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Design Catalogs: A Practical Real Options Valuation Tool for Real Estate Design and Development Planning

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Abstract. This paper proposes and demonstrates *design catalogs* as a practical and computationally efficient method for identifying and valuing improved and flexible development plans for real estate projects. This new process significantly speeds up the analysis for complex projects facing various uncertainty sources (e.g. market, regulations, technology). It enables analysts to explore the design space more fully, taking into account a greater number of design parameters and variables. It can lead to design and development solutions with greatly improved economic performance over the system's useful life. The design catalog consists of a small subset of design and development plans that collectively perform reasonably well over a range of possible scenarios. The catalog approach contrasts with the usual approach that optimizes development plans for each scenario, and thus can only afford to examine a limited number of situations. Each element in the catalog consists of combinations of design variables, parameters, and flexibility (or real option) decision rules. The set of designs in the catalog is determined using adaptive One-Factor-At-a-Time (aOFAT) analysis. An example shows how to use the proposed process to recognize additional value in a complex real estate project stemming from flexibility and real options. It shows improved economic lifecycle performance compared to a standard benchmark design and development plan.

1 Introduction

Real estate systems are characterized by a significant level of technical complexity, social intricacy, and elaborate processes aimed at fulfilling important functions in society (ESD 2011). Given they are typically long-lived (+20 years), they face much uncertainty at strategic, tactical, and operational levels. One can think of the complexity of projects in new city developments such as New Songdo City in South Korea, or Tianjin Eco-City in China. As seen in the last economic crisis, real estate systems also play an important role as backbone supporting society's main economic activities.

Designing and evaluating complex real estate projects thoroughly can be a demanding task from a computational standpoint. As summarized in Table 1, it involves modeling and optimizing basic infrastructures (e.g. commercial/retail space, power, transportation, water, etc.) considering a wide array of uncertainty scenarios (e.g. market demand, price, regulations) over long-term horizons. There can be many possible architectures and operating modes (e.g. number and size of buildings, deployment of housing infrastructures, etc.) The system can also be evaluated based on many lifecycle performance indicators (e.g. net present value (NPV), return on investment (ROI), etc.) It is practically intractable to consider all possible design combinations and alternatives.

A typical approach in real estate project evaluation is to simplify the full analytical problem. Instead of considering many scenarios of periodical data, designs are optimized for the most likely projection of major uncertainty drivers (Geltner et al. 2010). Typical project evaluation based on discounted cash flow (DCF) analysis, such as NPV, does not account for the fact that system operators and managers will react periodically to enhance the system performance (Trigeorgis 1996). Also, design decisions are often based on one evaluation metric like internal rate of return (IRR), NPV, or ROI. The combination of such practices in systems design and evaluation can lead to sub-optimal choices, and even economic failure (M.-A. Cardin et al. 2012).

Table 1: Full analytical problem for designing real estate systems.

Initial Design	Uncertain Variables	Developers Adjust	Lifecycle Performance
Physical infrastructure (Many possibilities)	Price, demand for services (Many possibilities)	Best use of existing facilities; development of additional phase (Many possibilities)	Realized net present value, rate of return, etc. (Many possibilities)

1.1 Flexibility in Engineering Systems Design: Computational Challenges

There has been a great deal of effort over the last two decades to improve standard design and evaluation practice by making more explicit considerations of uncertainty. Flexibility in engineering design – referred interchangeably here with real options – is one approach, which aims at designing a complex system so it can adapt and change pro-actively in the face of uncertainty in environment, markets, regulations, and technology (de Neufville and Scholtes 2011; Nembhard and Aktan 2010). In the literature, flexibility in design is often referred to as a real option embedded “in” the system (Wang and de Neufville 2005). Flexibility can improve expected economic performance by affecting the distribution of possible outcomes. It reduces the effect from downside (like buying insurance), risky scenarios, while positioning the system to capitalize on upside, favorable opportunities (like buying a call stock option).

An example flexibility in real estate is the ability to expand a building vertically (Guma et al. 2009). The Blue Cross Blue Shield (BCBS) Tower in Chicago exploited this strategy by “building small first, and expanding later *if and when needed*”. This strategy reduced exposure to downside risks because less capital was required upfront. It gave access to upside opportunities under favorable market conditions by providing contingencies to build more offices, hire personnel, and ultimately generate more profits. This strategy was enabled by carefully engineering the infrastructure for expansion in the early 1990s (e.g. larger elevator shafts, stronger structure). This flexibility was exercised a few years ago, with the expansion phase completed in 2011.

Flexibility has shown improvements typically ranging between 10% and 30% compared to the outcome from standard design and evaluation practice in other industries: strategic phasing of airport terminals development (de Neufville and Odoni 2003; Gil 2007), offshore platforms designed for future capacity expansion (Jablonowski et al. 2008), strategic investments in new nuclear plant facilities (Rothwell 2006), supply chain adaptation to fluctuating exchange rates (Nembhard et al. 2005), strategic investment in innovative water technologies (Zhang and Babovic 2012), etc. Examples abound.[a]

An important issue in designing real estate project accounting for flexibility and real options is the complexity of the analytical problem. In addition to the many design variables and parameters to consider, designers need to account for a wide range of uncertainty scenarios, periodic managerial adjustments, and evaluation metrics. For instance, a development company may decide to rely on a model integrating both engineering design aspects (e.g. piping, electricity, water, etc.) together with an economic model, and optimize the design and development plan based on average historical prices of used or rented space, demand at that particular location, and/or for the price of land. If one only considers one of these uncertainty sources and three distinct price scenarios in each year of a 20-year lifecycle (i.e. typical lifetime for such asset), the number of design and deployment plans to investigate would be 3^{20} ~3.5 billion. Consideration of so many scenarios is, as a practical matter, intractable, let alone with additional degrees of freedom stemming from explicit considerations of flexibility/real options in design, management, and deployment of such system.

In essence, the problem addressed in this paper is that the analysis of performance for complex real estate projects under uncertainty requires a special design or operating plan for each scenario. The definition of such plans and their economic lifecycle performance requires a lot of time and analytical resources, as exemplified

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[a] More case studies are available at http://ardent.mit.edu/real_options/Common_course_materials/papers.html, http://strategic.mit.edu/publications.php, and http://seari.mit.edu/publications.php.

above, so analysts can only look at a very few design and development plans fully. Therefore, solutions possibly improving economic performance cannot be examined due to time and analytical constraints.

1.2 Proposed Solution

This paper addresses this issue by devising *a priori* a set of operating plans or models that together deal reasonably well with a range of uncertainty scenarios. This speeds up the analysis for the most relevant design and development plans, allows analysts to consider more alternatives, and enables uncovering better solutions with improved economic performance. The proposed solution suggests a middle-ground approach standing between the simplest set of assumptions typically made in design and evaluation, and the full analytical problem summarized in Table 1. It relies on a representative range of possibilities small enough to be manageable analytically, and broad enough to enable a more informed analysis of the design problem. The aim is to provide a practical approach leading designers to rapid lifecycle performance improvements by explicit considerations of flexibility. It is also efficient in terms of the computational and analytical resources required.

Design Catalogs. The method simplifies the analysis by relying on the concept of a design catalog. The catalog provides a limited number of scenarios and responses intended to describe relevant patterns developers might wish to anticipate. An *operating plan* is therefore a combination of design variables, parameters, and flexible decision rules to manage the real estate system in operations, and over its lifecycle. For instance, instead of considering explicitly all possible 3.5 billion price scenarios, only a handful representative scenarios are considered. One operating plan is created to suit each scenario, thereby creating the catalog.

Representative uncertainty scenarios can be selected based on different criteria, and each operating plan crafted to deal best with each scenario. For example, consider a scenario where prices rise steadily at first, and start falling after some time. Another possibility is for prices to start low for the first few years of a project, and then incur a sudden surge due to high demand. Volatility around the main trend may vary between low, medium, and high values. In each case, a different flexible response might be required, and better supported by a different flexible design configuration. The catalog contains the flexible design alternatives that cope most appropriately with each scenario.

The concept of catalog is analogous to customers buying suits, typically coming in many sizes and shapes. While it is possible to hand-tailor suits for each customer, this can be demanding in terms of manufacturing and operations. One alternative is to have a range of suits (i.e. a catalog) that will reasonably fit any of the customers' needs. The items in the catalog provides a range of choices varying along several dimensions – as in the example below Section 4.2 – and as in real life (e.g. tall, short, large, thin, etc.).

Decision Rules. A decision rule defines the trigger point or mechanism at which time it is appropriate to exercise a designed flexibility/real option. It aims to simulate an appropriate decision taken by the developer at any point in time to adapt the system to arising conditions. Such rule is typically based on the observation of a given uncertainty source (e.g. demand, price, technological performance) to which the system is called to react. It is crucial for determining the lifecycle performance improvement and value-added by flexibility compared to standard design approaches. In the BCBS Tower example, a hypothetical decision rule could have been that if the need for office space reached a certain threshold (e.g. because the company is growing), the second phase would be started. While it is unclear what decision rule was used, it is clear that the decision to expand capacity was based on observed changes in the main uncertainty drivers (e.g. availability of funds, prospects for better business opportunities, etc.) Decision rules capture such managerial decisions to be included in the modeling.

A decision rule simplifies the analysis compared to full optimization on each uncertainty scenario. This is because it typically requires "looking back" over the information provided up to a certain point in time. Typical stochastic or dynamic programming algorithms used in real options analysis (Dixit and Pindyck 1994; Copeland and Antikarov 2003) consider the best sequence of decisions over the entire scenario period. On the one hand, this may not be realistic in an engineering context because a decision-maker does not know a priori how the future will unfold. Also, the number of possible combinations explodes exponentially as a function of the number of time periods – or stages – also making the problem quickly intractable. Decision rules, however, can rely on both "forward looking" and "backward looking" uncertainty realizations, providing much freedom to model the developer's decisions.

Design Space Exploration. The aim of the proposed approach is to reduce the complexity of the analysis. It focuses on investigating a suitable combination of physical design variables and parameters together with flexible decision rules available to better handle uncertainty. This abstract combinatorial space is referred in this paper as "design space". The approach structures the process of exploring the design space under considerations of uncertainty and flexibility, while still being tractable computationally.

The exploration process is inspired from the adaptive One-Factor-At-a-Time (aOFAT) fractional factorial algorithm by Frey and Wang (2006) used in statistical design of experiments (DOE). The approach consists of starting at a particular design combination (or factor level), and measuring the lifecycle performance obtained using a system model. One of the factor levels is then toggled to another level, and another performance measurement is taken. If the objective function is improved, the change is kept, and the analysis moves on to toggling another factor and level. If the response is not improved, the change is discarded, and another factor level is explored. The algorithm goes in sequence until all factors levels have been explored once.

This process reduces the number of search iterations tremendously, while still reaching a good solution. Frey and Wang (2006) showed that in a design space with n factors with 2-levels each, aOFAT reduces the number of experiments from 2^n to $n + 1$, while still reaching on average nearly 80% of the optimal response. The main motivation for using aOFAT is the good tradeoff it provides between computational efficiency and precision.

The remainder of the paper is organized as follows. In the next section, a short review of the literature is presented to highlight previous efforts in addressing this computational design problem more generally in engineering systems design research. Section 3 explains how the design catalog is developed, and how to evaluate flexible design alternatives. In Section 4, an example application is presented for the analysis of a real estate project that, while at a reduced scale, captures many of the issues encountered in more complex projects. Results, findings, validity, and limitations of the framework are discussed in Section 5, together with possible avenues for future research, followed by conclusions.

2 Literature Review

2.1 Conceptual Process

The conceptual process of generating flexibility and real options in complex systems typically requires five phases (Cardin 2013). It starts from an initial design, obtained by means of existing and/or standard design procedures (phase 1). This phase is necessary to circumscribe the initial design space, as it is difficult to consider flexibility without an initial design. A review of current procedures to generate initial design alternatives is provided by Tomiyama et al. (2009). The major uncertainty sources affecting lifecycle performance are recognized, modeled, and incorporated explicitly in the process (phase 2). Flexibility/real option strategies are generated to deal with these uncertainties, and enablers are identified in the design (phase 3). The design space is explored systematically to find flexible design alternatives leading to improved lifecycle performance, as compared to the baseline design (phase 4). Phase 5 oversees phases 1-4 to create a productive collaborative environment for designers.

2.2 Design Space Exploration

This paper is mainly concerned with design space exploration (phase 4). This phase involves developing efficient computational methods and search algorithms to find the most valuable flexible design configurations, subject to a range of design variables, parameters, decision rules, and uncertainty scenarios. This phase requires modeling explicitly the flexible design concepts generated in phase 3. For example, the flexible design concept explored for the BCBS Tower is capacity expansion. This could give rise to a wide range of flexible design alternatives with different decision rules. One could design additional capacity for one, two, or three extra floors when need for office space reaches threshold T, or do it all in one additional phase, etc. Given T alone can take on any value, there can be is are infinite combinations of physical design variables and decision rules enabling the flexibility, in terms of timing and capacity of each expansion phase, each leading to a different lifecycle performance outcome. Design procedures in phase 4 provide systematic ways to search effectively through this combinatorial space.

The methods in phase 4 typically integrate real options analysis tools based on dynamic programming and economics (Bellman 1952; Cox et al. 1979; Dixit and Pindyck 1994; Trigeorgis 1996) with standard optimizations and statistical techniques to assess the lifecycle performance of flexible design alternatives. To tackle this computational problem, Jacoby and Loucks (1972) first suggested screening methods to identify most promising design alternatives within reasonable time. de Neufville and Scholtes (2011) suggested three types of screening methods: bottom-up, simulators, and top-down. Bottom-up models use simplified versions of a complex, detailed design model. Simulators incorporate statistical techniques (e.g. response surface modeling) and/or fundamental principles to mimic the response of the detailed model. Top-down models use representations of major relationships between the parts of the system to understand possible system responses (e.g. systems dynamics).

Wang (2005) was first to apply screening methods in the context of flexibility. His approach was used to analyze water infrastructures in China. Lin (2009) developed a bottom-up screening model of an integrated oil and gas system to identify valuable flexible design alternatives in an offshore oil platform system. Yang (2009) used a response-surface methodology coupled with fractional factorial analysis to explore flexibility in the car manufacturing process. Hassan and de Neufville (2005) used genetic algorithms to structure the search process in oil platform design and planning. Olewnik and Lewis (2006) extended a utility-based framework to the context of flexibility in product development. Ross (2006) proposed Multi-Attribute Trade space Exploration (MATE) based on Pareto-optimal configurations. This process exploits tradeoffs between design performance utility attributes, and lifecycle cost.

2.3 Research Gap

The methods above all depend on simplifications of an engineering system model. Simplifications, however, can be difficult to achieve for many reasons, depending on the context. For example in bottom-up methods, it may be unclear what parameters to simplify. Should designers simplify considerations of demand and price to make the model run within reasonable time? Are there other factors more important to consider? In the case of simulators, it is unclear what is the best sampling mechanism to create the response surface. Different sample points may lead to different response surfaces, and different optimal design solutions. In top-down models used in systems dynamics, a deep understanding of the system's underlying feedback and feedforward mechanisms is required (Sterman 2000). Building such model requires intensive field research and data collection (Steel 2008), which can be constraining. In addition, for a variety of practical reasons (e.g. time and resource constraints), there might be situations where practitioners cannot use screening methods. In this case, it might be better to work directly from the model at hand, even if the model has high complexity. The methodology detailed in the next section introduces a complementary and practical way to address the above issues.

3 Methodology

Table 2 below summarizes the design catalog approach. The approach considers a handful of representative uncertainty scenarios (e.g. 5-10) and associated flexible responses to each scenario. The catalog approach also enables designers to consider several lifecycle performance metrics, depending on the context.

Table 2: A design catalog approach for designing real estate systems for flexibility and real options.

Initial Design	Uncertain Variables	Developers Adjust	Lifecycle Performance
Physical infrastructure (Many possibilities)	Price, demand for services (5-10 scenarios)	Best use of existing facilities; development of additional phase (5-10 responses)	Realized net present value, rate of return, etc. (Several)

The general methodology for developing a design catalog has five steps:

1- Develop a basic model for measuring economic lifecycle performance
2- Find representative uncertainty scenarios affecting lifecycle performance
3- Identify and generate potential sources of flexibility in design and management
4- For each uncertainty scenario, find the most appropriate flexible operating plan and construct the catalog using the aOFAT fractional factorial algorithm
5- Assess lifecycle performance improvement – if any – using the design catalog as compared to the baseline design under uncertainty

4 Analysis and Results

This section demonstrates application of the five-step process. The objectives are to demonstrate that the design catalog technique 1) can improve expected economic performance compared to a baseline design and development plan that is typically more rigid (i.e. inflexible), and 2) is computationally efficient compared to an exhaustive search. The former objective demonstrates the value of embedding flexibility and real options in the system. The latter shows that the technique is useful particularly when computational efficiency is required.

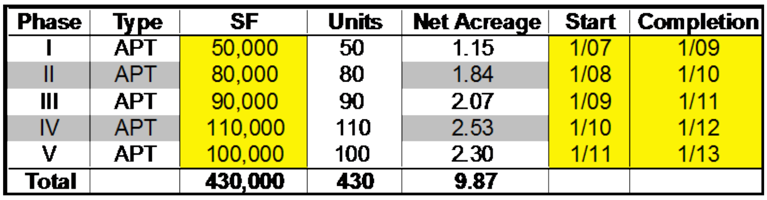
4.1 Case Study

This case study is inspired from a real estate development project considered by a renowned U.S. company in 2007. It consists of 430,000 square feet (SF) of apartment units deployed over five phases (one year per phase), along with relevant infrastructure (site grading, paving, utilities, and landscaping). Each apartment unit was designed to cover about 1,000 SF. An interesting feature was that phases were supposed to be developed around a park having an area of 200,000 SF (about 4.6 acres). Project developers counted on this feature to attract more buyers, and increase market value.

The original proposal was to develop all five phases, infrastructures, and park in a row between 2007 and 2013 to benefit from economies of scale and reduce costs. Each construction phase could take up to 24 months, and start one year after the other. The park and shared infrastructures were to be constructed along with each phase. Phase II was meant to start one year after the beginning of phase I, and so on for subsequent phases. Table 3 summarizes the timing of the development project.

The market value of built property, measured in dollars per square foot, was projected to be higher than development costs for the first few years of the project. This assumption implied that developing phases in a row would generate the highest NPV. It was therefore adopted as the best strategy for the baseline case based on deterministic projections of market value and development costs.

Table 3: Summary and timing of the real estate development project. APT stands for apartment building.



Phase	Type	SF	Units	Net Acreage	Start	Completion
I	APT	50,000	50	1.15	1/07	1/09
II	APT	80,000	80	1.84	1/08	1/10
III	APT	90,000	90	2.07	1/09	1/11
IV	APT	110,000	110	2.53	1/10	1/12
V	APT	100,000	100	2.30	1/11	1/13
Total		**430,000**	**430**	**9.87**		

4.2 Application

Step 1: Basic Model Development. In this case study, the metric for assessing value and performance is NPV. The main uncertainty drivers considered are market value and development cost of built apartment property per square foot. When an apartment building is completed, developers get its total value as revenue. This is determined by total apartment unit surface area multiplied by market value of built property per square foot. The same applies to development costs.

The basic model consists of a DCF Excel® spreadsheet using standard projections of market value of built property and development costs. For simplicity, the model assumes that only one phase can begin each year. Therefore, developers wait for a year before beginning a new phase, even if the previous one is half completed. The model was developed using the following assumptions, which are partially inspired from the study by Ariizumi (2006):

- The deterministic forecast is that market value of built property is currently evaluated at $350/SF (as of 2007), and increases linearly at a rate of 2.5% per year;
- Development costs are currently evaluated at $220/SF and increase linearly with inflation at a rate of 2.5% per year;
- The project can be developed over twenty years, starting in 2007 until the end of 2027;
- Land acquisition cost is $15 million (or $15M) to be paid as soon as phase I begins;
- The park has a surface area of about 200,000 SF (about 4.6 acres) and costs $1M to develop along with the five development phases. The cost is distributed among each phase as $200,000 per phase;
- Infrastructure development, which includes site grading, paving, utilities, and landscaping are estimated at $29/SF of apartment unit;
- The discount rate for market value of built apartment property (r_V) is 9%. The discount rate for construction costs (r_C) is 6%, close to currently prevailing risk-free rates.
- Development of all phases in a row benefit from cost reductions of 2.5% due to economies of scale.

To measure the static NPV, two different discount rates are used as proposed by Geltner et al. (2010). It is difficult for developers to evaluate the “unified” opportunity cost of capital (OCC), denoted as r_U, that takes into account both market value risks and construction cost risks. The OCC for discounting future revenues used by the developer, denoted as r_V, is different from the OCC used to discount potential construction costs (r_C). Developers give construction costs a relatively large weight in the project’s expected value calculation because they may turn out greater than originally projected. Therefore, a smaller discount rate r_C, around the prevailing risk-free rate, is used to discount future construction costs in the pro forma cash flow projections. The discount rate for revenues, r_V, is typically higher, and here is 9%.

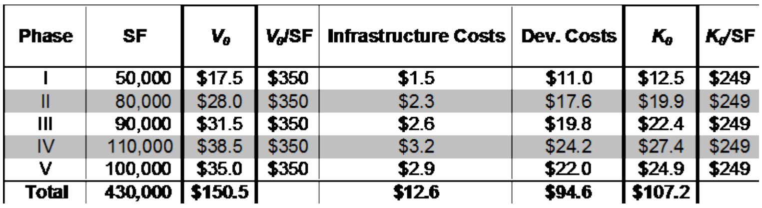
In other words, since it is difficult for developers to know r_U, it is suggested to use two different discount rates for real estate development projects such that

$$\frac{V_T - K_T}{(1+E[r_U])} = \frac{V_T}{(1+E[r_V])^T} - \frac{K_T}{(1+E[r_C])^T} \qquad (1)$$

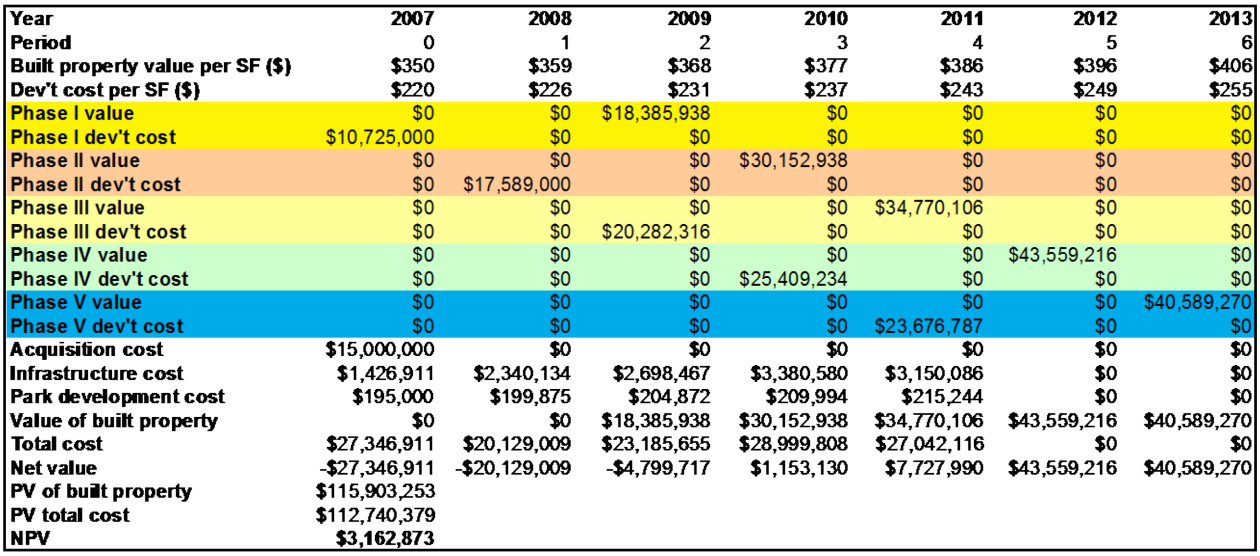
where V_T and K_T are the market value and construction cost of built property at time T.

Table 4 summarizes the initial estimated value (V_0) and construction costs (K_0) breakdown per square foot for the development project. Figure 1 shows a snapshot of the initial DCF model used to compute the project’s NPV under deterministic market value of built property and development cost shown in Figure 2.

Table 4: Summary of market value (V_0) and construction cost (K_0) figures for the apartment development project (in $millions).



Phase	SF	V_0	V_0/SF	Infrastructure Costs	Dev. Costs	K_0	K_0/SF
I	50,000	$17.5	$350	$1.5	$11.0	$12.5	$249
II	80,000	$28.0	$350	$2.3	$17.6	$19.9	$249
III	90,000	$31.5	$350	$2.6	$19.8	$22.4	$249
IV	110,000	$38.5	$350	$3.2	$24.2	$27.4	$249
V	100,000	$35.0	$350	$2.9	$22.0	$24.9	$249
Total	430,000	$150.5		$12.6	$94.6	$107.2	



Year	2007	2008	2009	2010	2011	2012	2013
Period	0	1	2	3	4	5	6
Built property value per SF ($)	$350	$359	$368	$377	$386	$396	$406
Dev't cost per SF ($)	$220	$226	$231	$237	$243	$249	$255
Phase I value	$0	$0	$18,385,938	$0	$0	$0	$0
Phase I dev't cost	$10,725,000	$0	$0	$0	$0	$0	$0
Phase II value	$0	$0	$0	$30,152,938	$0	$0	$0
Phase II dev't cost	$0	$17,589,000	$0	$0	$0	$0	$0
Phase III value	$0	$0	$0	$0	$34,770,106	$0	$0
Phase III dev't cost	$0	$0	$20,282,316	$0	$0	$0	$0
Phase IV value	$0	$0	$0	$0	$0	$43,559,216	$0
Phase IV dev't cost	$0	$0	$0	$25,409,234	$0	$0	$0
Phase V value	$0	$0	$0	$0	$0	$0	$40,589,270
Phase V dev't cost	$0	$0	$0	$0	$23,676,787	$0	$0
Acquisition cost	$15,000,000	$0	$0	$0	$0	$0	$0
Infrastructure cost	$1,426,911	$2,340,134	$2,698,467	$3,380,580	$3,150,086	$0	$0
Park development cost	$195,000	$199,875	$204,872	$209,994	$215,244	$0	$0
Value of built property	$0	$0	$18,385,938	$30,152,938	$34,770,106	$43,559,216	$40,589,270
Total cost	$27,346,911	$20,129,009	$23,185,655	$28,999,808	$27,042,116	$0	$0
Net value	-$27,346,911	-$20,129,009	-$4,799,717	$1,153,130	$7,727,990	$43,559,216	$40,589,270
PV of built property	$115,903,253						
PV total cost	$112,740,379						
NPV	$3,162,873						

Figure 1: Pro forma statement and DCF model based on deterministic projections for future revenues and costs of the apartment development project.

This initial analysis shows that the maximum NPV is obtained by building all phases in a row. This provides a NPV of about $3.2M. This static case corresponds to typical development practice when uncertainty is not explicitly recognized in the model, and flexibility is not factored in as a way to adapt (Geltner et al. 2010).

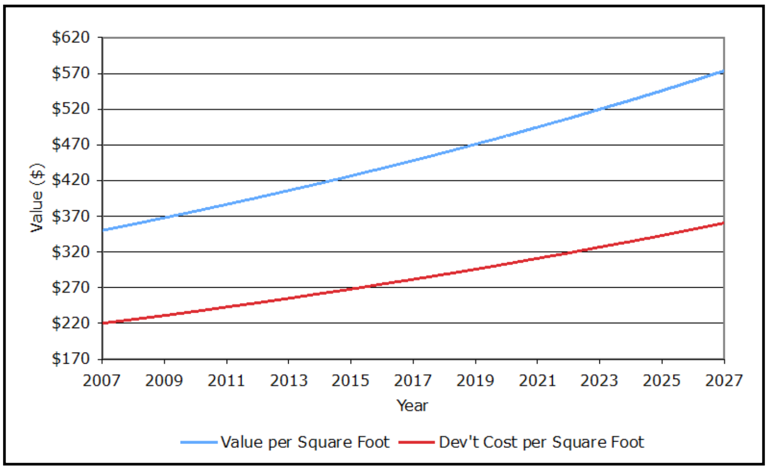


Figure 2: Deterministic projections of market value of built apartment property and development cost per square foot.

Step 2: Finding Representative Uncertainty Scenarios. This step finds a representative set of scenarios for the major uncertainty sources affecting lifecycle performance. To simplify the demonstration, market value of built property is the only source of uncertainty considered in this study. Development cost is assumed to increase at the same constant rate as inflation, assumed to be 2.5% annually. The deterministic model is augmented to account for stochastic fluctuations in market value, using the following equation:

$$V_{T+1}^{S} = g_T(1 + V_T) \qquad (2)$$

In Equation 2, V_T is determined from the deterministic projection in Figure 2, although now V_{T+1}^{S} is a random variable. V_0 is sampled from a uniform distribution with values ±50% off the initial projection of $350/SF. Inter-annual demand growth g_T is modeled using Geometric Brownian Motion (GBM):

$$g_T = g_P dT + \sigma dW_T \qquad (3)$$

where $g_P = V_T/V_{T-1} - 1$ is the projected inter-annual growth obtained using the stochastic version of the model, $dT = 1$ year time increment, $\sigma = 15\%$ is the assumed volatility of market value. Variable dW_T is the standard Wiener process, in this case sampled from a uniform distribution $U \sim (-1, 1)$ instead of a normal distribution for better computational efficiency. Using this model, the baseline inflexible design and development plan gives rise to an average NPV (or expected NPV: ENPV) $ENPV_{Inflexible.}$ = \$3.3M under 2,000 stochastic demand scenarios. An example of simulated market value pattern is shown in Figure 3.

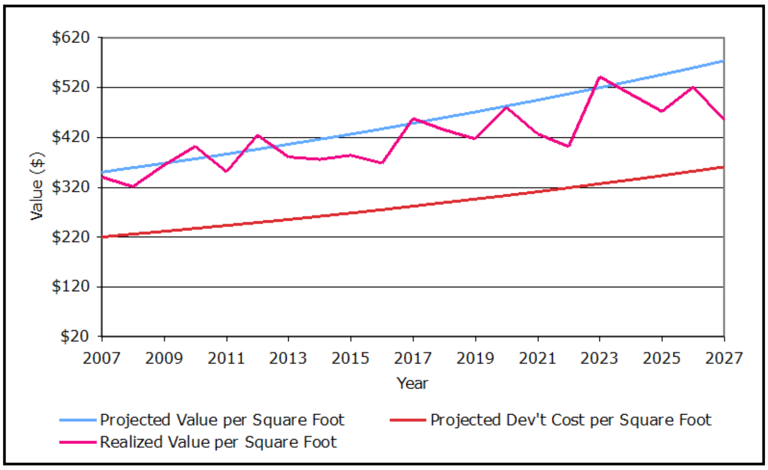


Figure 3: Example of one market value fluctuation from the 2,000 simulations used to incorporate uncertainty in the model.

At the moment there is no systematic approach to select a representative set of uncertainty scenarios, besides relying on expert inputs. Readers are referred to Morgan and Henrion (1990) for more systematic techniques to elicit scenarios and probability distributions. For illustration purposes, a set of three market value scenarios is created to support the creation of the design catalog of operating plans. The market value scenarios are chosen to represent simple situations program managers might have to deal with in reality.

Scenario 1 is chosen to represent an excellent evolution of market value through the lifecycle of the project with a high initial value and 3.5% annual growth. Scenario 2 is chosen to represent a situation where market allows construction at first, and then is unfavorable to development around 2013. Scenario 3 represents the case where no development should occur at all. The three market value scenarios are categorized by their initial values, as shown in Table 5. These categories are used to classify simulated scenarios in step 5 of the analysis.

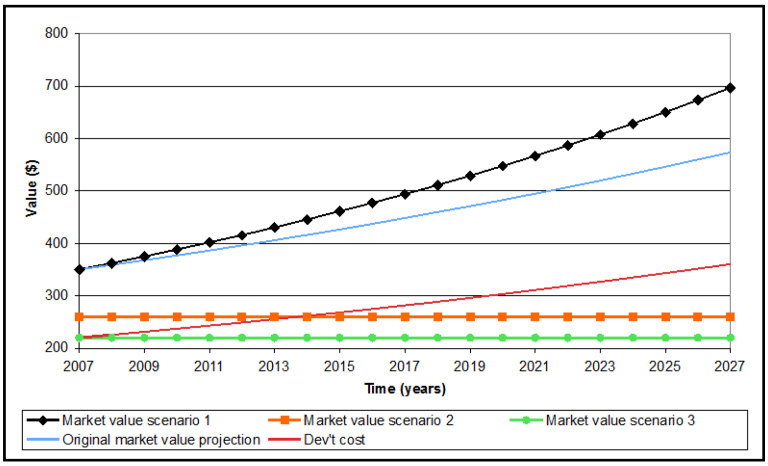


Figure 4: Selected market value scenarios for application of the aOFAT process, and creation of the design catalog. Initial projections of market value and development cost are also shown for reference.

Table 5: Initial value for the three market value scenarios. This value is used to categorize the different scenarios and classify simulated market value scenarios in step 5 of the analysis methodology.

Market Value Scenario Category	Initial Value
1	$350
2	$260
3	$220

Step 3: Identify/Generate Flexibility in System Design and Management. Generating flexibility and identifying enablers in design is a difficult process, and in fact a topic of active research (Cardin 2013; Michel-Alexandre Cardin et al. 2012). Every system is different, and faces different uncertainty sources. Flexibility/real option strategies must be carefully chosen to deal with these uncertainties, and enabled in the engineering design at the conceptual phase. The following sources of flexibility are incorporated in the model to benefit from upside opportunities in uncertain market value of built property, which is best captured by scenario 1 in Figure 4 (i.e. high growth). Flexibility is also acquired to guard against potential losses when market value is unfavorable, which is best captured by scenario 3.

4.2.1 Real Option "In" Design

The first source of flexibility to acquire "in" the design is to develop a park with the initial phase to attract more buyers and increase market value of the development site. Since the park is built all at once instead of in sync with the five phases, it is similar to a call option. The strike price of $1M is paid to exercise the option (i.e. developing the park), and a percentage increase in value above simulated market value is provided as the benefit of exercising the option. Here, 10% increase above simulated market value is suggested for demonstration purposes. A more thorough market study can help crystalize this parameter. This increase in market value, however, occurs only when the market value of built property is on the rise, or growing from the previous year. This reflects the fact that buyers may not necessarily be willing to pay more for this extra feature if the market is depressed and prices are low anyway. Hence, when market value is depressed, this extra feature provides no additional benefit. On the other hand, this flexibility contributes in increasing NPV in subsequent years when markets go well.

4.2.2 Real Option "In" Operations

This strategy exploits the flexibility to expand the different phases of the project at strategic times. It recognizes program managers' ability to wait until market conditions are favorable for a subsequent phase. The criteria for deciding on expansion to a subsequent phase is based on market value of built property being greater than a certain threshold percentage above development costs at a given time. Decision to develop at time T results in construction costs being incurred at T, and the phase being completed at $T + 2$ years. Since development is broken down according to the timing of the different phases, there are no economies of scale, and therefore no construction cost reduction associated with this flexible case.

4.2.3 Real Option "On" Project

The third source of flexibility is to abandon the project and sell undeveloped land at the end of the 20-year lifecycle, or if profit generated by selling the land is higher than profit made by developing it. This case assumes a starting price of undeveloped land of $3M that evolves at the same rate as market value of built property, and no rezoning cost.

4.2.4 Modifying the Basic Model to Incorporate Flexibility

The decision rules associated with the first real option strategy consists of building the park upfront in phase I for $1M along with a 10% increase in market value over simulated market value when market value is on the rise from the previous year. The second possibility is to build the park in phases I and II for $500,000 in both phases, together with a 5% increase in market value when market value is on the rise from the previous year. The third possibility is to build the park across all phases I to V with no increase in market value.

The second set of decision rules exploits the ability to expand in phases at strategic times. Program managers may decide to wait for the next phase development until market value of built property attains a certain percentage over development costs. The following three percentage criteria over development cost are suggested for deciding to expand: 10%, 50%, and 100%. For example, if at a given time development cost for a phase is $10M and a 10% percentage criterion is selected, market value of built property needs to be at least $11M for development to occur. Merely being above $10M is not sufficient.

The third real option to abandon development and sell remaining land is exploited through three different decision rules. Rule 1 is based on a decision to abandon if development profit is lower than abandonment profit, development value is above the percentage criteria for expansion, and at least one phase is built (because payment is made to acquire the land only when phase I is launched). If developers do not acquire the land, they cannot abandon it and get sales value from it, which is the reason motivating the last criterion. Rule 2 is based on having development profit lower than abandonment profit without the need to fulfill the percentage criteria for expansion. It is expected that abandonment will occur more frequently with this decision rule. Rule 3 does not allow abandonment and selling land throughout years 0 to 19. These are only allowed in the final year and for land remaining from undeveloped phase(s).

Many combinations of decision rules, design, and development variables exist to enable and manage the flexibility, each leading to a different operating plan. It is not clear what combination or operating plan gives better lifecycle improvement compared to the baseline design. Furthermore, one operating plan may be well suited for a particular price scenario, but not necessarily for another. It is better to adapt the operating plans depending on the uncertainty outcome. Figure 5 summarizes the variables and decision rules, also referred as factors. A level refers to the value a decision rule and/or design variable can take. Here, there are $3^3 = 27$ possible operating plans. This design space is not particularly complex, but is useful as a demonstration example. The analysis in Cardin (2007) shows that the method can scale up to a more complex design space, if needed.

		Levels		
DEs and Management DRs	**Description**	**-**	**o**	**+**
A	Abandonment option	Rule 1	Rule 2	Rule 3
B	Value over cost criterion for expanding	10%	50%	100%
C	Number of phases for developing the park	1	2	5

Figure 5: Design elements and management decision rules for the creation of the catalog of operating plans in the real estate development project. DE: design element, DR: decision rule.

Step 4: Construct the Design Catalog. aOFAT is used to accelerate the search process for the design catalog. It is used to explore the combination of design elements and management decision rules producing the highest NPV for all three market value scenarios introduced in Figure 4. Demonstration of the search process is shown only for the first market value scenario, which gives rise to the first operating plan in the catalog. The remainder of the analysis is shown in (Cardin 2007). As suggested by Frey and Wang (2006), the baseline experiment and the aOFAT sequence are determined randomly for each market value scenario, and those for scenario 1 are shown in Table 6.

Table 6: Baseline experiment and aOFAT sequence used to explore the combinatorial space for market value scenario 1.

DEs and Management DRs	Description	Baseline Experiment	OFAT Sequence
A	Abandonment option	Rule 2	A
B	Value over cost criterion for expanding	10%	C
C	Number of phases for developing the park	5	B

aOFAT is applied as shown in Figure 6. The baseline experiment is used first to produce NPV = $5.5M. Factor A level is then changed from abandonment Rule 2 to Rule 1, and no change in NPV is observed, so the change is not kept. The level is changed again from abandonment Rule 2 to Rule 3, again with no change. This process is applied by going through all factors in the sequence determined randomly, so that each level is explored at least once. One notices that changing the number of phases for developing the park from 5 to 1 at experiment 4 produces NPV = $17.5M, which is the only change observed for this operating plan. Only 7 evaluations were needed to construct the operating plan, as opposed to a full exhaustive search of the 27 possible combinations. This represents only 26% of the design space, a considerable economy in terms of analysis.

Experiment	DE and Management DR changed	Level changed to:	Output = NPV	Best output before step	Keep change?
1 (baseline)			$ 5.5		
2	A	Rule 1	$ 5.5	$ 5.5	No
3	A	Rule 3	$ 5.5	$ 5.5	No
4	C	1	$ 17.5	$ 5.5	Yes
5	C	2	$ 11.5	$ 17.5	No
6	B	50%	$ 17.5	$ 17.5	No
7	B	100%	$ - 7.7	$ 17.5	No

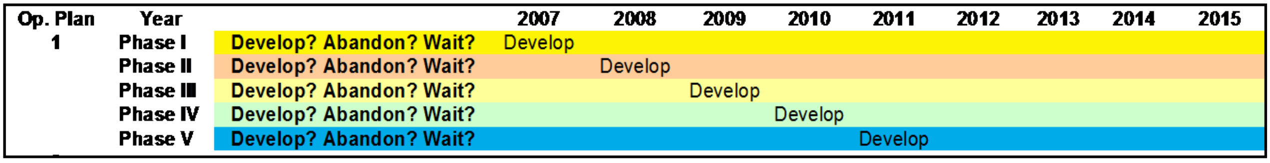
Figure 6: The aOFAT process exploring the combinatorial space for the best combinations of levels under market value scenario 1.

The resulting operating plan for market value scenario 1 is shown in Table 7 a). In Table 7 b), the operating plan is accompanied by a development plan to form a complete operating plan. This demonstrates another way to conceive of an operating plan, which in is a combination of design and management decision rules accompanied by a development plan.

Table 7: Best operating plan selected for scenario 1. Here, expansion occurs in a row starting in the first year. Decision rules (a) are associated with a development plan (b) to form a complete operating plan.

DEs and Management DRs	Description	Best Operating Plan for Scenario 1
A	Abandonment option	Rule 2
B	Value over cost criterion for expanding	10.00%
C	Number of phases for developing the park	1

(a)



Op. Plan	Year		2007	2008	2009	2010	2011	2012	2013	2014	2015
1	Phase I	Develop? Abandon? Wait?	Develop								
	Phase II	Develop? Abandon? Wait?		Develop							
	Phase III	Develop? Abandon? Wait?			Develop						
	Phase IV	Develop? Abandon? Wait?				Develop					
	Phase V	Develop? Abandon? Wait?					Develop				

(b)

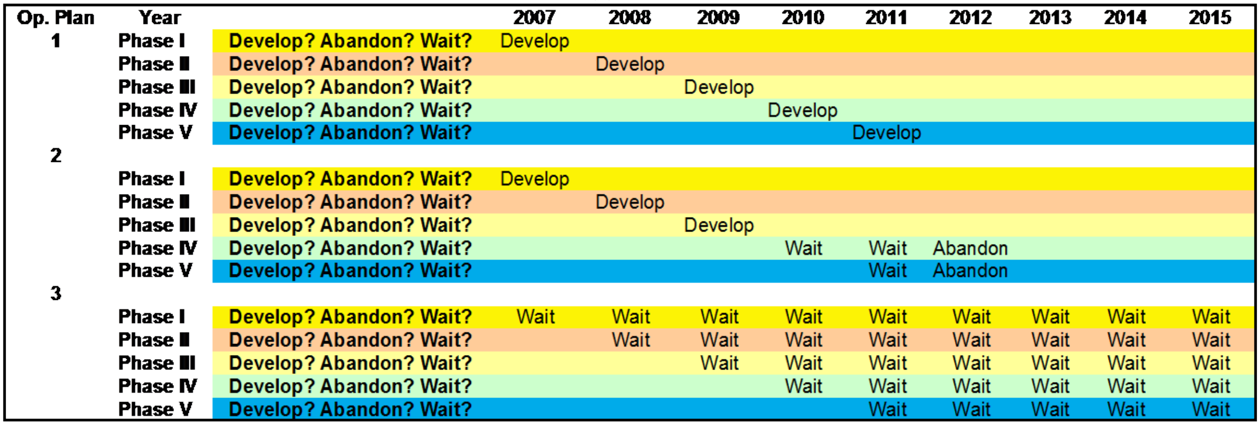
The same search algorithm is applied to the two remaining market value scenarios so that a catalog of three operating plans is created, and shown in Table 8. The operating plans are not the only ones possible. They have emerged from the assumptions made about market value scenarios, and the combination of real option and decision rules explored here. The latter were suggested from interactions with experts at the MIT Center for

Real Estate, and represent existing practices in the industry. The first operating plan suggest to develop all phases in a row to take advantage of rising market value. Operating plan 2 suggests developing phases I-III while market value is on the rise, but wait to see whether further development is needed. Assuming phases IV-V are not developed, this plan assumes that land will be sold in the last year. Operating plan 3 suggests to wait and not develop since market value is too low.

Table 8: Design catalog obtained from the analysis of three market value scenarios. Decision rules for each operating plan (a) are associated with a development plan (b) to form a complete operating plan.

DEs and Management DRs	Description	Op. Plan 1	Op. Plan 2	Op. Plan 3
A	Abandonment option	Rule 2	Rule 2	Rule 2
B	Value over cost criterion for expanding	10%	10%	10%
C	Number of phases for developing the park	1	5	5

(a)



Op. Plan	Year		2007	2008	2009	2010	2011	2012	2013	2014	2015
1	Phase I	Develop? Abandon? Wait?	Develop								
	Phase II	Develop? Abandon? Wait?		Develop							
	Phase III	Develop? Abandon? Wait?			Develop						
	Phase IV	Develop? Abandon? Wait?				Develop					
	Phase V	Develop? Abandon? Wait?					Develop				
2											
	Phase I	Develop? Abandon? Wait?	Develop								
	Phase II	Develop? Abandon? Wait?		Develop							
	Phase III	Develop? Abandon? Wait?			Develop						
	Phase IV	Develop? Abandon? Wait?				Wait	Wait	Abandon			
	Phase V	Develop? Abandon? Wait?					Wait	Abandon			
3											
	Phase I	Develop? Abandon? Wait?	Wait	Wait	Wait	Wait	Wait	Wait	Wait	Wait	Wait
	Phase II	Develop? Abandon? Wait?		Wait	Wait	Wait	Wait	Wait	Wait	Wait	Wait
	Phase III	Develop? Abandon? Wait?			Wait	Wait	Wait	Wait	Wait	Wait	Wait
	Phase IV	Develop? Abandon? Wait?				Wait	Wait	Wait	Wait	Wait	Wait
	Phase V	Develop? Abandon? Wait?					Wait	Wait	Wait	Wait	Wait

(b)

Step 5: Evaluate the Lifecycle Performance of the Catalog. The design catalog is tested under a set of 2,000 Monte Carlo simulations of market value of built property, using the stochastic model described in step 2. It is compared to the inflexible baseline case where all phases are developed in a row, with the park developed in sync with the five phases. This development strategy is the one producing the highest NPV based on assumptions about market value and development cost.

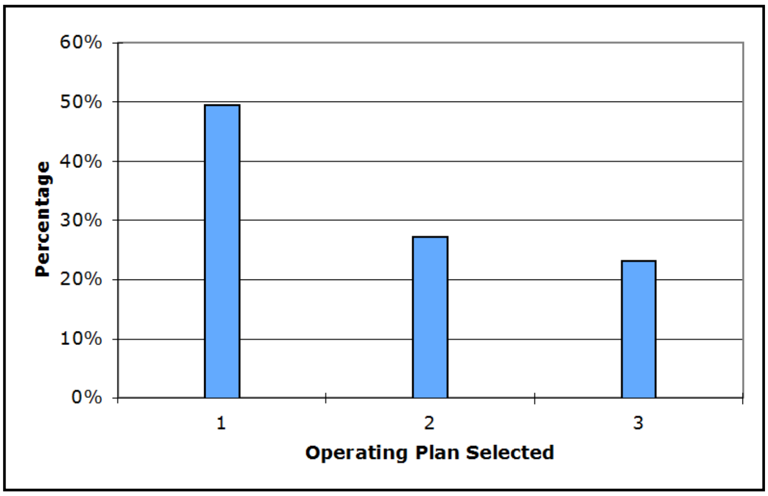


Figure 7: Percentage of simulated demand scenarios categorized as one of the three operating plans for the 2,000 scenario simulations. Each simulation is associated to one operating plan.

Each of the 2,000 simulations is categorized as one of the three market value scenarios shown in Figure 4, and associated to the corresponding operating plan. The criterion for classifying simulated market value patterns used for demonstration is the initial value – of course others can be used. Looking at Table 5 for instance, a market value pattern with initial value beyond $350/SF will be associated to operating plan 1. A pattern with an initial value between $260/SF and $350/SF is associated with operating plan 2, and below $260 is associated to operating plan 3. Figure 7 above shows how many simulated market value scenarios are classified in each of the three categories.

Table 9 summarizes the simulation results. Cumulative distribution function (CDF) or Value At Risk and Gain (VARG) curves are shown in Figure 8. Recognizing uncertainty and developing all phases in a row with no flexibility provides $ENPV_{Inflexible}$ = $3.3M. A flexible design using the design catalog approach generates an $ENPV_{Flexible}$ = $16.9M. The expected value increase provided by the real options and recognized via the design catalog approach is calculated as $E[V_{Flexibility}] = ENPV_{Flexible} - ENPV_{Inflexible}$ = $13.6M. The design catalog approach reduces the expected initial investment by approximately $5.9M, increases the minimum NPV by about $33.7M, and maximum NPV by $12.1M compared to the baseline. Both upsides and downsides for this real estate project are improved by introducing flexibility and the design catalog approach. As seen in Figure 8, both worst and best possible outcomes are improved, and the net effect is to shift the entire distribution towards better expected economic performance.

Table 9: Summary of results comparing valuation attributes between an inflexible real estate development project with all phases developed in a row, and a flexible design with the design catalog approach. In the latter case, each of the 2,000 simulations are assigned one of the three operating plans. All values are in $millions.

	Inflexible Design	Flexible Design with Catalog of Operating Plans	Which is Better?
Initial investment	$ 27.3	$ 21.4	Flex. and Catalog Better
Expected NPV	$ 3.3	$ 16.9	Flex. and Catalog Better
Minimum NPV	$ -59.2	$ -25.5	Flex. and Catalog Better
Maximum NPV	$ 77.9	$ 90.0	Flex. and Catalog Better
Value of Flexibility	$ 0.0	$ 13.6	

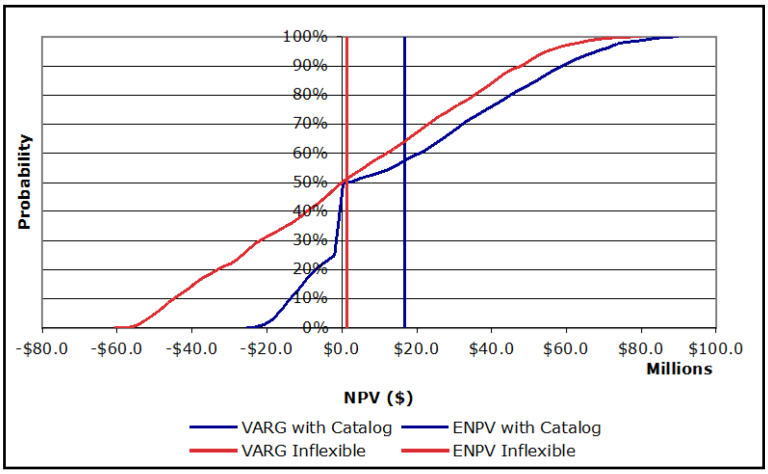


Figure 8: VARG curves and ENPVs resulting from Monte Carlo simulations for both the inflexible development project with all phases in a row, and using the design catalog approach with flexibility.

5 Discussion

The analysis above has two important benefits, observed in the example application. First, it improves the expected lifecycle performance of the real estate project compared to the baseline plan obtained via standard practice, by explicitly considering uncertainty in the early conceptual phase. It recognizes in the design and planning process that developers can adapt intelligently to different market conditions. This flexibility has value that needs to be considered explicitly in early design phases, and embedded physically in the design and development plan. Otherwise, alternatives offering less performance may be selected and implemented.

Three real option strategies brought significant value improvement in this case, in line with the results reported in the literature (Trigeorgis 1996; de Neufville and Scholtes 2011; Nembhard and Aktan 2010). Here, value improvements stems mainly from the ability to reduce downside losses when market conditions are not favorable, by stopping short the development phases, and deferring additional costs to later in the future.

Flexibility also positions the system to capture some upside conditions, by allowing all phases to be deployed at once if warranted by high price scenarios, and capitalizing on the market opportunity provided by the park.

These strategies are suited for different risk profiles, as measured by the different NPV metrics (e.g. maximum, minimum, expected initial investment). The analysis here only considers a few real option strategies, but more exist in real estate projects in general (e.g. switch product input/outputs to suit different markets at each phase, expand capacity within any given phase, etc.). This observation suggests that there might be even more value available from flexibility in design and real options thinking. Also, while the strategies are effective for this example project, analysis must be done on a case-by-case basis, because every system is different, and different real option strategies might have different effects depending on the uncertainty sources.

The design catalog technique reduces the number of alternatives to explore, thus addressing the computational issue highlighted in the introduction. Only seven iterations were necessary for each scenario to construct the catalog (i.e. about 26% of the full design space). This contrasts favorably to an exhaustive search requiring the analysis of 27 combinations in this particular example. This implies significant savings in terms of time and resources if a more detailed model is used, requiring more computational power. The analysis presented here is well suited for computational power that is available today. Furthermore, it can be tailored to the project under analysis, considering more or less scenarios and operating plans depending on available analytical resources.

5.1 Limitations and Results Validity

The cause and effect relationships reported here depend evidently on the modeling assumptions. Different values for the design variables, parameters, and decision rules may lead to different conclusions. The results are nonetheless valid and reliable in this case study because the same set of assumptions was used to analyze each scenario and design alternative.

One can assume that application of the design catalog method can be extended to other systems within and beyond the real estate sector. There was nothing particular about real estate in this particular approach, nor this particular real estate example. The catalog technique was used to analyze flexibility in parking infrastructures (Cardin 2007), and in mining operations (Cardin et al. 2008), leading to similar results and conclusions. Although current applications support the claim of generalizability, more applications are needed for further validation.

Another issue is that the set of representative market value scenarios in step 2 was chosen based on the authors' inputs. There was nothing special about this particular set. Others could have been chosen, leading to different operating plans, catalog, and results. There is a need for more research to find a better approach to generating this representative set, to determine useful criteria for terminating the search, and choosing the right number of scenarios. The work done in probability elicitation techniques (Brown 1968; Morgan and Henrion 1990; Clemen and Winkler 1999) represents an interesting area for further exploration.

As mentioned above, only three real option strategies were explored in this study, but more exist. Future work can extend this analysis by considering more possibilities. Also, more work is needed to understand the benefits as compared to full factorial analysis, and other optimizations techniques to explore the design space for each representative scenario.

Lastly, there is no guarantee that the optimal catalog can be found using the aOFAT technique. As mentioned by Frey and Wang (2006) for a system with n factors of 2-levels, the response can reach up to 80% on average of the optimal solution. This conclusion may not directly apply here since more levels for each factor were explored. On the other hand, the 412%[b] improvement in expected lifecycle performance shows that, as compared to a baseline design, the approach is worthwhile for real estate developers having limited time and computational resources. It produces a good enough solution, and does not require significant analytical and computational resources.

6 Conclusions

This paper presented a methodology to improve current design and evaluation practice in the real estate sector, which often relies on simplifying assumptions regarding the main uncertainty drivers affecting economic performance. The proposed approach relies on a set of representative uncertainty scenarios, constructions of a

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[b] Calculated as $(ENPV_{Flexible} - ENPV_{Inflexible})/ENPV_{Inflexible}$ = (\$16.9M – \$3.3M)/\$3.3M = 412%

design catalog, and notions of real options and flexibility in engineering design. Each flexible operating plan is devised to provide an appropriate and flexible development plan to suit each uncertainty scenario. This recognizes intelligent managerial decisions in operations and development available to developers, stemming from the flexibility embedded early on in the system.

The catalog approach was applied to the analysis of an example real estate project. Considerations of flexibility in the early design showed up to 412% improvements in expected lifecycle performance, as compared to the baseline design capturing standard design and evaluation practice. The analysis required exploring about 26% of the full design space, representing significant economies in terms of time and analytical resources.

More work is needed to fully validate the approach across a broader range of industry applications, and within the real estate sector. More efforts are needed to develop better approaches for selecting the representative set of uncertainty scenarios and real option decision rules. Similarly, computational efficiency needs to be explored more thoroughly in comparison to full factorial analysis, and other optimizations techniques.

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References

Ariizumi T (2006) Evaluation of Large Scale Industrial Development Using Real Options Analysis: A Case Study. Master of Science Thesis in Architecture, Massachusetts Institute of Technology, Cambridge, MA, United States

Bellman R (1952) On the Theory of Dynamic Programming. Paper presented at the Proceedings of the National Academy of Sciences of the United States of America, Santa Monica, CA, United States,

Brown B (1968) Delphi Process: A Methodology Used for the Elicitation of Opinions of Experts. RAND Corporation, Santa Monica, CA, United States

Cardin M-A (2007) Facing Reality: Design and Management of Flexible Engineering Systems. Master of Science Thesis in Technology and Policy, Massachusetts Institute of Technology, Cambridge, MA, United States

Cardin M-A (2013) Enabling Flexibility in Engineering Systems: A Taxonomy of Procedures and a Design Framework. Journal of Mechanical Design - Accepted Pending Revisions, 23 January 2013

Cardin M-A (2013) An Organizing Taxonomy of Procedures to Design and Manage Complex Systems for Uncertainty and Flexibility. Paper presented at the 3rd International Conference on Complex Systems Design and Management, Paris, France,

Cardin M-A, de Neufville R, Kazakidis V (2008) A Process to Improve Expected Value in Mining Operations. Mining Technology: IMM Transactions, Section A 117 (2):65-70. doi:10.1179/174328608X362631

Cardin M-A, Kolfschoten GL, de Neufville R, Frey DD, de Weck OL, Geltner DM (2012) Empirical Evaluation of Procedures to Generate Flexibility in Engineering Systems and Improve Lifecycle Performance. Research in Engineering Design, Accepted for publication on 09-28. doi:10.1007/s00163-012-0145-x

Cardin M-A, Kolfschoten GL, Frey DD, Neufville R, Weck OL, Geltner DM (2012) Empirical Evaluation of Procedures to Generate Flexibility in Engineering Systems and Improve Lifecycle Performance. Research in Engineering Design:1-19. doi:10.1007/s00163-012-0145-x

Clemen RT, Winkler RL (1999) Combining Probability Distributions From Experts in Risk Analysis. Risk Analysis 19 (2):187-203

Copeland T, Antikarov V (2003) Real Options: A Practitioner's Guide. Thomson Texere, New York, NY, United States

Cox JC, Ross SA, Rubinstein M (1979) Options Pricing: A Simplified Approach. Journal of Financial Economics 7 (3):229-263

de Neufville R, Odoni A (2003) Airport Systems: Planning, Design, and Management. McGraw-Hill Companies Inc., New York, NY, United States

de Neufville R, Scholtes S (2011) Flexibility In Engineering Design. Engineering Systems. MIT Press, Cambridge, MA, United States

Dixit AK, Pindyck RS (1994) Investment under Uncertainty. Princeton University Press, NJ, United States

ESD (2011) Engineering Systems Division Strategic Report. Massachusetts Institute of Technology, Cambridge, MA, United States

Frey DD, Wang H (2006) Adaptive One-Factor-at-a-Time Experimentation and Expected Value of Improvement. Technometrics 48 (3):418-431

Geltner D, Miller N, Clayton J, Eichholtz P (2010) Commercial Real Estate Analysis and Investments. 2nd edn. Cengage Learning Inc., United States

Gil N (2007) On the Value of Project Safeguards: Embedding Real Options in Complex Products and Systems. Research Policy 36:980-999

Guma A, Pearson J, Wittels K, de Neufville R, Geltner D (2009) Vertical Phasing as a Corporate Real Estate Strategy and Development Option. Journal of Corporate Real Estate 11 (3):144-157

Hassan R, de Neufville R, McKinnon D (2005) Value-At-Risk Analysis for Real Options in Complex Engineered Systems. Paper presented at the IEEE International Conference on Systems, Man, and Cybernetics, Hawaii, United States,

Jablonowski C, Wiboonskij-Arphakul C, Neuhold M (2008) Estimating the Cost of Errors in Estimates Used During Concept Selection. SPE Projects, Facilities, and Construction 3:1-6

Jacoby H, Loucks D (1972) The Combined Use of Optimization and Simulation Models in River Basin Planning. Water Resources Research 8 (6):1401-1414

Lin J (2009) Exploring Flexible Strategies in Engineering Systems Using Screening Models – Applications to Offshore Petroleum Projects. Doctoral Dissertation in Engineering Systems, Massachusetts Institute of Technology, Cambridge, MA, United States

Morgan MG, Henrion M (1990) Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. Cambridge University Press, United Kingdom

Nembhard HB, Aktan M (2010) Real Options in Engineering Design, Operations, and Management. Taylor and Francis, Boca Raton, FL, United States

Nembhard HB, Shi L, Aktan M (2005) A Real-Options-Based Analysis for Supply Chain Decisions. IIE Transactions 37:945-956

Olewnik A, Lewis K (2006) A Decision Support Framework for Flexible System Design. Journal of Engineering Design 17 (1):75-97

Ross A (2006) Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration. Doctoral Dissertation in Engineering Systems, Massachusetts Institute of Technology, Cambridge, MA, United States

Rothwell G (2006) A Real Options Approach to Evaluating New Nuclear Power Plants. Energy Journal 27:37-54

Steel KD (2008) Energy System Development in Africa: The Case of Grid and Off-Grid Power in Kenya. Doctoral Dissertation in Engineering Systems, Massachusetts Institute of Technology, Cambridge, MA, United States

Sterman JD (2000) Business Dynamics: Systems Thinking and Modeling for a Complex World. McGraw-Hill/Irwin, Boston, MA, United States

Tomiyama T, Gu P, Jin Y, Lutters D, Kind C, Kimura F (2009) Design Methodologies: Industrial and Educational Applications. CIRP Annals – Manufacturing Technology 58:543-565

Trigeorgis L (1996) Real Options. MIT Press, Cambridge, MA, United States

Wang T (2005) Real Options in Projects and Systems Design – Identification of Options and Solutions for Path Dependency. Doctoral Dissertation in Engineering Systems, Massachusetts Institute of Technology, Cambridge, MA, United States

Wang T, de Neufville R (2005) Real Options 'In' Projects. Paper presented at the Real Options Conference, Paris, France,

Yang Y (2009) A Screening Model to Explore Planning Decisions in Automotive Manufacturing Systems Under Demand Uncertainty. Doctoral Dissertation in Engineering Systems, Massachusetts Institute of Technology, Cambridge, MA, United States

Zhang SX, Babovic V (2012) A Real Options Approach to the Design and Architecture of Water Supply Systems Using Innovative Water Technologies Under Uncertainty. Journal of Hydrodynamics 14 (1):13-29