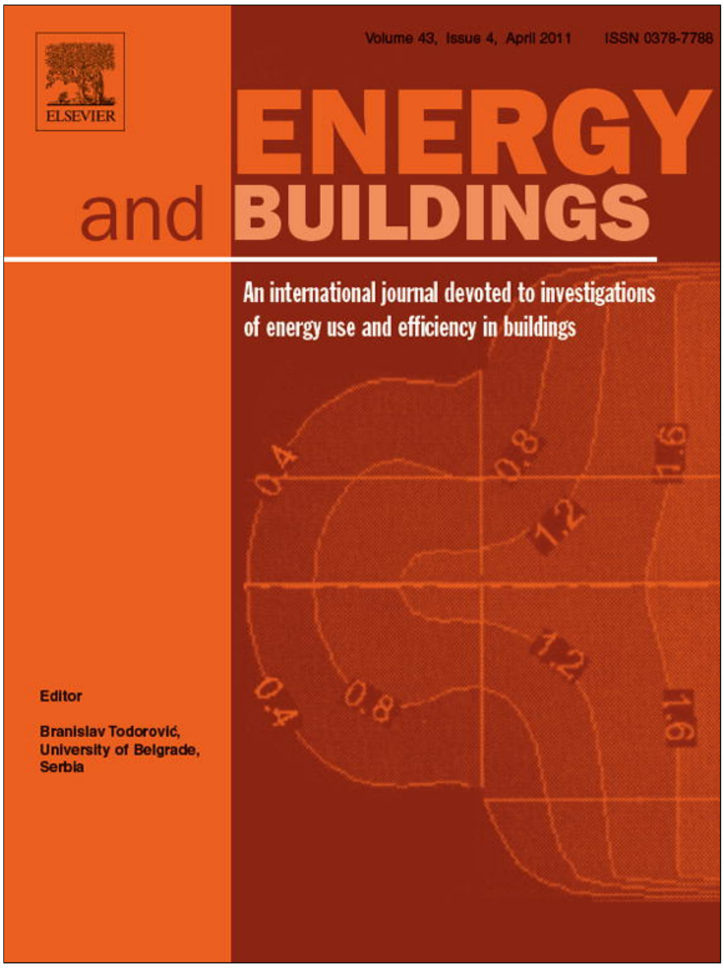
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The anatomy of investing in energy efficient buildings

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ABSTRACT

A building investment is a real decision because the allocated resources are typically irrevocable for long times. Investment appraisal is a logic method to process elapsing time, uncertain benefits and costs, and irrevocability related to decisions. Most analysts stop halfway the appraisal process when they carefully assess net present values and their sensitivity to uncertain future events. But sidelining irrevocability and the dynamic sequential analysis of future events and actions cause wrong decisions when the energy performance endowment of a new building is decided. Irrevocability and preclusion are explained, and their impact illustrated with a case study. Adopting realistic assumptions about the uncertain future and applying the proper methodology reveal as financially best choice the immediate investment in passive attributes and items. Irrevocability is of high relevance for building efficiency investments and for the implementation of the EU-2010 buildings directive.

1. Introduction

In industrialized countries, almost 40 percent of all commercial energy supplied as processed fuels and grid electricity is used in buildings [1,2]. The fourth assessment report by IPCC [3] is very optimistic about the contribution of the buildings sector in reducing the emissions of carbon dioxide by energy efficiency. The UK Code of Sustainable Homes sets the zero carbon target for houses by 2016 [4]. The EU buildings directive article 4 [2] states: “Member States shall take the necessary measures to ensure that minimum energy performance requirements for buildings or building units are set with a view to achieving cost-optimal levels”, but also: “A Member State shall not be required to set minimum energy performance requirements which are not cost-effective over the estimated economic lifecycle”. The directive defines ‘cost-optimal level’ in article 2 (Definitions), but does not cover the crucial elements of time, uncertainty, and irrevocability that determine the optimality of investing in energy efficient buildings.

Policy bets most on regulation by standards to improve the energy quality of buildings. The prescribed standards are derived from extensive technical analysis of materials, building physics modeling, demonstration projects, statistical studies of the building stock, etc. Fixing the various standards requires economic and financial assessments of the benefits and costs that imposed standards may imply. Experience teaches that a regulation is more successful, easier to implement, control, and enforce when prescribed rules and imposed standards correspond with beneficiary practices and pursued objectives hold by the target constituency. Hence, many architects and building physicists have taken courses in financial appraisal methods, and deliver careful net present value calculations with measuring estimated benefit/cost ratio’s on their sensitivity for uncertain events in the future. However interesting such studies are, the results and conclusions can be erroneous and misleading, for mainly two reasons. The first major reason is that few studies spend (enough) attention to the non-monetary benefits and costs connected to the energy quality of buildings. This issue is mentioned in this article, but not discussed because it necessitates full-sized publications of its own.

All focus here is on the second cause of erroneous and misleading advice regarding the *energy performance endowment*[1] (EPE) of new constructions. The second reason is methodological: when investments encompass a significant degree of economic irrevocability,[2]

Abbreviations: EPE, energy performance endowment; NPV, net present value.

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[1] ‘Energy Performance Endowment’ (EPE) extends the EU Directive’s ‘energy performance’ with a focus on endowment. It refers to a wide range of attributes (size, compactness, etc.) and items (components, equipment, etc.) that have an impact on the later energy use of the building, although later use depends on more variables like the functional use of the building, plug-in appliances, occupants’ behavior, etc. The endowment encompasses, for example orientation, compactness, availability of passive construction parts (e.g. a cellar for cool storage), shading blades, heat distribution equipment, coolers, sensors, meters, etc. The concept is further elaborated in Section 4 (about irrevocability and preclusion).

[2] Irrevocability is systematically used instead of irreversibility, because a building is perfectly substitutable. For a detailed analysis, see Verbruggen [29].

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one must take that factor into account [5,6]. Investments in EPE attributes and items are highly irrevocable, and need consideration during the planning phase [1]. Few analysts are familiar with irrevocability and its analysis.

Decision analysis of attributes and items of a building's EPE leads to "Choose or Loose" (provide now to avoid preclusion) situations, opposite to the common "Wait and Learn" (defer the irrevocable investment and keep the option to decide later) of the real option literature. The irrevocability characteristics of energy efficiency investments stimulate immediate very efficient (passive) buildings rather than standards obeying buildings. The latter are mostly advised on the basis of traditional net present values or life-cycle costing that in this setting "may give very wrong answers" [5]. The theory is illustrated with a case study on the investment in a single family house.

Investing is for some people a daily decision, for others an occasional one. There are two major classes of investments: financial investments where others care about the actual use of the capital, and physical investments where the decision-maker selects the investment object (here being a building and its EPE). Our analysis is valid for all types of buildings, but for didactic clarity focus is on the private house and on its EPE.

An investment decision is "an irrevocable allocation of resources, in the sense that it would take additional resources, perhaps prohibitive in amount, to change the allocation" [7]. In addition, decisions can only be made for the future, and by definition the future is uncertain. For simple nearby things suffice our intuitive decision processor. But for complex, long-term, and unique investments only correct, scientifically based methods are adequate. Deciding on building a house is for most households a unique and complex action with wide-ranging, lifetime consequences. Overcoming spatial and temporal myopia is an important challenge for enlightened and successful decision-making.

Investment theory and practice provide a guide for the ones willing to improve their decision process and final decisions. Unfortunately even the best decision is no guarantee for the best outcome because fate, if not the Fates, intervene between our sowing now and harvesting later. But addressing fate still requires the best decision, being the one that logically takes into account all available information (including the information that could become available in the future) and matches available resources with pursued goals. For digging up the best decision, we must explore three spheres: future time, uncertainty, and irrevocability. Deciding for the future is helped more by a look into the future than by blind chance, but looking into the (far) distant future remains utterly precarious [8,9]. The sphere of uncertainty has gained more recognition over the last decades, but only static uncertainty analysis has propagated in the literature on building investment. Extension to the dynamic approach is necessary for good decision-making, and for opening the way to the third sphere, the one of irrevocability. The latter is a crucial dimension for "avoiding very wrong answers that the traditional net present value rule can give" [5].

The article has four more sections after this introduction. Sections 2–4 discuss the anatomy of investing in energy efficient buildings in three stages. Section 2 treats the aspect of time (discounting) and net present value (stage 1), familiar to many readers. In Section 3 risk, uncertainty and ignorance (stage 2) are introduced. Static decision making is presented as the approach used by most net present value analysts. Section 3.3 shows the dynamic time sequential approach as bedrock for real option analysis. The latter is illustrated with a textbook example of "Wait and Learn". Section 4 introduces the factors irrevocability and preclusion. Section 4.1 presents a framework to classify the degrees of irrevocability [29]. It is applied in Section 4.2 on attributes and items of the EPE. In Section 4.3 is argued why this case leads to "Choose or Loose" approaches, being the reverse of the traditional "Wait and Learn".

In Section 5 the methods and concepts developed in Sections 2–4 are illustrated with a case study. A conclusion is offered in Section 6.

2. Future time in investment analysis

Analyzing investment opportunities is an exercise in looking into the future. Who looks how far, at what, and for what in the future is case dependent. Investments bifurcate between private and public goods, and investment studies bifurcate between private and social decision makers. While both use a same methodology for processing the time factor, significant differences exist in temporal and spatial scope of implementation and therefore in numerical values of crucial parameters [10,11]. First, the method of discounting cash flows is reminded. Next are stated the arguments why discounting occurs, to conclude on some differences between private and social investment appraisals.

2.1. Discounting [12,13]

Discounting is the inverse of exponentially growing compound interest. Therefore discounting at a positive rate represents exponential decay.

Let:

H = project horizon in number of years (index j);

dr = yearly discount rate expressed as a positive decimal (e.g. 0.03 for 3%);

RB_j = revenues/benefits of the project in year j expressed in monetary units;

EC_j = expenditures/costs of the project in year j expressed in monetary units.

The discounted value of the net cash flows occurring in the project's lifetime from year 0, the initial year or year of initial investment EC(0), to the horizon year H, equals the net present value (NPV) or:

$$\mathrm{NPV} = \frac{\sum_{j=0}^{H} RB_j - EC_j}{(1+dr)^j} \tag{1}$$

The formula shows that the height of NPV depends on the actual cash flows in the various years, and on the parameters dr and H. To emphasize the role of the parameters one may write NPV as NPV(dr, H). NPV is a proper standard to measure the performance of a project over a horizon H because it includes all revenues/benefits and all expenditures/costs at the moment of their occurrence and it assigns a time value to that moment by applying the discounting operator. The main criteria for accepting (yes or no) projects are based on NPV calculations, as follows:

- NPV(dr, H) ≥ 0 expresses that the invested capital generates a return of at least dr percent per year over the period H.
- The Internal Rate of Return (IRR) over the period H is the dr number where NPV equals zero, or IRR solves NPV(IRR, H) = 0.
- The Discounted Pay Back (DPB) [14] is the number of years required to grow from a negative to a positive NPV value crossing the zero value in year DPB, or DPB solves NPV(dr, DPB) = 0.

The methods of discounting are now well acquainted beyond the business, financial and economics departments, and also applied by architects, constructors and other building experts [14–20].

2.2. Why discounting for time?

Although discounting is a wide-spread practice there is no unanimity on the height of the discount rate to apply [9]. For particular settings it is argued that discount rates should equal zero, but two main observations support a positive discount rate ($dr > 0$). On the one hand consumers reveal a propensity to obtain and enjoy goods and services rather earlier than later; this is called "consumer time preference" and explains the willingness of households to pay real interest on money (purchasing power) for buying goods and services earlier in time. The building sector is most familiar with the practice of borrowing and mortgage payments.

On the other hand money can be invested in production facilities or other undertakings for generating more money; this is called "productivity of capital". To get a return in the future one must command capital today and be willing to freeze it in the investment project during some time. This abstinence merits a positive return. A significant part of productive capital is also invested in buildings, some for own use, some for renting.

Once consumers or producers have established their weighing of time, the latter can be fixed as the hurdle rate dr in the NPV(dr, H) formula. Along choosing dr numbers, also fixing the horizon H asks for a choice. Both choices are related: adopting a high dr means assigning little weight to distant occurrences (see exponential decay by discounting) what erodes the significance of the horizon distance. Otherwise, when the horizon must be far-distant (e.g. when evaluating the impacts of climate change or the burdens of nuclear waste), dr must be low to escape the disappearing act of exponential decay [8,21].

2.3. Private and social perspectives

The discussion on the "right" or "best" discount rate and time horizon culminates when adding the divergence in perspectives by private and social investors. Although the mathematical NPV expression remains valid for both perspectives, the implementations are of a different nature. To summarize the main differences:

- Types of investment projects considered: building a house is still minor compared to building the EU headquarters.
- Scope of project coverage: a private investor considers only his benefits gained and his expenditures spent by the decision considered; the public interest scopes all benefits and all costs that fall on society wherever, whenever and whoever acquires or pays. For a private investor it is already utterly complex to identify and next monetize all the various benefits (above revenues) and costs (above expenditures) related to housing. For example aspects of comfort, absence of illness, amenities, security, reminiscences, etc. may be connected to one's house, with a significant higher value than the market price of renting or selling expresses. Positive benefits are enjoyed more in energy efficient, sustainable housing than in standard ones [22]. Also costs can be higher than measured expenses. For example when a house brings more maintenance, repair, illness, sorrow, danger, etc. occupants will face costs on top of the bills of janitors, doctors, etc.
- Time horizons: private people observe horizons from years to decades shifting focus along the own finite lifecycle. A house often survives the initial builder, and a long horizon should be considered [23]. Because societies are permanent (eternal), in principle the horizon in social decision making is infinite.
- Discount rates: depending on their personal preferences and capital endowment private investors can assess their appropriate discount rates within narrow ranges; for social investments there is no agreement on the right discount rate to apply. There are propositions from a zero discount rate (for escaping temporal myopia) to a very high rate (for avoiding capital guzzling by the public sector so prohibiting investment in the productive private sector). Generally is accepted to appraise social projects at low real discount rates [9].

Table 1
Three depths of doubt: risk, uncertainty and ignorance.

Depth of doubt	Events	Probabilities
Risk	X	X
Uncertainty	X	?
Ignorance	?	–

The mechanics of discounting are well understood, and their application is straight forward when the project horizon does not surpass 30–40 years. Many studies on house building adopt this time horizon [15,20]. Investments in buildings typically bridge this borderline: some buildings end their life around that age; most buildings stand for the double or multiple of that age with a thorough refurbishment every 30–40 years for residential buildings [1: 8].

3. Uncertainty and timing

Analyzing investment opportunities is an exercise in looking into the future, while lacking a crystal ball. The future is by definition unknown and predictions are seldom confirmed by reality. Although uncertainty is common to name our doubts about the future, one may recognize three levels of doubt (Section 3.1). Section 3.2 discusses the static approach of processing uncertain futures of possible events and alternative actions. However, reality is a dynamic sequence of events and decisions, and is better modeled in that way (Section 3.3).

3.1. The depth of doubt

Doubt about the future consists of our incomplete knowledge about events that may happen and of the likelihood or probability that the events may occur. Depending on the subject, on the investigated aspects and on the distance in time, three levels of doubt can be identified: risk, uncertainty, and ignorance. Risk is the most informative level: the relevant future events are recognized and the probabilities of their occurrence are assessed, based on long-time experience and scientific evidence. Uncertainty has a good record of possible events too, but very little information about probabilities that are therefore assessed in a subjective way. Ignorance is deeply problematic because future events cannot be forecasted, a fortiori not their probabilities. Ignorance must be considered when the likelihood exists that at this moment unknown events important for our decisions may emerge in the future [24,25] (Table 1).

The builder of a house enjoys mostly the relative comfort of shallow doubt: most risks can be inventoried and modeled. Uncertainty concerns drastic changes in economic policy regarding the use of fossil fuels, affecting significantly future prices of fossil fuels and grid power. Also ignorance about future technologies or about catastrophic impacts triggered by climate change or by nuclear accidents, can affect the decisions and their outcomes. Private investors mostly adopt spatial and temporal perspectives excluding society wide events, but this does not guarantee they will be saved from the impacts.

3.2. Static approach

Investment studies that process risks and uncertainties generally adopt a static approach [26], as shown in Table 2. The future is modeled by combinations of events and actions. For example: the possible occurrence of k different events (scenarios) S_i $\{i = 1, \ldots, k\}$, and the availability of m different investment alternatives A_j $\{j = 1, \ldots, m\}$. The net present values NPV (S_i, A_j) for all $k \times m$ combinations can be estimated with a spreadsheet or more sophisticated model.

Table 2
NPV contingent on assumed future events and on selected alternative investment.

Chance	Events	Alternative investments A_j,$\{j = 1, \ldots, m\}$			
		A_1	A_2	...	A_m
P_1	S_1	NPV(S_1, A_1)	NPV(S_1, A_2)	...	NPV(S_1, A_m)
P_2	S_2	NPV(S_2, A_1)	NPV(S_2, A_2)	...	NPV(S_2, A_m)
...	...	...	...	...	...
P_k	S_k	NPV(S_k, A_1)	NPV(S_k, A_2)	...	NPV(S_k, A_m)
Decision rule					
A_j that maximizes minimum NPV		Minimum NPV(S_i, A_1) i {1, ..., k}	Minimum NPV(S_i, A_2) i {1, ..., k}	...	Minimum NPV(S_i, A_m) i {1, ..., k}
A_j that maximizes expected NPV		$\sum_i P_i$. NPV(S_i, A_1)	$\sum_i P_i$. NPV(S_i, A_2)	...	$\sum_i P_i$. NPV(S_i, A_m)

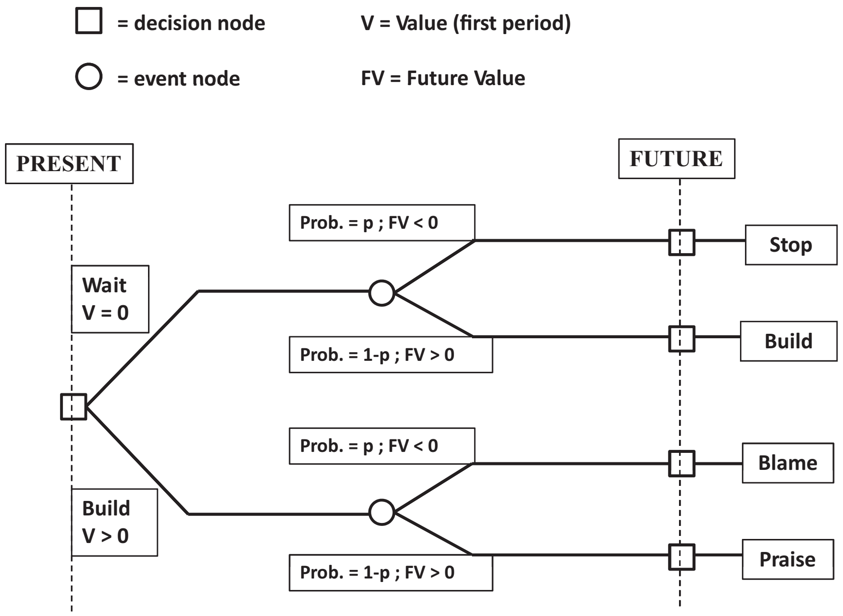

Fig. 1. Sequential decision framework for real option investment appraisal.

Most analysts are satisfied with the obtained NPV matrix, and will use it as the basis for advising about the optimum decision. Finding the best alternative (decision) is based on two additional steps: probabilities (chances) P_i $\{i = 1, \ldots, k\}$ are assigned to the possible future events S_i, and a decision rule is adopted and applied. In Table 2 two popular rules are detailed. The "maximin" is making the best of the worst that could happen in the future: for every alternative (column in Table 2) the least NPV-value is identified, and the alternative with the highest minimum is chosen (this provides some comfort that the future likely could be brighter than announced).[3] Maximin excludes the information on probabilities related to the events. The rule advocated as best is including the assessed probabilities and maximizes the expected NPV by alternative (bottom line in Table 2).

The static approach is useful in structuring the decision problem: systematically listing events and alternatives reveals new likely scenarios and overlooked alternatives, often by recombining parts of already identified ones. It also shows which clusters of events and alternatives command more analysis and which are of less interest. It is a good first step in investment appraisal, but it can "give very wrong answers" when the analysis stops here. Its shortcomings lay in assuming the bundle of future scenarios as composed of once-through trajectories starting with investment (year 0) and ending in year H (mostly with decommissioning). This static assumption does not reflect real life processes that actually are sequential: decisions and events alternate over time.

3.3. Dynamic approach

Sequential decision making is critical for analyzing investments than span a long period (beyond the 30–40 years wherein discounting is not challenged), but is also appropriate and recommended for analyzing many shorter-term investments. "A sequential approach involves changing and updating decisions as new information becomes available over time. There are at least three important reasons for delaying decisions under these circumstances. First, by waiting we will have better information; second, by waiting we will have improved technical options for addressing a problem; and third, we can use the resources we would have spent for other valuable activities or investments." [27: 175]. Sequential decision making is related to considering at the consecutive decision nodes in a decision-making process whether some (part of) decisions are better deferred for acquiring more information in the meantime and keeping the resources in standby or using them for other goals [7].

Sequential decision-making processes are represented by decision trees [28]. Fig. 1 shows the most basic decision tree covering two periods of decision moments (present and some moment in the future) with an intermediary stochastic event evolving (with only two possible outcomes: negative future value with probability p and positive future value with probability $1 - p$).

[3] Maximin is for the pessimistic decision-maker; the optimistic one could apply Maximax by choosing the strategy where the highest NPV is noted.

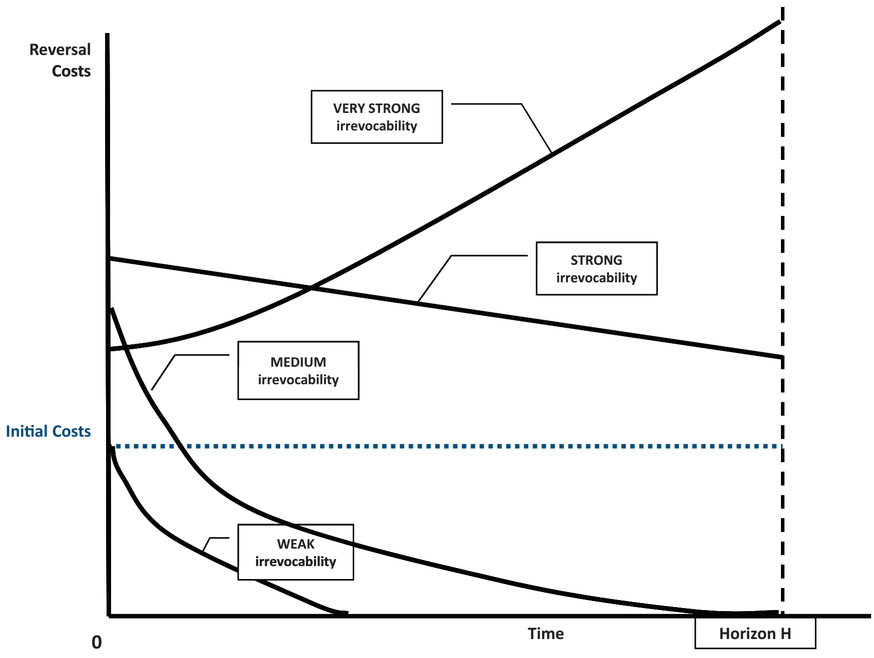

Fig. 2. Reversal costs in the future for undoing a past decision.

At the starting stage (present) one may choose to wait (defer) or to build. In principle, building at present only happens when its value in the first period is positive ($V>0$). When one decides to wait, the first period positive value is foregone ($V=0$). In the years between present and future (assume a 5 year period) some uncertain events dissolve: for example the location of the real estate where the house would be constructed is YES (negative FV) or NO (positive FV) over-spanned by a mega traffic bridge. Placing you as decision-maker five year in the future, the feasible actions depend on the history that evolved up to that moment, and where the decision from 5 years earlier takes a big stake. Four cases may happen:

- you waited and the bridge hangs above your plot: you STOP the construction plan there (likely frustrated, but at least happy that you do not have to live for the rest of your life under continuous traffic flows);
- you waited and the bridge project is definitely ditched: you can now BUILD your house (you have lost the V over the then passed first 5 years, but this is the price of the option to decide with hands free at this future moment);
- you have built and the bridge and traffic are there above your roof (BLAME is your part; your investment is almost worthless and you have spent your credit so you cannot move);
- you have built and the bridge project is definitely ditched (PRAISE is yours; you already enjoyed the value V during 5 years, and you can continue to live quietly on the plot you wanted).

What decision (Wait or Build) is best at the start of this process depends on the actual height of V, FVs (negative and positive) and the probabilities p and $1-p$. But only the sequential lay-out of the decision process makes apparent the option of "Wait and Learn". That option may be obscured when sticking to the easier static approach, what is to our knowledge done by all investment studies in the building sector [14–20]. The necessity to perform a careful sequential decision analysis grows with the degree of irrevocability that characterizes particular investments.

4. Irrevocability and preclusion

This section does not exhaust the analysis of irrevocability, being a constituent of irreversibility [29]. It only presents necessary concepts and vocabulary for the case of investing in the EPE of buildings. In Section 4.1 degrees of irrevocability are classified in categories (very strong, strong, medium, and weak). In Section 4.2 the classification is applied on buildings. In Section 4.3 is argued how the nature of irrevocability regarding the building's EPE switches from the "Wait and Learn" approach (see Section 3.3) to the "Choose or Loose" approach.

4.1. Defining irrevocability as constituent of irreversibility

Irrevocability is an attribute of every decision as its definition "an irrevocable allocation of resources" [7] reveals, and comes in degrees [30: 8]. Verbruggen [29] explores the widely used, but poorly defined, concept of irreversibility in economics, and shows that irrevocability is its economic constituent. Practical use of the attribute irrevocability requires a workable metrics for gauging degrees of irrevocability. Workable metrics are based on reversal costs implied at a given moment in the future for undoing a previous decision. "Undoing" is considered feasible when accepting substitutability of all types of goods and values. This article deals with buildings made of substitutable materials and undoing a previous resource allocation is technically feasible, however costly it may be in reality.

Fig. 2 shows four degrees of irrevocability as a function of how undoing costs develop over time: very strong, strong, medium, and weak. The reference point for categorizing irrevocability is the initial (investment) cost at point zero in time. Visual inspection of Fig. 2 shows that 'very strong' refers to reversal costs that increase over time. 'Strong' is when reversal costs in the future remain above the reference of the initial costs but decay over time. This may be the case when non-unique natural landscapes are converted to building areas, requiring more resources to restore than was needed to develop for use, but with technological progress decreasing the expenses over time. 'Medium' refers to undoing costs higher than initial costs at moment zero and for some years, but falling below

Table 3
EPE attributes and items; their preclusion, rigidity, and ex-post adaptability/add-ability.

EPE attribute or item	Ex-post adaptability/add-ability
Location (access to main destinations; position vis-à-vis other buildings)	Precluded (destinations of occupants and accessibility may change over time)
Facilities (natural gas; water supply; sewage and sanitation; waste collection and bio-waste processing)	Precluded/rigid/addable (depending on exogenous supplies, accessibility and space on-site)
Rainwater capture and storage (storage tank; piping)	Precluded/rigid/addable (depends on accessibility and space on-site)
Orientation	Precluded
Size (extensions, contractions)	Precluded/rigid (buildings 'contract' space by mothballing m^2)
Basement – cellar (storage; access)	Precluded
Massive building components	Precluded
Compactness	Precluded
Natural light access (orientation; placement and size of windows; light transfer provisions)	Precluded/rigid (secondary measures are addable, e.g. use of light colors inside; e.g. substitute glass for solid doors)
Living space: separation, connectivity	Rigid/adaptable (depends on initial and target lay-outs, and constructive constraints)
Roof construction (passive shading; receptive for renewable energy capture)	Rigid/addable (overarching requires new roof; other shading constructions fixable)
Insulation roof (high resistance, excluding thermal bridges)	Rigid/addable (if space available and thermal bridges excludable)
Insulation of (cavity) walls (high resistance, excluding thermal bridges)	Precluded/rigid/addable (if space available and thermal bridges excludable)
Insulation floors	Precluded/rigid/addable (when basements available)
Windows (frames); glass	Rigid (needs replacement)
Window shading (external blades)	Rigid/addable (causing visual hindrance)
Heat distribution low temperature (<45 °C)	Rigid (if floor heating); for room radiators, space may lack or cause hindrance
Solar energy (thermal; electricity)	Rigid/addable (if RE ready)
Ventilation D (heat exchanger; ducts)	Rigid/addable (when space permits)
Condensing boiler for add-on heat supplies	Addable (drain for condensation needed)
Heat pump	Addable (depends on lay-out heating and cooling systems and ambient heat sources)
Cooling system (active air-co)	Addable (visual, acoustic, draught issues)

the initial costs later. For example when a new construction has to be undone the value lost is not only the full price of erection but also the cost of demolishment and removal of the materials to recycling or dumping facilities. With time passing a construction is depreciated and the sunk costs decline. 'Weak' irrevocability is when the investment could be undone at a price equal or lower than the initial costs. For example, one can discard a piece of equipment without removal costs. With time passing depreciation further reduces incurred costs when one wants to undo the decision taken. With decommissioning a building, the issue of related irrevocability ends. When an investment can be undone at the initial cost price (for example by re-using a piece of equipment or selling it at the initial price paid or at its residual value during its depreciation lifetime), the decision is fully revocable at all time (the abscissa in Fig. 2).

Prevalence of categories of reversal costs and patterns of reversal cost curves depend on several variables, for instance: physical characteristics of the object, sunk-ness of initial investments, technological innovation and economies of learning regarding possible substitutes in the future, etc.

4.2. Irrevocability in house building

Building a house implies a large number of decisions, with some being related or conditional, others being independent. At the outset, it is important to clarify the distinction between physical and economic irrevocability: a house is physically an irrevocable investment but is economically a liquid one when there is a (lively) market for housing transactions (selling/buying; letting/renting). When a decision-maker has avoided irrevocability funnels like a bad location illustrated in Section 3.3, weak or medium irrevocability mostly applies on a house investment. Also, many buildings are constructed with an eye on selling it with profit. However, several attributes and parts of a building are tied up with the construction and physically and economically irrevocable. This is particularly true for most energy performance attributes and items.

At the planning and design phase, the EPE of a house is decided. EPE is the incorporated capability (made up by attributes, structures, installations, equipment, etc.) of a house that largely determines energy use in delivering the functions wanted by the occupants [22]. The literature pays little attention to distinguishing between the house as such and its EPE, because both are highly interwoven. The custom is to label houses as a whole on their energy efficiency merits, although precise delineations are absent on what distinguishes standard houses (meeting the imposed energy standards, expressing the EPE level considered as optimum by regulators), low energy houses, passive houses, net zero energy, and energy producing houses [1,23,31].

Houses differ in initial EPE at construction. A new building is holding many degrees of freedom in EPE optimizing. Table 3 shows in the first column a selection of attributes and items that affect the EPE of a house, mostly increase the EPE towards the high-efficient (passive) quality. The second column provides information on the ex-post adaptability/add-ability of the various attributes and items, once a house has been built without these. For the attributes and items is indicated whether being "precluded" (strong irrevocability), or "rigid" (medium irrevocability), or "adaptable/addable" (weak irrevocability). Classification is blurred when specific circumstances on-site or design decisions taken during the planning phase involve specific rigidities or flexibilities. Table 3 reveals that several important features that make a construction passive belong to the strong irrevocability or preclusion class: costs to adapt the attribute or add the item after finishing the construction are higher than costs of realization during construction and remain higher (mostly prohibitive) during the building's lifetime. For example the provision of cellars (basements) in houses was a common practice before the diffusion of refrigerators. With that diffusion it became 'modern' not to provide a cellar in new houses. However, cellars provide cheap and cool storage space for food and beverages, for placing the freezer, at an ambient temperature about 10–15 °C lower than in the living space above. Integrated analysis shows cellars save on investment, maintenance, and energy expenditures. However, omission in the planning rules out in advance – precludes – the (ex-post) addition of a cellar.

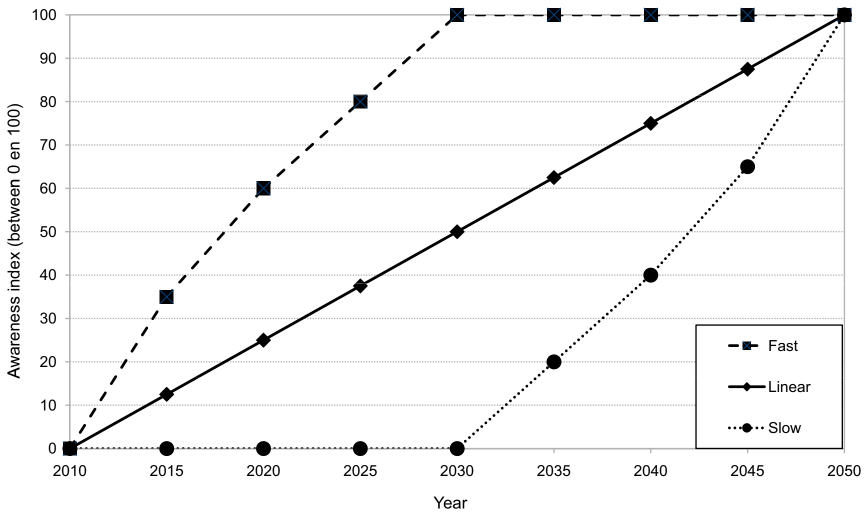

Fig. 3. Patterns of undeniable climate change taking place in the next 40 years.

4.3. *"Choose or Loose" versus "Wait and Learn"*

Section 3.3 illustrated how applying option theory mostly advises: defer the physical investment, and collect additional information [7]. Dixit and Pindyck [5: 135] state clearly: "In this chapter and throughout this book, our main concern will be with investment expenditures that have two very important characteristics. First, the expenditures are at least partly irreversible; in other words, *sunk costs* that cannot be recovered. Second, these investments can be delayed, so that the firm has the opportunity to wait for new information to arrive about prices, costs, and other market conditions before it commits resources." EPE investments do obey the first condition, but not the second one. Obviously, many EPE attributes and items are characterized by a high degree of irrevocability (Table 3). But delay in deciding the EPE attributes and items of a building is impossible once construction is decided.[4]

Under Dixit–Pindyck [5] conditions more irrevocability strengthens the wait option. In the EPE case the thrust is opposite: more irrevocability stimulates to choose now for the most irrevocable EPE attributes and items in order to avoid preclusion of efficiency solutions in the future. The attributes and items in Table 3 that are precluded for adaptability and add-ability, are the ones to rank highest in the EPE merit order when the future imposes very high energy efficiency housing with a high standard of living.

In Section 5, a short case study illustrates the mechanisms without exhausting the vast domain that opens for practical studies, in particular when investigating building codes and standards [2].

5. Illustrative case study

Every application of investment decision theory and its results are circumstantial. This section aims at illustrating the methodology focusing on the aspects irrevocability and preclusion. For the aspects time and uncertainty plausible values are adopted. The case study is based on a fictive single family 200 m^2 house in Belgium, occupied by a three person family. This explains the numbers (heating, water, electricity use, prices, investment budgets, etc.).

In 2010 the house is constructed and two levels of EPE are compared: passive and (advanced) standard. The passive house owns all 20 first-ranked attributes or items in the left column of Table 3, and does not need active air-co to realize a good cooling comfort. For realizing the passive attributes and items, the passive house requires €25,000 more investments than a standard house. Installing renewable energy capacity for a yearly production of 2500 kWh solar power and 2000 kWh solar heat an additional €15,000 needs to be invested. A rainwater unit that supplies yearly 80 m^3 requires another €5000, or in total €45,000. Yearly the passive house purchases 6000 kWh heat, 2500 kWh electricity, and 50 m^3 water (uses are 8000 kWh heat, 5000 kWh electricity and 130 m^3 water).

A standard house does not invest €45,000 in high-efficiency attributes and items. Yearly it uses and purchases 16,000 kWh heat, 5000 kWh electricity, and 130 m^3 water. Except for heating, all other energy and water use is assumed equal as to the passive house.

5.1. *Time*

The analysis occurs over the period 2010–2080, covering 70 years. The horizon of 70 years exceeds conventional time discounting periods (Section 2). The applied discount rates are borrowed from Weitzman [21: 29]: "For about the next 25 years from the present, use a 'low-normal' real annual interest rate of around 3–4%. For the period from about 25 to about 75 years from the present, use a within-period instantaneous interest rate of around 2%." Such real terms rates have a high impact due to exponential decay (€1000 at the end of 70 years counts but €196 now). The US Department of Commerce recommends a 3% real discount rate for life-cycle cost assessments in the building sector [32].

5.2. *Uncertainty*

Energy and climate change policies are intensively intertwined. Science argues that end-use prices of energy must go up to stimulate energy efficiency innovations and practices [33]. But disruptive taxing and pricing decisions remain postponed, while greenhouse gas emissions continue to rise and climate change is speeding up. This situation of multiple uncertainties plagues investors in long-term endeavors.

[4] It may be understood that the standard option theory as described in Section 3.3 and in Dixit and Pindyck [5], also can be applied to find the optimum date for starting the construction as such, a timing also influenced by EPE choice opportunities. However, many other (for people more important) considerations will fix the date of constructing, and therefore analytical separation of the two decisions is plausible.

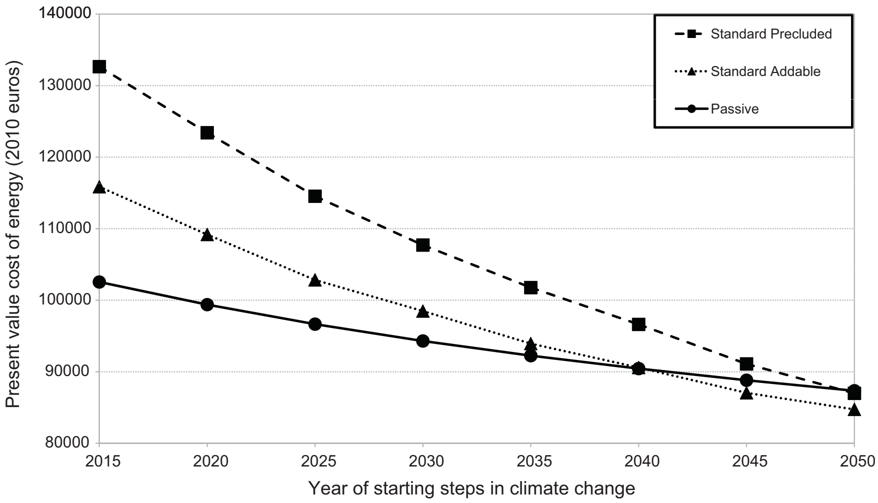

Fig. 4. Costs of three EPE packages for eight starting dates of undeniable climate change.

Climate change is entraining irreversible states of nature (the increasing concentration of greenhouse gases in the atmosphere; increasing ambient temperatures) and effects thereof like melting glaciers, land-ice, permafrost, loss in biodiversity, and disrupted hydrological cycles [3]. This case study accepts the findings of IPCC [3] that for the coming decades climate change is an irreversible process with major irreversible impacts that evolve rather rapid but the timing of their onset is uncertain. The case study models three cumulative steps in undeniable climate change taking place consecutively at 5-year intervals once initiated. Initiation may be triggered from 2015 onwards, also per 5 year interval, with the latest date being 2050. The year of occurrence of the first step is probabilistic (between 2015 and 2050). Fig. 3 shows fast, linear and slow starting paths of undeniable climate change. For example, the fast path assigns probabilities of 0.35, 0.25, 0.20, and 0.20 that the first step arrives in 2015, 2020, 2025, and 2030, respectively.

For housing the stylized effects of undeniable climate change are: step 1 (temperature rise) makes space cooling wanted for comfortable living; step 2 (fresh water shortage) makes rainwater capture and storage recommended for sufficient and affordable supplies; step 3 (absolute reductions in fossil fuel supplies) makes renewable energy generation at houses a good bet. At every step the heating, grid electricity, and supplied water prices in 2010 at, respectively, €ct6/kWh, €ct12/kWh and €4/m^3 are raised by, respectively, 25, 25 and 50 percent.

5.3. Preclusion of EPE attributes and items

Depending on the EPE attributes and items selected in 2010, owners are accordingly equipped to face the climate change challenges or adapt their house to new conditions. A passive house is robust enough to absorb the steps without extra investment. In standard houses air-co is installed at step 1, investing €5000 and consuming 500 kWh electricity more per year. For steps 2 and 3, two situations are modeled. On the one hand a standard house with preclusions for adding rainwater and renewable energy installations. On the other hand a standard house that can add both facilities at the same terms the passive house installed them in 2010. Because of the price increases accompanying the three climate change steps, the investments are profitable. The difference between the two standard house cases shows the impact of preclusion and irrevocability of EPE decisions.

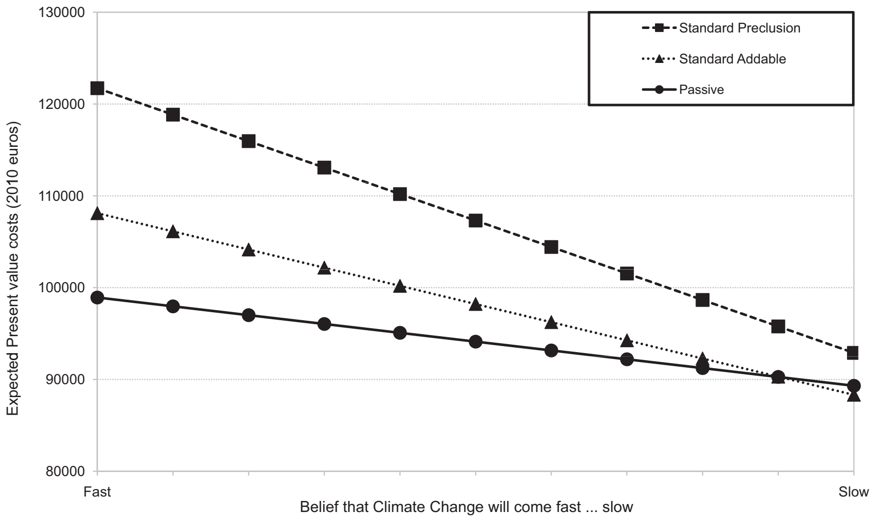

Fig. 5. Expected costs for three EPE packages depending on beliefs whether climate change will come fast . . . slow.

5.4. Illustrative results

Fig. 4 shows for the three EPE packages (Section 5.3) eight present value costs for the eight triggering dates (2015–2050, every fifth year) of undeniable climate change (Section 5.2). With the numbers of the case study is shown: passive is the lowest cost option when climate change evidence is triggered before 2040. After that date a standard house that owns the flexibility of adding efficient EPE attributes and items shows lower costs. But when efficient EPE additions are precluded the standard house shows higher costs for all triggering dates before 2050 because of “Choose or Loose” irrevocability. Discounting erodes the cost advantage of passive housing (with an upfront investment of €45,000) when climate change effects would be delayed with 30–40 years from today and energy prices stay low in the meantime. In Fig. 4, the shallow slope of the costs of the passive house reveals that this option is more robust (resilient) than the other ones for future climate randomness.

The results above condense uncertainty about the future in triggering dates of undeniable climate change. Decision-makers (house builders; building code regulators) add their expectations about the future by assigning probabilities to the paths (Fig. 3). In computing expected values the future is assumed to be putty rather than clay, and possible preclusions caused by early decisions are forgotten. Fig. 5 shows expected costs from normally distributed expectations about the fast and slow paths of climate change deployment (Fig. 3). The differences between standard and passive EPE packages become smaller the more it is believed that climate change is far off. When the decision-maker denies climate change, he opts for the standard package because that is what NPV calculations will show to be least cost. However the case study shows that standard is not the best option when preclusion is taken into account (Fig. 5).

6. Conclusion

Three dimensions – time, uncertainty, and irrevocability – in decisions on the EPE attributes and items of buildings are discussed. The importance of time sequential decision analysis and of irrevocability has been documented. Application of concepts and tools available in the decision-making literature on the case of energy efficiency of buildings induces new insights and more appropriate concepts. Section 4.1 classifies irrevocability in categories as a frame for measuring the degrees of irrevocability. Section 4.2 applies the classification on the EPE of houses, highlighting the occurrence of preclusions, rigidity and adaptability/add-ability depending on the attribute or item considered and on circumstantial factors. In Section 4.3 is argued that timing of EPE decisions is locked to the building's design/construction year, and therefore the “Choose or Loose” approach substitutes for the “Wait and Learn” option of standard decision theory. The methodology is illustrated with a case study revealing the impact of irrevocability, and the misleading information and advice simple net present value studies may generate.

The focus of the article is on methodology, but the lessons for practical decision-making are of high relevance. First, obvious is the necessity for proper investment appraisals of the EPE attributes and items. Proper methodology includes the consideration of irrevocability and preclusion, what is omitted in all studies that we surveyed. Second, this recommendation is particularly valid for the “economic studies” that support the EU Buildings Directive [2] and all other regulations that prescribe (or allow) EPE packages not avoiding the many preclusions for high-efficiency performance in the future life of a building. Third, when opening our eyes for upcoming climate change events and effects, it seems utterly important to avoid preclusions in the EPE of houses and of any other building. It makes sense to choose the highest quality EPE when designing a building in order to avoid losing flexibility and resilience in the coming years. And as said in passing: we did not insert the significant amenities and positive externalities that high-quality energy performance offers the occupants of buildings and society at large.

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