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Evaluating sustainable retrofits in existing buildings under uncertainty

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ABSTRACT

This paper presents a quantitative approach to determining the value of the investment in sustainable retrofits for existing buildings by taking into account different uncertainties associated with the life cycle costs and perceived benefits of the investment. To achieve this objective, principles from modern option pricing theory in finance are used to augment the traditional net present value method. In particular, an analogy between investment in sustainable building retrofits and American option is established and used to develop a framework for single or multi-phase investment evaluation. The parameters of the proposed framework are determined using the capital asset pricing model. The case study example illustrates that the proposed methodology provides the decision maker with managerial flexibility to determine, prioritize and evaluate the required retrofits over time. Retrofit measures that can be implemented without delay are distinguished from those that can be delayed because more information can be obtained in the future, or their implementation is contingent on successfully implementing other retrofit measures first.

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1. Introduction

In 2010, the building sector in the United States (US) consumed 50% of the total energy used by the built environment, and was responsible for approximately half of total greenhouse gases [1,2]. In addition, more than 80% of the energy consumed by a building during its life-cycle occurs when the building is in actual occupancy and use [3]. This makes the existing building stock a key target for energy efficient interventions to substantially reduce the adverse impacts of buildings on the environment, human health and the economy. A study of the US green building retrofit industry in 2009 indicated that there is ongoing growth in sustainable retrofit of existing building market that is projected to dramatically increase in the next 20–25 years [4]. This transformation over the next 25 years represents a historic and strategic opportunity for building stakeholders in developed countries with a large existing building stock, increased interest in the adoption of green business practices, and rising government regulations to significantly reduce energy demands required to operate their buildings [5].

However, investing in sustainable building retrofits is a highly uncertain endeavor (in terms of benefits and costs), which often results in overlooking more than 50% of possible energy savings alternatives [6]. This uncertainty results from technical challenges like demonstrating achievement of the necessary energy efficiency while respecting allocated budgets; as well as, indirect and strategic challenges like increasing tenants/occupants satisfaction [2]. A study of 750 corporate real estate executives cites high construction costs (61%), long pay back periods (57%), and difficulty in quantifying the benefits of green building (43%) as the main obstacles to sustainable retrofits [7]. Although a sustainable retrofit to an existing building is expected to increase the market value of this building, the uncertainty about the effectiveness of the chosen retrofit methods in achieving stakeholder objectives renders the actual increase in building value hard to estimate upfront to allow for a proper economic analysis prior to starting the retrofit endeavor [4].

This paper presents a quantitative approach to determining the value of the investment in sustainable retrofits for existing buildings by taking into account different uncertainties associated with the life cycle costs and perceived benefits of this investment. To achieve this objective, principles from modern option pricing theory in finance are used to augment the traditional net present value (*NPV*) method. In particular, an analogy between investment in sustainable building retrofits and perpetual American options is established and used to develop a framework for single or multi-phase investment evaluation. The parameters of the proposed framework are determined using the capital asset pricing model (*CAPM*). These techniques provide the building stakeholders with the flexibility to value different alternative retrofit solutions for their buildings under conditions of uncertainty especially those related to increase in value of the building, increase in possible demand for green space, fluctuating cost of energy and the

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perceived savings in the building operation and maintenance costs. The case study example illustrates that the proposed methodology provides the decision maker with managerial flexibility to determine, prioritize and evaluate the required retrofits over time.

2. Characteristics of investment in existing building retrofits

Sustainable retrofit is a capital improvement with an associated cost that resets the building life, improves performance, and makes the building's use more predictable for an extended period of time [5,8–10]. A considerable amount of research provides a basis for investigation into the economic and environmental impacts of existing building retrofit measures [11–17]. However, the decision to retrofit existing buildings still presents a number of challenges to the building stakeholders due to lack of information and benchmarks about the actual performance of the building and its systems after the design phase [12,18], reluctant stakeholder commitment because energy prices and taxes are not high enough to create a strong incentive for retrofits [19], and perceptions from early green buildings that significantly higher costs outweigh economic and environmental benefits [20]. This is intensified by the 2008–2009 global economic recession which presented the additional challenge of ensuring investment and debt capital to finance any sustainable retrofit activities in buildings. All of the above increase the uncertainty surrounding the expected benefits from any investment in sustainable retrofits, and forces building stakeholders to postpone investment until more proven returns are available [21]. In addition, a financial decision framework that facilitates the process of evaluating energy/water retrofit measures, and illustrate their long term economic benefits for all involved building stakeholders does not exist yet [2,22].

3. Limitations of traditional evaluation methods

From an economic perspective, the decision on what techniques to adopt and when to implement them during the building life cycle remains highly dependent on traditional quantitative capital budgeting techniques like pay-back period, internal rate of return (*IRR*) and net present value (*NPV*). Among these methods, *NPV* is the only technique that ensures the stakeholder objectives of maximizing return on investment [23,24]. However, the *NPV* method has several limitations. First, it requires a discount rate which cannot be easily determined when the stakeholders want to investigate managerial flexibility and is often the decision maker's prerogative to establish this rate [25–27]. Second, there are significant uncertainties that need to be accounted for during the economic valuation phase of the sustainable building retrofit decision. These include: physical, business and institutional uncertainties as listed in Table 1 [28–30]. Adjustment for these uncertainties in the *NPV* method is typically done by modifying the discount rate, or using the *NPV*-at-risk method where the primary variables underlying a project's *NPV* are simulated to obtain a distribution and confidence intervals [31,32]. However, there are several objections to adjusting both the discount rate and the variables in the *NPV* method because this amounts to double counting the risk [33].

Third, the *NPV* assumes that all future cash flows for a given investment are known in advance [23,34]. This is considered a limitation when performing an investment evaluation for sustainable building retrofits when it is impossible to predict energy use accurately due to differences in occupancy, hours of building system operations, control-point settings, building and system maintenance conditions, and actual versus estimated weather conditions among others [25]. Finally, the *NPV* technique does not allow the decision maker to account for the indirect and strategic values of an investment that might create future growth opportunities to the owner of the existing building either through follow up retrofits on other buildings in his/her portfolio, or acquiring new buildings and sustainably retrofitting them. Examples of possible strategic scenarios for an investment in building retrofits are given in Table 2.

All of the above issues are barriers that inhibit building stakeholders from making reasonable and effective decisions to sustainably retrofit their existing buildings using the *NPV* approach. However, concern about future volatility of energy prices and increased legislation regulations requiring buildings to adhere to certain energy consumption standards is going to impose additional pressure on building stakeholders to move forward with sustainable retrofits. Therefore, from a technical, strategic and political perspective, an investment valuation method that overcomes the limitations of the traditional *NPV* method will allow the decision maker to effectively quantify the economic value of any sustainable retrofit investment, and suggest optimal investment strategies when the future is uncertain. In the subsequent section, option pricing in financial market is presented as a basis to develop an improved framework for single or multi-phase investments in sustainable building retrofits.

4. Option pricing theory

Options on traded assets like stocks give the holder the right (or option) to buy (i.e., call options) or sell (i.e., put options) assets at a pre-fixed price referred to as the exercise price (K) on or before a specified expiration date [35,36]. The investor has the flexibility to postpone buying or selling the underlying asset (e.g., stock with value S) until information about future market conditions become available. In this case, the investor benefits from an increase in the upside potential of the investment whereby he/she commits to buying/selling the stock only if positive payoffs are realized. On the other hand, the down side losses are truncated at the cost of the option (i.e., no negative payoffs) [37,38].

The cost of an option involves taking a position in a replicating portfolio where the investor buys a certain number of shares in the underlying stock, and borrows against them the exercise price amount at the risk free interest rate [35,36]. The basic assumption underlying this solution is that the change in the stock price follows the Geometric Brownian Motion (*GBM*) $dS/S = (\mu_s - \delta)dt + \sigma_s dz$ [36,39]. The $(\mu_s - \delta)dt$ component is the deterministic value of the change in the stock price as a function of the instantaneous growth rate in the price of the stock over time μ_s, and the dividend δ which is a portion of a company's earnings given to the shareholders (i.e., actual owners of the stock but not the option holders) [24,39,40]. The $\sigma_s dz$ component represents the stochastic change in the value of the stock as a function of the standard deviation (i.e., volatility) σ_s, and the increment of the Standard Wiener process dz which is normally distributed with a mean of 0 and a variance that increases linearly with the time interval dt.

A European option can be exercised on the expiration date only, while American options can be exercised any time before expiration. Black and Scholes [35] and Cox et al. [41] pioneered the two most used techniques to value European options, namely: the analytical method and the numerical binomial tree distribution, respectively. The latter method is a more general approach that can also be used to solve American options [40]. This method is illustrated in Fig. 1. Given a specific distribution of the stock price, the binomial tree is constructed with each node of the tree (shown on the left of Fig. 1) representing a possible future realization of the stock price at each time interval. At each period the stock price can either go up or down with probabilities p and $(1 - p)$, respectively. For example, S_{uud} shows the S goes up in first and second time periods and then down in the third time period. The most important aspect of this method is that the probabilities p and $(1 - p)$ are not the stock's actual probability but risk neural probabilities which

Table 1
Examples of investment uncertainties in existing building technologies.

Physical risks	Business risks	Institutional risks
Building design	Unpredictable fluctuations in the market	Changing regulations on construction and real estate
Material functional characteristics	Increased disposal taxes on non-recyclable material disposal	Environmental changes leading to different policies
Changes in performance	Revenue from building operation	Political decisions prohibiting certain building materials

Table 2
Examples of strategic value to sustainably retrofit existing buildings.

Option category	Definitions [adopted from [37]]	Application to investments in sustainably retrofitting existing buildings
Option to stage	The project is divided into distinct stages. The costs/benefits of a completed stage are assessed to determine if subsequent stages can be pursued	The retrofitting can be divided into stages depending on available budget. First stage might involve replacing light bulbs with more energy efficient ones, and use plug-load occupancy sensors to turn off lights when no one is using the space
Option to abandon	Terminate a project any time prior to completion and deploy resources to other projects	An exhaustive feasibility study of the existing building condition might indicate that the associated incremental costs to make the building energy efficient are too high. In this case the owner might abandon the project
Option to defer	A decision on whether to invest in a project can be postponed without imperiling the potential benefits	A decision to sustainably retrofit an existing building can be deferred until debt financing becomes available at attractive rates to the owner, or until the tenants can arrange to lease alternative space for the duration of the retrofitting project
Option to grow	An initial baseline investment allows the project managers to pursue a variety of follow on opportunities	The owner of several existing buildings nationwide can decide to retrofit one building as a pilot project, and decide to expand retrofit work to the remaining of his/her existing building stock once perceived benefits from retrofitting the pilot project outweigh the costs incurred
Option to reduce	Reduce current scale of the project and save costs	Reduce the scope of the retrofitting endeavor when the costs of the retrofitting exceed the allocated budget. For example, replacing the existing HVAC system might exceed the allocated costs due to lack of information about the existing system and how it is distributed throughout the building. In this case, other scheduled energy efficient replacements or updates for the building will need to be postponed or forgone all together
Option to switch	An asset developed for one purpose can be switched or redeployed to serve another purpose	An existing office building owner might decide to switch the tenant occupancy of certain floors from three to four tenants per floor to only one tenant per floor

remain constant throughout the analysis period. The tree on the right hand side of Fig. 1 shows how the option value changes with the change in the underlying asset value (i.e., stock). The value of the European option (F) is obtained by solving this tree backward starting at the last period and using the risk free interest rate (r) to discount cash flows to present time. For an American option, this solution needs to be repeated at each time period to determine whether it is optimal to exercise the option earlier or wait until expiration. The option is exercised earlier (say at time period 2) if the exercise payoff ($S_2 - K$) is greater than the option value F_2. There is an optimal stock price S^* below which exercising an American option is not optimal, and the value of waiting to exercise that option is higher [40,42].

Perpetual American options are a special case of an American option where the option does not have an expiration date and lives infinitely [43]. Thus, the investor is continuously evaluating early exercise versus option value at a given period in time, and would only exercise when S is greater than S^*. Several analytical and numerical solutions are available to evaluate perpetual American options. These solutions form the basis for the framework to evaluate investments in sustainable retrofits of existing buildings as discussed in the subsequent sections.

5. Model assumptions and parameters

As discussed earlier, evaluating investments in sustainable retrofits for existing buildings presents a number of challenges to the decision maker particularly related to the unexpected future benefits of such an investment. These benefits include savings from more efficient energy consumption in the building resulting in reduced life cycle costs, increase in value of the retrofitted property and increase in occupant satisfaction among other. All these uncertain benefits from a sustainable retrofit of an existing building will determine the contingent payoff of the investment, and are considered to represent the major risk creating unknown factor in

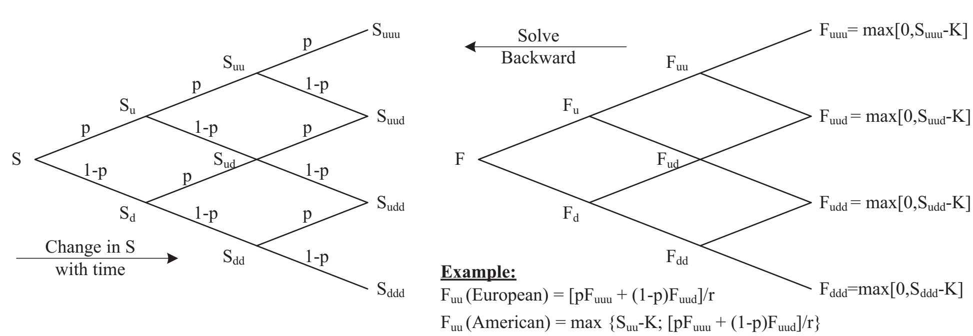

Fig. 1. Binomial trees for solving European and American call options.

the investment evaluation. In this paper, these benefits are therefore assumed to represent the underlying asset of the investment which will be denoted by V. Note that V in this case corresponds to the uncertain value of the stock price S in the previous section.

V will off course vary with time due to uncertainties of the effectiveness of the retrofit measures to reduce energy consumption, uncertainty about market conditions and competition that will directly affect the value of the building and other variables. For capital or real projects (i.e., not traded in financial markets), a number of researchers have consistently assumed that the change in the value of the underlying asset under uncertainty follows the same lognormal or *GBM* distribution as that of financial market stocks [24,42,44–48]. Therefore, the change in value of the expected benefits V from sustainably retrofitting an existing building is assumed to follow the *GBM* process given in Eq. (1), $(\mu_V - \delta_V)$ and σ_V represent the deterministic and stochastic change in the value of the benefits from the retrofit project over time, respectively.

$$\frac{dV}{V} = (\mu_V - \delta_V)dt + \sigma_V dz \quad (1)$$

where μ_V is the market equilibrium rate of return of the completed retrofit project; δ_V is the rate of return shortfall or opportunity cost of delaying the retrofit; σ_V is the volatility of future benefits from the retrofit project.

The main advantage of this assumption is that it allows the decision maker the flexibility to align the dynamics of V, a non-market traded security, with those of securities traded in the capital market. This assumption simply means that there exists a traded financial asset (e.g., a stock) that has the same risk characteristics (i.e., $\sigma_V dz$) as V. Thus, μ_V can be obtained similar to that of the traded financial asset by using the Capital Asset Pricing Model (*CAPM*) [49–52], which states that that the expected return of an asset equals the risk free rate of return, r, plus a risk premium required by investors due to the correlation of the asset with the market, and accounts for the systematic non-diversifiable risk [53].

Finally, δ_V is obtained as the difference between μ_V (i.e., rate of return on traded financial asset) and μ_{Vr}, the rate of return for the real non-financial traded asset. In this case, the non-traded asset is V if the sustainable retrofit program is implemented [42,44]. Since V is realized only if the retrofit is undertaken in the future, then δ_V represents the opportunity cost of delaying the investment [42].

Given this assumption about V, the subsequent sections will discuss the analogy between this type of investment and that in a perpetual American option, and illustrate how solutions to the latter problem can be used to analyze single and multi-stage investments in sustainable retrofits of existing buildings.

6. Framework to evaluate investments in existing buildings retrofits

As discussed earlier, the traditional *NPV* method does not allow the decision maker to effectively quantify the value of any sustainable retrofit investment, and suggest optimal investment strategies when the expected future benefits are uncertain. Even if initially the *NPV* of the retrofit project is positive, there might be additional value to postpone the investment until some of the uncertainty is resolved. On the other hand, if the *NPV* is negative, increased uncertainty typically provides enough incentive to delay the investment until the project's value exceeds the cost by a certain positive amount [45].

Thus, the question that should be addressed is whether the investment in the sustainable retrofit should occur now or sometime in the future. If it is the latter, when is the optimal time to invest and should this investment be done in a single stage where all necessary sustainable retrofits are implemented in one single investment, or should the investment be distributed over multiple stages. The distribution over multiple stages can be for two main reasons. First, the decision maker might want to wait and observe the results of current investments in sustainable retrofits to see if some of the uncertainty about the future expected benefits can be reduced by observing the building performance due to the first set of retrofits. In this case, the decision maker can decide whether to continue with the planned retrofits or quit after each phase if the results are not satisfactory.

The second reason for phasing the investment is because this involves sustainably retrofitting an existing occupied building so the decision maker prefers to stage the investment to minimize disruption to building functions during the retrofit process. This multi-stage approach can be constrained by a maximum rate of expenditure during a certain period of time although the total budget is known in advance. In this type of projects, it is expected that the benefits from the sustainable retrofit of the building will not be realized until the whole retrofit is completed.

The subsequent sections describe the framework that decision makers can use to evaluate single and multi-stage investments in sustainable retrofits of existing buildings.

6.1. Single stage investment – option to defer

In the single stage sustainable retrofit project, the building stakeholders want to commit a fixed amount I to cover the costs of the sustainable retrofits. An important aspect of a single stage investment in sustainable retrofits for existing buildings is that once the money is committed, the decision cannot be reversed regardless of how the building performs in the future. This presents a challenge to the building stakeholders especially when uncertainty about future benefits V is very high. Simply relying on a positive *NPV* analysis might be misleading because of the irreversibility of the investment which means that the selected retrofit measures (e.g., new electrical/mechanical systems) placed inside of the building cannot be simply dismantled and moved to another building if the required energy efficiency and building performance are not achieved. In this type of investment, postponing the decision to invest in the sustainable retrofit effort is beneficial (i.e., can invest at anytime in the future) to allow for some of the uncertainty about retrofit benefits to unfold. For example, testing of a given technology at another building might result in more accurate information about its effect on the building retrofit (refer option to defer in Table 2). Thus, the building stakeholders should evaluate the investment with the time to wait to determine if this alternative adds value to their investment. This is analogous to the perpetual American option case where the investor decides to wait and exercises the option only when market conditions are favorable. Using this analogy, the exercise price K and stock price S correspond to the total cost of investment I and expected benefits V of the sustainable retrofit project. However, as discussed in the previous section, the option might be more valuable if left unexercised until $S > S^*$ even when market conditions are favorable (e.g., $S > K$ for a call option). In this case, the solution of a perpetual American option proposed by McDonald and Siegel [43] can be used to determine the value and time of the investment in single stage sustainable retrofit projects as given in Eq. (2). This value will be the modified *NPV* for single retrofit project, NPV_m. Whenever, $NPV_m > NPV$, the building stakeholders should wait.

$$\begin{aligned} NPV_m(V,I) &= (V^* - I)\left(\frac{V}{V^*}\right)^{\beta} \quad \text{when} \quad V \le V^* \\ NPV_m(V,I) &= V - I \quad \text{when} \quad V > V^* \end{aligned} \quad (2)$$

where $V^*/I = \beta/(\beta - 1)$; $\beta = (0.5 - (r - \delta_v)/\sigma_v^2) + \sqrt{((r - \delta_v)/\sigma_v^2 - 0.5)^2 + 2r/\sigma_v^2}$. The ratio V^*/I is known as the critical ratio for investment to be undertaken without waiting.

6.2. Multi-stage investment – option to stage and option to abandon

The option to defer the investment as presented in the previous section is one alternative to deal with the uncertainty of the expected benefits from the sustainable retrofits of the building. Another alternative would be to stage the investment to give the building stakeholders the option to continue investment if expected benefits are realized or stop the investment otherwise (refer to option to stage and option to abandon in Table 2), respectively. For example, the building stakeholders might decide to replace all windows to improve thermal insulation prior to replacing the whole heating, ventilating and air conditioning (HVAC) systems. This problem of investment staging can be divided into two main categories discussed below.

6.2.1. Multi-stage investment with option to abandon

Each stage of the investment provides the decision maker with more information that can be used to decide whether to go ahead with the subsequent stages of the investment [54]. In this case, I_k ($k = 2, 3, \ldots, n$) defines the amount of investment at each stage/time period, k, during the retrofit process. This provides the decision makers with strong flexibility to stop or abandon the investment at any stage when it becomes apparent that the expected benefits V are not attainable. If the *NPV* approach is to be used, then costs incurred at different stages of the investment are discounted to current time and compared to the benefits. This directly assumes that all stages of the sustainable retrofit will be implemented and does not provide the decision maker with the flexibility to determine whether to implement the next stage or abandon it. The valuation of this flexibility is similar to that of an exchange option [54–56]. An exchange option, a special case of American option, involves the exchange of one asset, S_1 (risky asset), for another asset S_2 (can also be risky).

In the case of sustainable retrofits of existing buildings, at each stage of the investment evaluation, the cost of implementing an additional retrofit measure, I_k, is exchanged for the expected benefits V. The decision to invest in the each stage, $k-1$, is dependent on the present value of exchange option, NPV_{mk}, at the subsequent stage k. If $NPV_{mk} \geq I_{k-1}$, then investment in stage $k-1$ should be undertaken. This will allow for subsequent investments; otherwise, the project should be abandoned and no further retrofits are necessary as their costs exceed the expected additional benefits. This is repeated at each stage to determine if the investment should be undertaken until all stages are completed or the condition $NPV_{mk} < I_{k-1}$ is reached. Using Villani [56], McDonald and Siegel [54] and Margrabe [55], NPV_{mk} is calculated using Eq. (3) below by assuming that the investment I_k can alternatively be invested at the risk free interest rate r between time periods $k-1$ and k:

$$NPV_{mk}(V, I_k) = Ve^{-\delta_v t}N(d_1) - I_k e^{-rt}N(d_2) \tag{3}$$

where $N(y)$ = Probability $\{Y \leq y\} - Y$ is a standard normal random variable; $d_1 = (\ln(Ve^{-\delta_v t}/I_k e^{-rt}) + (r - \delta_v + 0.5\sigma_v{}^2))/\sigma_v\sqrt{t}$ and $d_2 = d_1 - \sigma_v\sqrt{t}$; t is the time period between $k-1$ and k.

6.2.2. Multi-stage investment with option to stage

In this scenario, all stages of the investment need to be implemented before the building can be operated, and occupied again. However, because of budgeting, financing and technical constraints, the decision maker wishes to stage the investment over a period of time. This might be the case where the building requires major retrofit that forces all the existing tenants of the building to move to an alternative accommodation during the retrofit process. The total investment expenditure is still I; however, the expenditures at any specific stage cannot exceed a preset rate i. Thus, if the sustainable retrofit is to be implemented in n stages, then $I \leq \sum_{k=1}^{n} i_k$ where $i_k \leq i$. This type of the investment allows the decision maker to stage the investment and to stop or abandon the investment at any given stage [45,57]. However, if the project is abandoned after several stages of investing, then the building owners will not be able to operate the building because not all the retrofit measures are in place. This is a major difference between this scenario and that presented in the previous section. Majd and Pindyck [45] developed the partial differential equations along with the boundary conditions for this type of investments assuming a perpetual American option with time to build. A discussion of the numerical solution can be found in both [45] and [42]. For the purpose of this paper, the approximate solution proposed by Espinoza and Luccioni [57] is adopted to determine the value of this investment at each stage NPV_m. The assumptions underlying this approximate solution are:

(1) I_0 is the present value of investment cost assuming that investment is continuously made over a period of time $T = I/i$ at a rate that does not exceed i. The value of this investment cost at time $k = 0$ and $k = m$ is given in Eqs. (4) and (5), respectively:

$$I_0 = \int_0^T ie^{-rt}dt = (1 - e^{-rT})\frac{i}{r} \tag{4}$$

$$I_m = \int_m^T ie^{-rt}dt = (e^{-rm} - e^{-rT})\frac{i}{r} \tag{5}$$

(2) V_0 is the present value of expected benefits from the investment that is made continuously over T until the whole sustainable retrofit is completed. The expected value of benefits from this investment at time $k = 0$ and $k = m$ is given in Eqs. (6) and (7), respectively:

$$V_0 = (Ve^{\mu_{vr}T})e^{-\mu_v T} = Ve^{-\delta_v T} \tag{6}$$

$$V_m = (Ve^{\mu_{vr}(T-m)})e^{-\mu_v(T-m)} = Ve^{-\delta_v(T-m)} \tag{7}$$

(3) Thus, the value of this multi-stage investment in sustainable retrofit of a given building at time $t = 0$ is given in Eq. (8) below:

$$\begin{aligned} &NPV_m(V, I) = (V^* - I_0)\left(\frac{V_0}{V^*}\right)^{\beta} \quad \text{when} \quad V_0 \leq V^* \\ &NPV_m(V, I) = V_0 - I_0 \quad \text{when} \quad V_0 > V^* \end{aligned} \tag{8}$$

where $V^*/I_0 = \beta/(\beta - 1)$; $\beta = (0.5 - (r - \delta_v)/\sigma_v^2) + \sqrt{((r - \delta_v)/\sigma_v^2 - 0.5)^2 + 2r/\sigma_v^2}$

It is important to note that Eq. (8) has a similar structure to that of Eq. (2) because they are both solutions to a perpetual American option with time to build. The only difference is this case is that the investment expenditure is spread over a period of time $T = I/i$. The project value at each stage of the investment can be assessed based on the remaining investment I_k at that stage by simply replacing V_0 and I_0 in Eq. (8) by V_m and I_m, respectively.

7. Case study

Suppose that an existing building requires \$10 million in energy upgrades investment. This includes changing all the HVAC systems, installing high performance windows and replacing all light fixtures with more efficient LED lights. Preliminary energy analysis for the building indicates that these changes will result in an expected \$1.65 million reduction in annual costs (A) of operating and maintaining the building for the next 20 years. If the minimum attractive rate of return (MARR) for the building owner is 15%, then the *NPV* for this investment will be (\$10.33–\$10) \$0.33 million. Therefore, the building owner should invest immediately in sustainable retrofitting the building to reduce costs of operation.

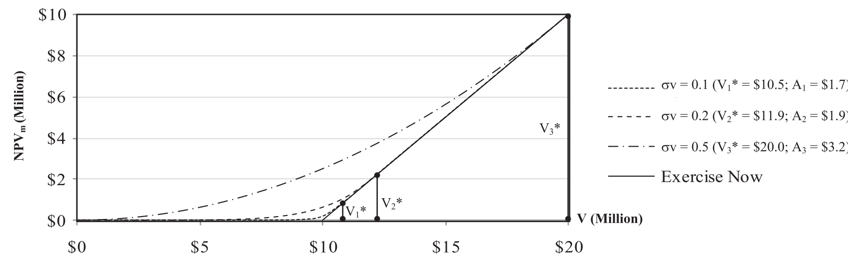

Fig. 2. Value of single stage investment under uncertainty.

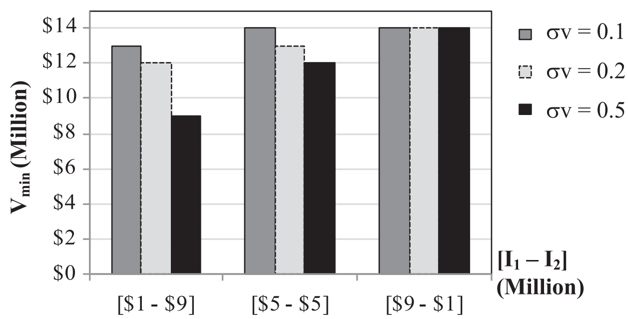

Fig. 3. Two stage investment with option to abandon $V_{\min}$ to implement stage 1.

However, if the expected annual operation cost reduction slightly fluctuates to $1.60 million or less due to changes in energy prices and inability to accurately evaluate building performance when the new systems are installed, then the *NPV* becomes zero or less. Thus, a slight uncertainty about the annual cost savings will change the decision from invest to do not invest even when there are other strategic benefits to the retrofit. If the uncertainty is represented by σ_V (see Eq. (1)), and we assume that $r = 0.05$ and $\delta_V = 0.15$ (i.e., corresponds to the building owner's MARR), then the investment decision can be analyzed for the three scenarios from the previous section.

7.1. Single stage investment – option to defer

Eq. (2) is used to determine whether it is optimal to invest at an expected A = $1.65 million when there are different levels of uncertainty. Fig. 2 shows the change in value of NPV_m versus the expected benefits from the investment V, for different levels of σ_V. The results indicate that when the level of uncertainty increases the value of V^* at which the option to retrofit an existing building increases. This in turn implies that investment should only be undertaken in the future when A is greater than initially estimated $1.65 million even when level of uncertainty is low at $\sigma_V = 0.15$ where the corresponding A = $1.7 million. The solid line indicates the "exercise now" option if all uncertainty is resolved about V. It is clear from Fig. 2, than when there is uncertainty, simply making a decision based on a positive *NPV* (represented by the "exercise now" line), will ignore additional value of postponing this investment to resolve uncertainty.

7.2. Multi-stage investment with option to abandon

This problem is analyzed for the two stage investment scenario where the $10 million total investment is divided into two stages. Investment in the first stage I_1 depends on the value of the investment in the subsequent stage NPV_{m2}. Thus, using Eq. (3), the retrofit investment was analyzed to determine the minimum cut-off value of V at which investment should occur for a given initial investment I_1. This off course depends on the level of σ_V. Fig. 3 shows the cut-off value $V_{\min}$ for different initial or first stage investments I_1 for three level of uncertainty σ_v. Investment I_2 will only be undertaken if $V > V_{\min}$.

Two main observations can be made from these results. First, for the same level of initial investment I_1, the cut-off value of V decreases with increase in uncertainty σ_v. This indicates that the higher the uncertainty associated with the investment, the lower the expected value of benefits V at which the retrofit investment should be abandoned. Second, the higher the initial stage investment I_1, the higher is the cut-off value V for same level of uncertainty. This indicates that when the initial investment is high, the expected benefits from subsequent investments should be high because most of the uncertainty surrounding this value would have been resolved during the initial stage of investment. That is a higher initial stage of the investment indicates higher confidence by the decision maker about the expected value of their project.

7.3. Multi-stage investment with option to stage

Finally the investment problem is analyzed for the case where the decision maker decides to spread the $10 million investment over a period of time T with a maximum investment per time period i. The building will only be operational after all of the planned retrofits are completed over the period of time T. Fig. 4 shows the cutoff values of V^* at each time period for the case where the investment is divided into $T = 2$ years and $T = 5$ years, respectively.

These results indicate that V^* decreases with the decrease in time period for the same level of uncertainty indicating that most of the project has been completed in prior periods and uncertainty does not affect the value of the retrofit project towards the end

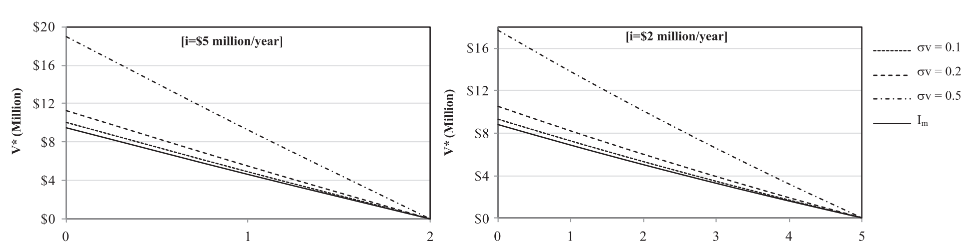

Fig. 4. Multi-stage investment without option to abandon.

of the investment period. On the other hand, V^* increase with the increase in uncertainty for a specific time period indicating that investment decision is more stringent with higher uncertainty at a given time period. Finally, V^* in the left hand side of Fig. 4 is greater than $V_{\min}$ in Fig. 3 for ($5–$5) million case, indicating that staging the investment with the option to abandon provides more flexibility in terms of the value of expected benefits because the building stakeholders can abandon the project and still benefit from the retrofits made in the previous stages. The option to stage alone requires a higher expected value of benefits for the investment to be undertaken under uncertainty because the stakeholders will not be able to use the building unless all retrofits are completed.

8. Conclusions

This paper presented a framework to evaluate investments in sustainable retrofits of existing buildings under uncertainty. The framework is developed to account for three main scenarios encountered in retrofit projects including single stage investment, multi stage investment with option to abandon and multi stage investment with option to stage. The proposed methodology draws from financial option pricing method and uses the *CAPM* method to estimate the parameters for the model. An important aspect of this framework is that the building stakeholders do not have to estimate parameters beyond those that are typically known to them including the MARR and risk free interest year. In addition, the case study example illustrates the possible cases where this framework could be applied and the benefits to decision maker beyond the traditional *NPV* approach that would typically be used to evaluate this type of investment.

The proposed framework can help existing building stakeholders in evaluating investment in sustainable building retrofits and develop optimal investment strategies. In the single stage investment, the building stakeholders can decide to postpone the investment until uncertainty is resolved. This will result in a higher NPV_m for the investment even when initially the traditional *NPV* is positive. For the multi-stage investment, the staging with the option to abandon provides a better opportunity as opposed to the case where the whole project is contingent on the completion of all stages. Thus, the framework provides a good alternative to the *NPV* approach when uncertainty is high, and the building stakeholders want to incorporate more strategic investment opportunities in their analysis.

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