-based building facility management. *Computer-Aided Civil and Infrastructure Engineering, 25*, 269–284. doi:10.1111/j.1467-8667.2009.00633.x

Zhao, T., Sundararajan, S. K., & Tseng, C.-L. (2004). Highway development decision-making under uncertainty: A real options approach. *Journal of Infrastructure Systems, 10*, 23–32. doi:10.1061/(ASCE)1076-0342(2004)10:1(23)