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Dynamic adaptive policies: a way to improve the cost–benefit performance of megaprojects?

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Abstract. Megaprojects are large, costly, complex infrastructure projects. To assess the financial viability of a megaproject, a cost–benefit analysis (CBA) is usually performed; the results depend upon the accuracy of the cost estimations and the predictive models used to forecast future demand for the use of the infrastructure. The outcomes of the models are very vulnerable to unexpected events. As a result, the CBA may become unreliable and give an unrealistic picture of the financial viability of a project. An alternative way of policy making that tries to take uncertainty into account is the dynamic adaptive policy (DAP) approach. This approach involves a systematic method for designing and implementing a policy over time that is based on a clear set of constraints and objectives and that involves monitoring the environment, gathering information, and adjusting and readjusting to new circumstances. The efficacy of this type of policy making has already been shown, but whether DAP leads to a better cost–benefit performance of megaprojects is unknown. In this paper we focus on answering two research questions: How can CBA be applied to DAP? How good is the cost–benefit performance of megaprojects when using DAP compared with the cost–benefit performance when using the static policy-making approach? In this paper a framework based on real options theory is specified, enabling a CBA to be performed on a dynamic adaptive policy. This framework is then applied to a case involving Schiphol Airport, Amsterdam, to compare the cost–benefit performance of the static policy with the cost–benefit performance using the DAP approach. For this case, the cost–benefit performance of the megaproject under the DAP approach turns out to be better compared with its performance under the static policy. This result provides a first indication that adaptive policies might be able to improve the cost–benefit performance of megaprojects.

Keywords: cost–benefit analysis, adaptive policies, airport strategic planning, uncertainty, megaprojects

1 Introduction

Over recent decades many megaprojects (large, costly, complex infrastructure projects) have been built and new ones are being planned. Some examples are the Channel Tunnel, Great Belt link, and Øresund link (Flyvbjerg et al, 2003). Megaprojects are built in order to cope with an expected demand in the future. Typically, this expected demand is forecast using

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predictive models. This demand is then used as input to predictive models that try to estimate the behavior of the system in question. Finally, the results from these system models are used in a cost–benefit analysis (CBA) to identify the best policy option for the expected future. There are many problems with this approach. The main problem concerns the reliability of the models that try to predict future demand. Future demand is inherently unpredictable. Instead of a single point estimate, estimates of multiple futures (called scenarios) are sometimes used. However, in the face of deep uncertainty about the future, one has little idea about whether the range of futures provided by the scenarios covers all, 95%, or some other percentage of the possible futures. Thus, even if we choose a policy that performs well in our scenarios, we have no idea whether or not this policy will perform well in the real future. We can only say that the policy will perform well in the future if the future turns out to resemble one of the futures we have included in our scenarios. There are also problems with the models that try to describe the behavior of very complex (transport) systems in the distant future. The behavior of the actors in the system and the resulting system outcomes are also highly uncertain, even if the demands are known precisely. This leaves us with outcomes that are highly uncertain. As a result, CBA also produces unreliable results and gives an unrealistic picture of the financial viability of the project. Often the result is huge cost overruns, overestimated benefits, and construction delays due to unexpected events, leading to even more costs (Dempsey et al, 1997; Flyvbjerg et al, 2003; Kaliba et al, 2009). Using a database from Flyvbjerg (see Flyvbjerg et al, 2003) and other sources, Cantarelli (2011) examined cost overruns for 806 transport infrastructure projects worldwide, and found that the cost overruns were 20% for road projects, 30% for bridge projects, 34% for rail projects, and 35% for tunnel projects. One of the most important reasons for the huge cost overruns is that the current, static policy-making process is not capable of designing policies that can handle complex and dynamic systems with unpredictable states in the future (de Neufville and Scholtes, 2011; Walker et al, 2001).

An alternative way of policy making under conditions of deep uncertainty is the dynamic adaptive policy (DAP) approach (Walker et al, 2001). This type of policy making tries to cope with uncertainties about the future by being able to adapt itself to the changes that occur, thus producing a robust policy [where 'robust' means that it performs well under a wide range of futures (Lempert et al, 2003)] . The efficacy of DAP has already been shown by Kwakkel et al (2012), but whether this leads to a better cost–benefit performance of megaprojects is unknown. DAP can affect the cost–benefit performance substantially, since major investments are made only if there is a high degree of certainty about the efficacy of the investment. This flexibility in implementation of an adaptive policy is usually gained by investing more money and more time in developing and implementing the policy compared with a static policy. If there is no improvement in the (long-term) cost–benefit performance of megaprojects when using an adaptive policy, then, from a financial point of view, there is no need to use this type of policy.

To investigate whether DAP improves the cost–benefit performance of megaprojects, the CBA of a static policy needs to be compared with the CBA of an adaptive policy. The difficulty is that adaptive policies have contingency plans that may be activated, which would affect the costs and benefits of the policy. To make things worse, it is unknown when, or even if, a contingency plan will be activated. To be able to compare the cost–benefit performance of both types of policy, we have to find a way to apply CBA to DAP. With this in mind, in this paper we focus on answering two research questions:

(1) How can CBA be applied to DAP?

(2) How good is the cost–benefit performance of megaprojects when using DAP compared with the cost–benefit performance when using the static policy-making approach?

To answer these questions, we start in section 2 by developing a framework that enables us to apply CBA to DAP. In section 3 the framework is used to compare the cost–benefit performance of a static policy with that of DAP using a case study. In section 4 we discuss the results of the case study, and draw conclusions from the research.

2 Applying CBA to DAP

Before we can compare the cost–benefit performance of a static policy with that of DAP, we have to be able to apply CBA to the DAP. The problem is that the CBA method is a static method, which gives one outcome for one policy. In the case of a static policy this is no problem, since it is not able to adapt itself to a changing future. For an adaptive policy, this becomes a problem, because the final form of the policy depends on how the future evolves. This means that the final costs and benefits depend on what happens in the future. Basically, a CBA can deal with only one future at a time, while an adaptive policy tries to deal with multiple plausible futures. To understand the problem in combining the two methods, we first discuss them separately, starting with DAP.

2.1 DAP

DAPs use "a systematic method for developing and implementing a policy over time that is based on a clear set of constraints and objectives, and that involves monitoring the environment, gathering information, and adjusting and re-adjusting to new circumstances"

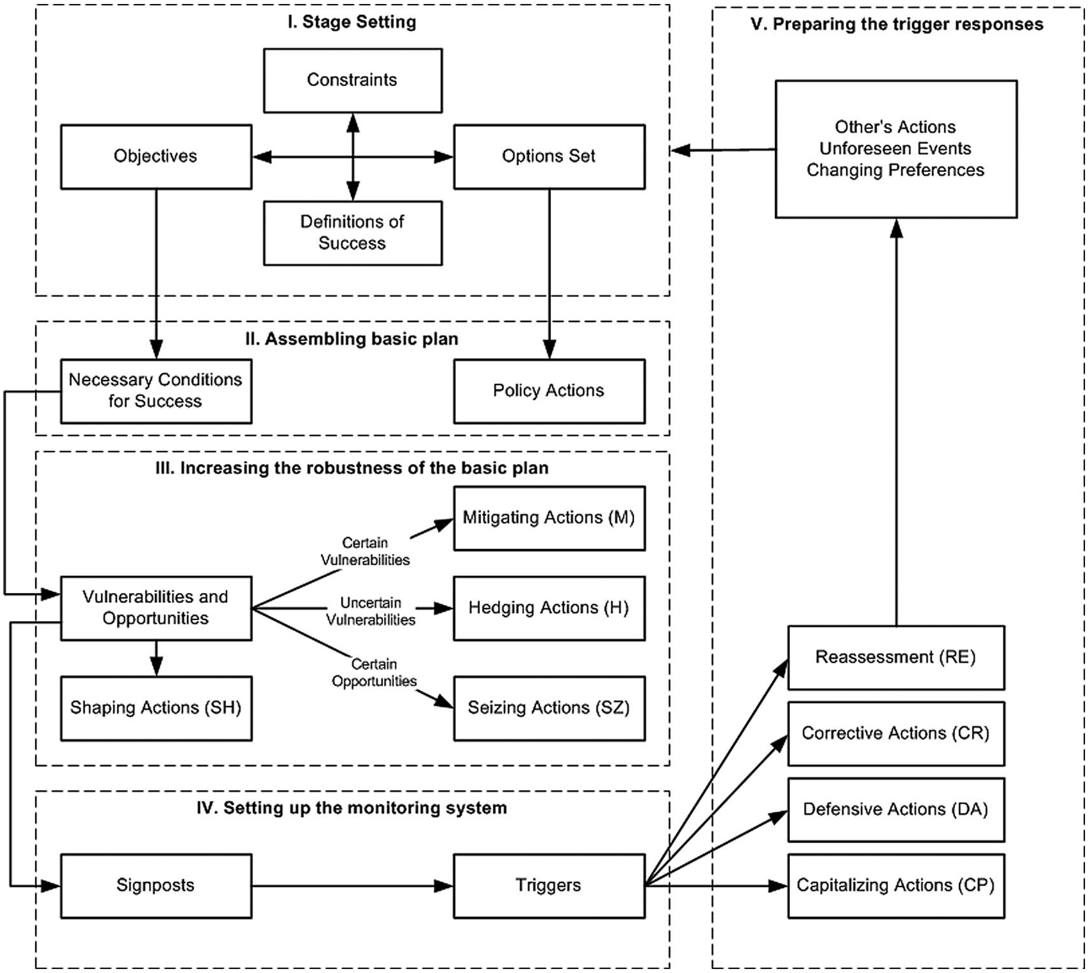

Figure 1. Steps in designing a dynamic adaptive policy (DAP) (Kwakkel et al, 2010).

(Walker et al, 2001, page 284). DAP can be divided into two phases: a policy design ('thinking') phase, and a policy implementation phase. Figure 1 presents the framework for the design phase. For a detailed description of the framework, see Kwakkel et al (2010).

The policy design phase consists of five steps—one (step I) that sets the stage for policy making, three (steps II, III, and IV) for designing the portions of the adaptive policy that get implemented initially (at time $t = 0$), and one (step V) that designs the portions of the adaptive policy that may be implemented in the future (at unspecified times $t > 0$). So, the implementation phase consists of two parts—implementation of the portions of the policy that get implemented initially (the portions that were designed in steps II–IV) and adaptation of the initial policy (taking actions that were designed in step V). But, this adaptation has already been planned for, and a monitoring system has been set up to warn of the need for adaptation.

In the first two steps a basic policy is developed. This includes the identification of the conditions needed for the basic policy to succeed. In step III the actions to be taken immediately (ie, at time $t = 0$) to enhance the chances of success of the policy are specified. This step is based on identifying in advance the vulnerabilities associated with the basic policy, and specifying actions to be taken in anticipation. Vulnerabilities are external developments that could degrade the performance of the policy so that it is no longer successful (ie, not able to meet its original objectives). In short, what we are doing is asking 'how can the basic policy fail?', and then designing ways to prevent it from failing. To protect the policy against the identified vulnerabilities, some actions (mitigating and hedging actions) are developed and implemented at the same time the basic policy is implemented (ie, at time $t = 0$). Also in this step, seizing and shaping actions are identified. Seizing actions are actions taken to change the policy in order to seize available opportunities (ie, to adapt to new favorable developments). In contrast, shaping actions are proactive and aim at changing the external situation in order to change the nature of the vulnerability or opportunity.

After designing the actions to increase the robustness of the basic policy prior to implementing the policy, there are also plans made to adapt the policy when the vulnerabilities and opportunities become reality despite the actions taken in step III (steps IV and V). These contingency plans can save the policy in the future when the conditions for success are not being met. These conditions are monitored by converting them into signposts, meaning that a condition is converted in such a way that it is possible to measure it. These signposts are connected to triggers, which are the critical levels for each signpost that trigger one or more of the stepV actions. In the implementation phase, the basic policy is implemented, together with the actions designed in step III. Also, the monitoring system is begun and information about the signposts begins to be collected. When a trigger is activated, the policy will be changed and one or more of the actions designed in step V will be activated. If none of the triggers is activated, then none of the contingency plans of step V will become active. A question that arises is how the costs and the benefits of the policy can be calculated, since the costs and benefits will look different when a contingency plan is activated from when it is not. More on the adaptive policy-making approach and its implementation can be found in Kwakkel et al (2010), Marchau et al (2008), and Walker et al (2001).

2.2 CBA

Megaprojects are built in order to cope with an expected demand in the future. This expected demand is usually forecast by predictive models and is used as input into other predictive models that try to estimate the behavior of the system in question. This set of models is used to identify the best (static) policy for the expected future(s). To assess the financial viability of a megaproject a CBA is performed; this is very much dependent on the accuracy of the predictive models that are used to forecast future demand and system behavior. The

CBA returns the net present value (NPV) of the megaproject: that is, the revenue minus the costs. The problem starts with the reliability of the models that try to estimate the behavior of very complex systems. The outcomes of these models are very vulnerable to unexpected events (Walker et al, 2001). This leaves us with outcomes that are highly uncertain and are only valid for a limited set of futures. For each future, a CBA is carried out for the chosen policy and the assumption is made that these are the only possible outcomes for this policy.

When comparing CBA with DAP, there is a fundamental difference in the underlying way of thinking about the future. Under the CBA method it is assumed that the future is more or less known, while under the DAP method the underlying idea is that what happens in the future is unknown. This difference results in a DAP method that is flexible and tries to adapt to changes in its environment, while the CBA method is static and deals only with the future that has been predicted. In order to overcome this difference, and to combine both methods, the following two questions need to be answered:

- How does one include contingency plans in a CBA (since it is unclear if and when they will be used and how much their use will cost)?
- How can a reassessment of the plan (in step V) be monetized?

To deal with these problems, a concept from financial markets (called 'real options') is used in combination with the CBA method.

2.3 Applying CBA to DAP

To be able to apply CBA to DAP, we use 'real options'. Real options are based on the concept of financial options, which are contracts that give a buyer the right, but not the obligation, to buy or sell an underlying asset (for instance shares of stock) for a certain price within a certain time span (de Neufville, 2000; de Neufville and Scholtes, 2011). Real options have the same characteristics as financial options. The difference is that real options are focused upon physical objects instead of financial products (Luehrman, 1998). For instance, real options could be used to create an option to expand an infrastructure project. Especially useful in this concept is the time aspect that is embedded in the option, since it enables us to include contingency plans that can be used only within a certain time frame, or may not be used at all. The idea of using options not only in financial markets, but also for other types of investments, has been mentioned in other studies (de Neufville, 2000; Luehrman, 1998). What has not yet been considered, as far as we know, is the use of real options to link adaptive policies to CBA. To do so, we developed a framework that is based on the idea of converting an investment into an option. The type of option we use is the American option, a type of option that can be sold or bought until the expiration date has passed. (In contrast, a European option can be bought or sold only on the expiration date itself.) In figure 2 a call option (a right but not an obligation) is converted into a CBA–DAP option, which can be used to link adaptive policies with CBA.

As can be seen from figure 2, the stock price for a call option has been replaced by the benefits of the contingency plan, and the exercise price has been replaced by the costs of the contingency plan. The variables VB and VC (see figure 2) indicate the possible variance in the predetermined costs and benefits of the contingency plan.

In subsection 2.1, the DAP framework was presented. Now we go through the steps of the framework to show how a CBA can be performed on an adaptive policy using real options (this is the CBA–DAP option shown in figure 2). The two phases described below correspond to the two levels of analysis shown in figure 3.

2.3.1 *Phase 1: construct a traditional CBA for steps I to IV*

In this phase a CBA is constructed for steps I to IV of the DAP framework (see subsection 2.1). In steps I and II of the DAP framework, the basic policy is chosen and constructed. In these two steps a prediction is made about the costs and the benefits of the basic policy, which will

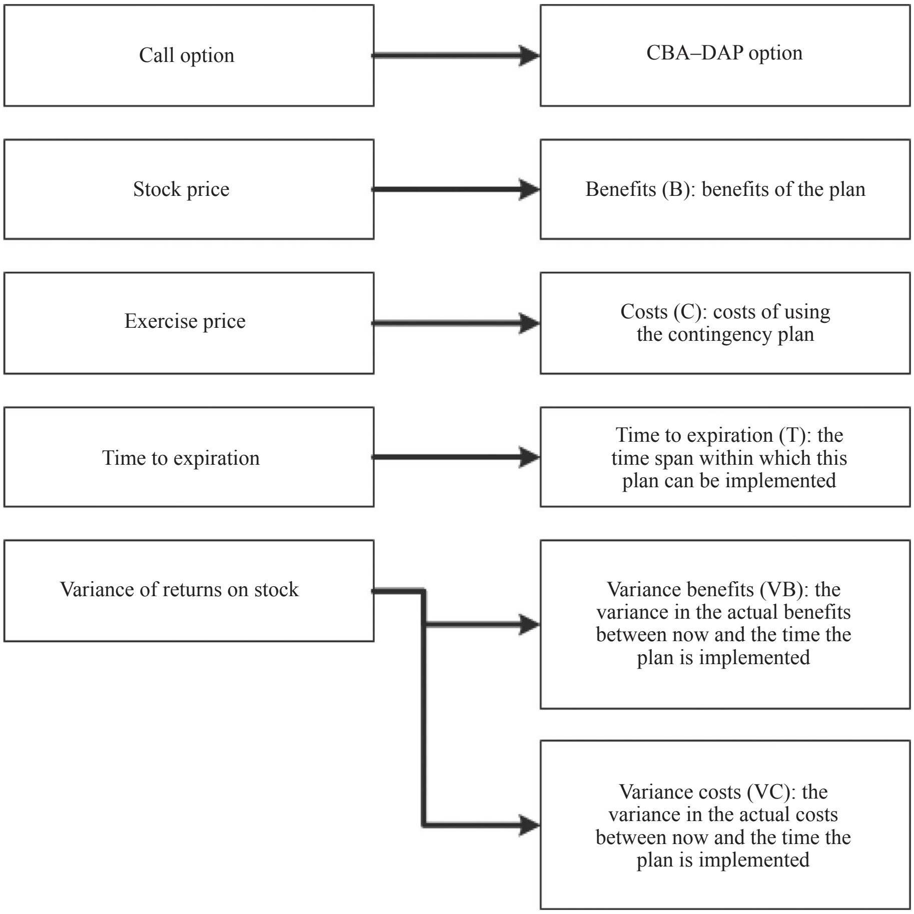

Figure 2. Converting a call option into a cost–benefit analysis–dynamic adaptive policy (CBA–DAP) option [call option scheme adopted from Luehrman (1998)].

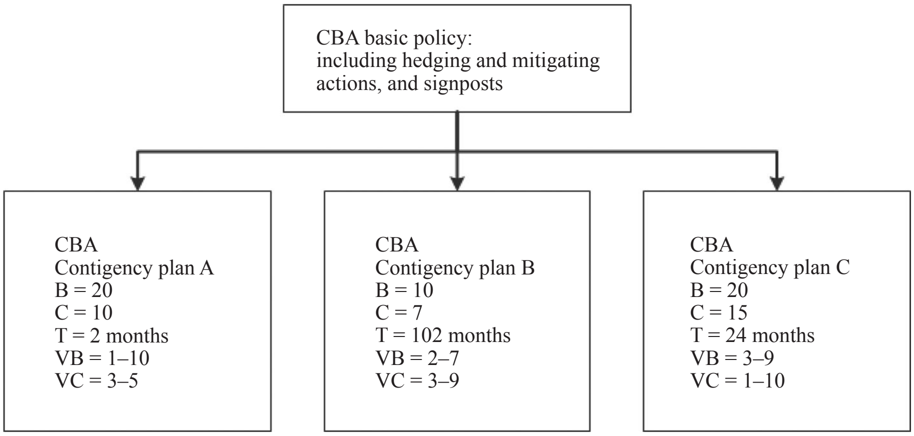

Figure 3. Example of adaptive cost–benefit analysis (CBA) framework. The definitions of the variables are given in figure 2. Numerical values are shown for illustrative purposes only.

be included in the CBA. In step III the policy is made more robust by adding mitigating, hedging, seizing, and shaping actions. Since these actions are taken at the same time as the basic policy is implemented, they will be included in the CBA for the basic policy. In step IV signposts and triggers are defined for the contingency plans. Signposts are used to monitor information in order to determine whether a trigger should be activated. A trigger is the critical value of the variable being monitored that will lead to the activation of a contingency plan. Monitoring information costs a certain amount of money, which will be included in the CBA. Finally, the NPV of the basic policy will be calculated by subtracting the estimated costs from the estimated benefits.

2.3.2 *Phase 2: create CBAs for the different contingency plans*

In this phase, a CBA is constructed for step V of the DAP framework, which is the construction of different contingency plans. The CBA for step V consists of estimating the costs for the different contingency plans using the CBA–DAP option shown in figure 2.

Carrying out both phase 1 and phase 2 produces the framework shown in figure 3. Here we made a CBA framework of a fictitious case. We start with the CBA of the basic policy from phase 1. Below this, the different CBAs of the contingency plans are represented. These CBAs indicate what the costs and benefits of the contingency plans would be if they were activated. Furthermore, it is indicated when each plan will expire and what the variance is of the costs and benefits.

This framework enables us to perform CBAs on adaptive policies. But, there is one remaining problem: how to estimate the costs and benefits of the reassessment of an adaptive policy. In the case when a whole policy fails, a reassessment is activated. This means that with the knowledge of how and why the current policy failed, a new adaptive policy will be created, possibly containing some useful elements of the failed policy. It could be that a whole new policy is being created, using a whole new analysis, but using the knowledge gained by the failure of the previous policy. To incorporate this into the CBA, we have made the conservative assumption that all investments are lost if a reassessment is triggered.

3 Schiphol Airport case study

To gain insight into whether DAP can indeed improve the cost–benefit performance of megaprojects, we performed a single in-depth case study. The idea is that, through the case study, a better understanding can be developed about the way adaptive policies might be able to improve the cost–benefit performance of a megaproject. The case is adapted from work by Kwakkel et al (2012), who compares a static and an adaptive policy on their performance, but not on their costs and benefits. The case focuses on long-term strategic planning for Schiphol Airport. We focus in particular on the economic efficacy of the two types of policies (static and adaptive), which is a critical performance measure from a business point of view.

3.1 Background

Aviation demand continues to grow, due to economic growth, privatization, and liberalization (Kwakkel et al. 2010). In the next twenty years it is expected that aviation will grow even further, though at a slower pace (FAA, 2010). For Schiphol, the largest airport in the Netherlands, this means that the operators will have to think of ways to defend Schiphol's position as one of the major airports in Europe. In 2006 Schiphol lost its fourth-place ranking to Madrid's Barajas Airport in terms of aircraft movements (Kwakkel et al, 2010). Schiphol is a hub airport, which means that it is dependent on developments in aviation at an international level. Also, Schiphol is important for the Dutch economy, making this issue also very relevant for the Dutch government (Rijksoverheid, 2009). For Schiphol to be able to defend its position and deal with this increase in flight operations its capacity must be expanded to enable a higher rate of incoming and outgoing flights to be processed.

In doing this, the airport operators face two problems (Schiphol Group, 2007; V and W, and VROM, 2007). First, it is uncertain whether Schiphol will benefit from the growth in aviation. This is due to the fact that the hub position of Schiphol is dependent on factors that are beyond its operators' control (eg, network decisions by major airlines). It is therefore important that Schiphol is able to maintain its competitive position by providing high-quality services (eg, short waiting times and easy transfers). Second, the available space in the Netherlands is very limited, and the operators of Schiphol are in a constant struggle to retain land for possible future growth. Furthermore, there are environmental issues (CO_2 and noise hindrance), which are increasingly problematic. Apart from these problems, the airport operator might want to improve the capacity of the airport in such a way that there is a better balance between supply and demand. Constraints on policy options are, for instance, safety, costs, environmental restrictions, and public acceptance.

3.2 The static and adaptive policies

In order to defend Schiphol's current position, a number of stakeholders are drafting a plan for the long-term development of Schiphol (Kwakkel et al, 2010). Their main goals are: (1) to create room for the further development of the network of Air France–KLM and its Skyteam partners, and (2) to minimize (and, where possible, reduce) the negative effects of aviation in the region. There are several types of changes that are currently being considered in order to achieve these goals. The physical capacity can be expanded by using the existing runways and terminals more efficiently and/or building new capacity. More explicitly, among the options being considered are:

(1) Add a new runway parallel to one of the existing runways;
(2) Move charter operations out of Schiphol [to Lelystad and Eindhoven, which have a planned capacity of roughly 70 000 operations per year (Rijksoverheid, 2009; Schiphol Group, 2007)];
(3) Limit available (take-off and landing) slots.

For the static plan, we assume that the new runway will be constructed at Schiphol, and that this will become operational in 2020. Furthermore, up to 70 000 operations will be moved away from Schiphol over the period 2015–2020. No slot limitation will be implemented. This is essentially the plan currently under consideration (Rijksoverheid, 2009).

Table 1. Hedging and mitigating actions in the adaptive policy for Schiphol Airport (Kwakkel et al, 2010).

Vulnerabilities and opportunities	Hedging (H) and shaping (SH) actions
Demand for air transport grows faster than forecast	H: prepare Lelystad and Eindhoven airports to receive charter flights
Population density increases in the area affected by noise	H: test existing noise abatement procedures, such as the continuous-descent approach, outside the peak periods (eg, at the edges of the night) SH: maintain land-use reservation that allows for building the new runway
Noise from flights increases	SH: negotiate with air traffic control on investments in new air traffic control equipment that can enable noise-abatement procedures, such as the continuous-descent approach SH: invest in research and development, such as noise abatement procedures
Wind conditions change due to climate change	H: have plans ready to build the sixth runway quickly, but do not build it yet. If wind conditions deteriorate, start construction

Table 2. Contingency plans in the adaptive policy for Schiphol Airport (Kwakkel et al, 2010).

Vulnerabilities and opportunities	Monitoring and trigger system	Actions [reassessment (RE), corrective (CR), defensive (DA), capitalizing (CP)]
Demand for air transport grows faster than forecast	Monitor the growth of Schiphol in terms of aircraft movements. If this exceeds 450 000 operations, start building the new runway. The new runway becomes available five years after this trigger is reached. If demand exceeds 510 000 aircraft movements, activate CR action. If it exceeds 580 000, trigger RE.	CP: begin to implement the plan for the new runway CR: move up to 70 000 operations to Lelystad and Eindhoven RE: reassess entire plan
Number of people affected by noise increases	Monitor number of people affected by noise. If this increases by 20% compared with start year, take DA action; by 50%, take CR action; by 75%, take RE action. If area decreases by 20%, take CP action.	DA: slow down of growth by limiting available slots CR: slow down of growth by limiting available slots even more RE: reassess entire plan CP: make new slots available
Wind conditions change due to climate change	Monitor the usage percentage of the cross-wind runway, If this increases by more than 10% compared with the start year, take DA action.	DA: Begin to implement the plan for the new runway. If this action is taken, the new runway becomes available in five years.

The adaptive policy used in this research comes from Kwakkel et al (2010). It consists of a basic policy that includes planning for all the infrastructure options, but not starting to build any of them. The hedging and mitigating actions are presented in table 1; in table 2 the contingency plan is presented.

The costs for implementing these policies are: €950 million for the static policy and €328 million for the adaptive policy (without any contingency actions activated) (Yzer, 2011). Also, the costs per contingency action are calculated. In figure 4 the costs of both policies and the costs of the contingency actions are shown. Benefits are a function of accommodated demand and will vary from one scenario to another. Note that not all contingency actions have direct costs associated with them. These are therefore not shown in figure 4. Also note that, for this case, the costs for implementing the adaptive policy are lower than the costs for implementing the static policy. More information about the CBA module can be found in Yzer (2011).

3.3 Comparing the cost–benefit performance of the static and adaptive policies

To obtain insights into the cost–benefit performance of the static policy compared with that of the adaptive policy, we used a fast and simple model for airport performance analysis (Kwakkel and Pruyt, 2013; Kwakkel et al, 2009). This model is based on the computational core of the HARMOS decision support system for airport strategic planning (Heblij and Wijnen, 2008; Wijnen et al, 2008). This computational core is an integrated combination of established tools for calculating key airport performance metrics (capacity, noise, emissions, and external safety). The selection of tools included in the computational core is motivated by the purpose of the model: to allow for a quick scan of the performance of alternative plans. Therefore, macroscopic tools have been used (de Neufville and Odoni, 2003; Stamatopoulos et al, 2004). Table 3 specifies the tools that are used in this model. Apart from the fact that the integrated noise model (INM) has been replaced with the area equivalent method,

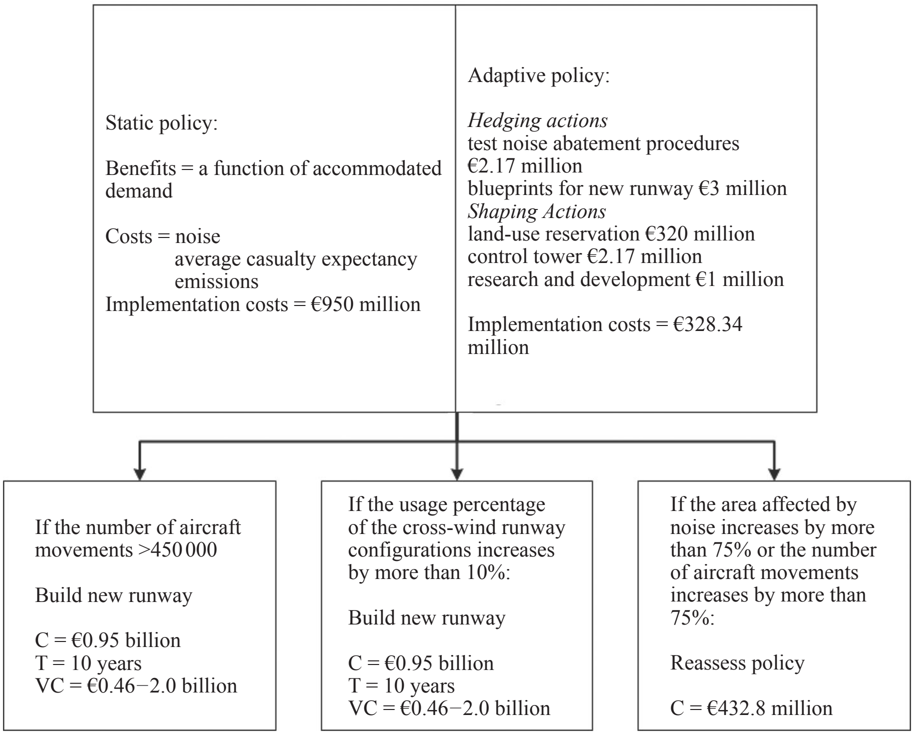

Figure 4. Cost–benefit analysis module for static and adaptive policies at Schiphol Airport. (The definitions of the variables are given in figure 2.)

which approximates INM results quickly, the tools are the same as those used in HARMOS (Wijnen et al, 2008). The model was implemented using the programming language Python. For more details on the model and its validation, see Kwakkel et al (2009).

3.3.1 *Monetizing the outcome indicators*

The existing tools integrated in the fast and simple model do not include costs. In order to compare the cost–benefit performance of a static policy and an adaptive policy, we therefore developed a CBA module that calculates the NPV. This CBA module was constructed in three steps:

(1) monetize the outcomes of the fast simple model (ie, capacity, noise, emissions, and external safety);

(2) implement the static policy (taken from the case) in the CBA module;

(3) implement the adaptive policy (taken from the case) in the CBA module.

The model estimates four outcome indicators. These are monetized as described below. [For more detailed information, see Yzer (2011).]

Capacity: The airport's capacity is calculated using the Federal Aviation Administration (FAA) airfield capacity model (de Neufville and Odoni, 2003; FAA, 1981). The capacity is based on the maximum hourly throughput capacity of the runway system, using a simplified representation of the fleet serving the airport. The fast simple model generates a flight schedule in a simulated year at the airport. In order to monetize these numbers, the income per type of plane is calculated, looking at the fee a company has to pay per aircraft. This depends on the weight of the aircraft, the noise the aircraft makes, whether or not the aircraft is connected to a terminal, the time of the day the aircraft wants to make use of the airport, and the type of aircraft (freight, passenger, mixed).

Table 3. Tools integrated in the fast and simple model.

Airport performance aspect	Tool
Capacity	Federal Aviation Administration (FAA) airfield capacity model (FCM)—an extension of the classic Blumstein model developed by the FAA (de Neufville and Odoni, 2003; FAA, 1981). It is a macroscopic tool for estimating the maximum hourly throughput capacity of different runway configurations and final approaches. It does not consider aprons, taxiways, and the terminal area airspace. Airport capacity can be estimated, given information on the usage of the different runway configurations.
Noise	Area equivalent method (AEM)—a model that approximates results of the integrated noise model (INM) (FAA, 2008). INM is the de facto standard for noise calculations in aviation. Compared with INM, AEM does not consider flight paths. Other than this, the method for calculating the size of noise contours is the same. That is, AEM uses the same algorithm and framework from the SEA AIR 1845 standard, which is based on noise–power–distance data.
Emissions	Emission dispersion modeling system (EDMS)—the FAA required tool for emission analysis (FAA, 2009). EDMS is also the de facto standard for emission modeling in aviation. EDMS consists of an emissions inventory system that calculates the sum of emissions from various sources including aircraft, auxiliary power units, and roadways.
Third-party risk	Methodology developed by the National Air Traffic Services (NATS) for third-party risk (Cowell et al, 2000). The NATS methodology has been extended to apply to multiple runways (Heblij and Wijnen, 2008). The NATS methodology calculates the probability and effect of a crash for a given location relative to a runway in light of historical data about the crash frequency for different aircraft categories and the different parts of the landing–take-off cycle.

Emissions: The following pollutants are considered: hydrocarbons (HC), carbon monoxide (CO), nitrous oxides (NO_x), sulphur dioxide (SO_2), carbon dioxide (CO_2), and nitrogen dioxide (NO_2). The model calculates the tonnes per year emitted at the airport per pollutant. Lu and Morrel (2006) show what the social costs are per type of pollution. We translated their figures for 2001 into figures for 2010, as shown in table 4. By multiplying these cost figures by the emissions, the costs of pollution per year can be calculated. More detailed information can be found in Yzer (2011).

Third-party risk: The average value of a human life in 2003 has been estimated to be around \$7 million (Viscusi and Aldy, 2003). Considering inflation and translating this into Euros, the average value of a human life is €6 million. Multiplying this by the average casualty expectancy calculated through the National Air Traffic Services (NATS) methodology (Cowell et al, 2000) in the fast simple model, gives the average expected yearly cost due to casualties.

Table 4. 2010 social costs of different pollutants (€/kg) (inflation rate of 21% for the period 2001—July 2010) (Centraal Bureau voor de Statistiek, 2011).

	HC	CO	NO_x	SO_2	CO_2	NO_2
Social cost	4.22	0.08	11.72	62.57	0.024	1.25

Noise: The noise levels around the airport are given by the fast simple model in terms of noise contours. In order to calculate the costs of noise hindrance, there are two possible methods: (1) the hedonic pricing method, which is based on the willingness-to-pay principle derived by observation (Lu and Morrel, 2006), and (2) the contingent valuation method, in which people are asked how much they are willing to pay for something (in this case a house within a certain noise contour) (Mitchell and Carson, 1989). We have chosen to use the hedonic pricing method, since this method is more fully developed and adopted by policymakers (Lu and Morrel, 2006). To use hedonic pricing for this case, the formula of Lu and Morrell (2006) has been adopted:

$$C_{\mathrm{n}} = \sum_{i} I_{\mathrm{NDI}} P_{\mathrm{v}} (N_{\mathrm{a}i} - N_0) H_i \,,$$

where C_{n} represents the costs of the noise hindrance, I_{NDI} is the noise depreciation index [the percentage reduction of house price per dB(A)], P_{V} is the annual average house rent, $(N_{\mathrm{a}i} - N_0)$ is the noise level above the ambient level, where N_0 is the background noise and $N_{\mathrm{a}i}$ is the noise contour that is being considered, and H_i is the number of residences within a certain noise contour. This formula produces the cost of noise hindrance, given a certain level of hindrance per 1 dB(A) increase. This number was derived by Lu and Morrell from several studies. See, for example, Lu and Morrell (2006).

3.3.2 *Implementing the static policy*

The static policy was implemented in a fairly straightforward way. The model uses the emission, third-party risk, and noise indicators to calculate the costs of the policy to society. Added to that are the costs for implementing the policy. The benefits of the policy are calculated based on the accommodated demand. The benefits are the income from landing fees. Finally, the costs and benefits are transformed into present values; the NPV over the thirty-year period being simulated is calculated.

3.3.3 *Implementing the adaptive policy*

Implementing the adaptive policy is more complex, since the costs for the total policy cannot be known in advance (due to the contingency plans). The model starts with the CBA of the static policy and includes the costs of the different hedging and shaping actions. After this, the model becomes ‘reactive’, in the sense that it simulates the system dynamically thirty years into the future and monitors the different signposts. If one of the signposts is triggered during the thirty years, the appropriate contingency plan is activated, and the costs of this plan are added to the total costs of the policy. At the end of the simulation, the NPV is calculated.

3.3.4 *Using exploratory modeling and analysis (EMA) to compare the cost–benefit performance of the adaptive policy and the static policy*

In order to compare the cost–benefit performance of the adaptive policy with that of the static policy, we need to compare them for a large number of different plausible futures. In order to generate these futures, we used a set of input generators. A specific combination of generator components could be called a ‘scenario generator’ (Lempert et al, 2003). This scenario generator allows for generating demand volumes, wind conditions, technological developments, and changes in demographic patterns around the airport. This approach is known as EMA. EMA is a research methodology that uses computational experiments to analyze complex and uncertain systems (Agusdinata, 2008; Bankes, 1993; Bankes et al, 2013), and multiple models that are consistent with the available information. Instead of building a single model and treating it as a reliable representation of the information, an ensemble of models is created and the implications of these models are explored. A single model run drawn from this set of models is not a prediction; rather, it provides a computational experiment that reveals how the world would behave if the assumptions that particular model makes about the various uncertainties are correct. By conducting many such computational experiments, one can explore the implications of the various assumptions. EMA offers support for exploring this set of models across the range of plausible parameter values and draws valid inferences from this exploration (Bankes et al, 2013). EMA has been used to design strategic plans under deep uncertainty for several policy domains (Gober et al, 2011; Hamarat et al, 2013; Kwakkel and Pruyt, 2013; Kwakkel et al, 2012). For our particular case, we generated 5000 computational experiments, which produced 5000 distinct thirty-year transient scenarios for, for example, demand, wind conditions, and technological developments.

3.4 Comparing the NPV of the adaptive policy with the NPV of the static policy

In order to compare the NPV of the static policy with the NPV of the adaptive policy over the 5000 experiments (transient scenarios), we generated the boxplots shown in figure 5. One can see that the bandwidth of the NPV is much larger for the static policy than for the adaptive policy. Moreover, the median value for the static policy is substantially lower than that for the adaptive policy. This indicates that the adaptive policy can cope better with different futures. The adaptive policy is able to adjust itself to different situations, leading to a smaller range (and generally higher values) of the NPV.

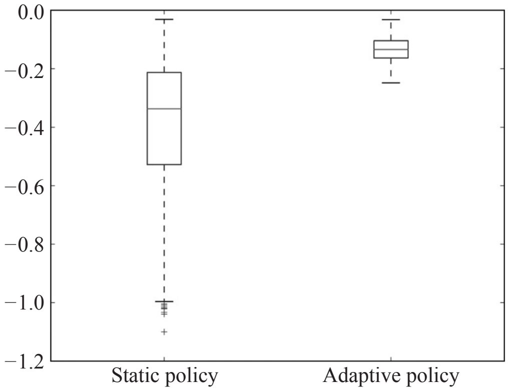

Figure 5. Boxplot of the net present value (NPV) for both policies.

We analyzed the results in more detail by looking at the difference in NPV values between the two policies for each of the 5000 cases. In particular, we examined the gain in NPV achieved by the adaptive policy. Figure 6 shows both the cumulative distribution of the gain in NPV and a Gaussian kernel density estimate (effectively, a probability density). From the cumulative distribution, we see that in 95% of the 5000 cases the adaptive policy produces a net gain in NPV. From the Gaussian kernel density estimate, we see that in most cases the gain is relatively minor (the estimate peaks at around 0.0002). Combined, these figures clearly demonstrate that the adaptive policy is, from a cost–benefit perspective, better in all but 5% of the simulated transient scenarios.

Note that in this case, we used expert judgment in determining the conditions under which the contingency actions would be activated. It is plausible to assume that by experimenting with different trigger values or more complicated triggers that look at multiple factors, the difference in performance could be made even smaller, or made to disappear entirely. One promising way of making sound choices in selecting these trigger values is through the use of robust optimization (Hamarat et al, 2013). However, our case shows that, even with relatively simple rules based on expert judgment, substantial cost–benefit improvements can be achieved by adopting an adaptive policy.

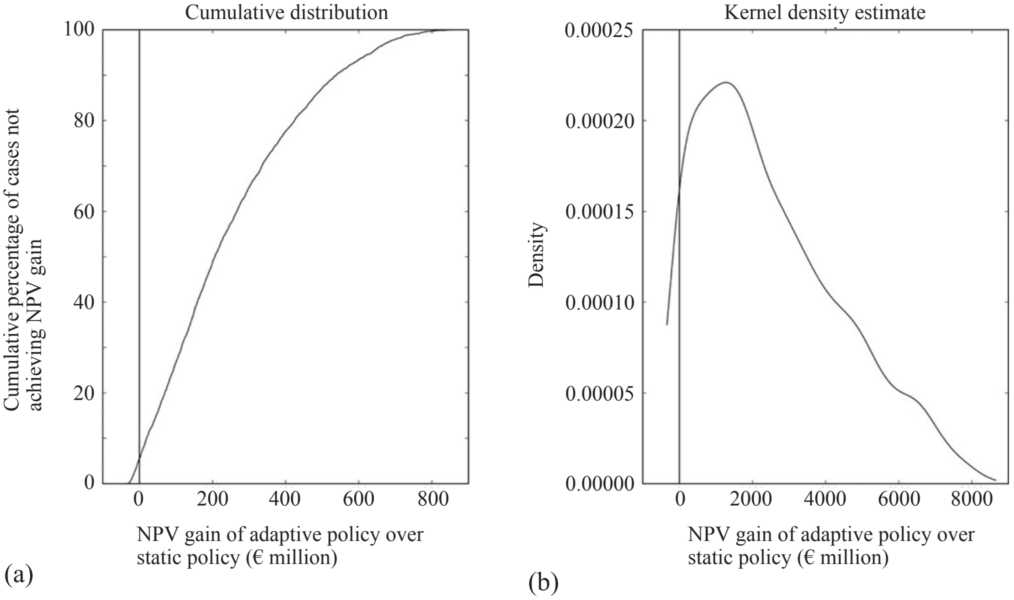

Figure 6. The cumulative distribution (a) and Gaussian kernel density (b) of the gain in net present value (NPV) of the adaptive policy over the static policy.

The next question is whether there exists a relationship between the size of the gain in NPV from the adaptive policy and the NPV of the static policy. This is a form of regret analysis (de Neufville and Scholtes, 2011). Figure 7 shows the results of this analysis. We can see that the poorer the NPV of the static policy (the ‘master plan’), the larger the gain in NPV for the adaptive policy. This is not surprising, for the adaptive policy can better accommodate the scenarios with low growth, or even shrinkage, while in those scenarios, the static policy would still build the additional runway, resulting in excess capacity. In figure 7 we also see that for the 5% of cases where the static policy has a higher NPV than the adaptive policy, the regret of using an adaptive policy is rather small. Thus, the adaptive policy is able to reduce the downside risk of the static policy substantially, without exposing itself to substantial downside risk.

Notice that the values of the NPVs in figure 7 are negative. This is because only the incoming and outgoing flights are considered, a limited list of aircraft types is used, no income per passenger is included, and other sources of income (such as the revenues of shops at Schiphol) are not included (see also Yzer, 2011). However, these caveats on the results do not invalidate the comparative results shown in figure 6 and described above.

A third important analytical question to ask is ‘what are the conditions under which we experience minor regret from adopting an adaptive policy’? That is, which combination of

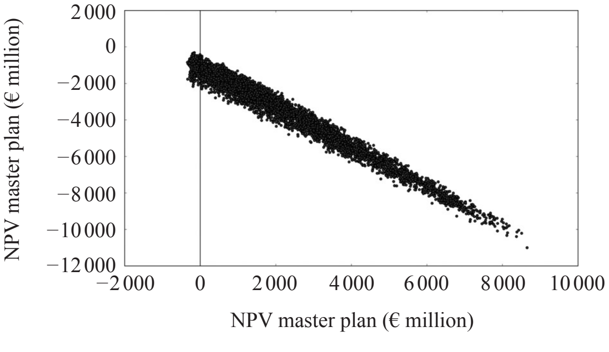

Figure 7. Regret analysis of the adaptive policy versus the static policy. NPV = net present value.

uncertain factors and their associated range is responsible for the 5% of cases in which the static policy outperforms the adaptive policy? In EMA this type of analysis is treated in detail (Bryant and Lempert, 2010; Lempert et al, 2008). The key idea is to apply a 'rule induction algorithm' to the data. The de facto standard is the patient rule induction method (PRIM) (Friedman and Fisher, 1999). PRIM can be used to find combinations of values for input variables that result in similar characteristic values for the outcome variables. Specifically, one seeks a set of subspaces of the model input space within which the values of the output variables are considerably different from their average values over the entire domain. PRIM describes these subspaces in the form of 'boxes' of the model input space. This results in a very concise representation since, typically, only a limited set of dimensions of the model input space is restricted. That is, a subspace is typically characterized by upper and/or lower limits on only a few input dimensions. In our case, the PRIM analysis shows that minor regret from adopting an adaptive policy occurs if the cost of building the new runway is very low and the runway is constructed well within schedule.

Concerning our research question "how good is the cost–benefit performance of megaprojects when using DAP compared with the cost–benefit performance when using the static policy-making approach?", we can answer this by saying that, for this specific case, DAP improves the cost–benefit performance in all but about 5% of the computational experiments. For those 5% the regret of choosing an adaptive policy is small. Moreover, we have seen that this regret occurs only if the construction of the runway can be done cheaply and on schedule. The results from this case study show that, in general, the cost–benefit performance of the adaptive policy is better than the cost–benefit performance of the static policy. Not only is the range of possible NPVs for different futures better but, in 95% of the simulated cases, the adaptive policy has a better NPV after thirty years than the static policy.

4 Conclusions

In this paper a framework was presented that applies CBA to the dynamic DAP approach. This framework uses the concept of real options. We transformed an American call option into a CBA–DAP option, enabling us to monetize the contingency plans. Concerning the reassessment part of the policy, we assumed that all investments that have been made would be lost if a reassessment is triggered. This framework was then applied to the case of strategic planning for Schiphol. By using an existing fast simple model in combination with EMA, static and dynamic policies for 5000 different futures for the Schiphol case could be simulated over a period of thirty years. From our case study we found that, for 95% of the simulated futures, the NPV of the adaptive policy was better than the NPV of the static policy.

This research gives some initial insights into the cost–benefit performance of DAP. But some limitations need to be pointed out. These can be divided into limitations of the methodology and limitations in the generalization of the results. With respect to methodological limitations, it should be noted that we did not include the incomes gained per passenger or for freight. One of the consequences is that our NPVs are negative and do not give a realistic and complete view of the actual situation [for example, in 2009 Schiphol actually gained net sales of €1.2 billion (Schiphol Group, 2010)]. Related, to this point, we looked only at the costs and benefits to Schiphol. If operations were to be moved to another airport, there would be other costs and benefits to other parties. These are not accounted for. However, as our interest involves the difference in cost-benefit performance between the adaptive policy and the static policy for Schiphol, these costs and benefits will not affect our conclusions.

A second limitation concerning our CBA for the DAP approach is that we assumed that in case of a reassessment all investment costs already made would be lost. However, an alternative seems more promising—extending DAP by adding the concept of 'adaptation pathways' (Haasnoot et al, 2011; 2012) to the conceptual framework. The analysis of adaptation pathways includes an evaluation of the different adaptation options available if a contingency plan fails. Furthermore, the adaptive pathway decided upon can be updated over time to remain relevant for the situation at that time. One could say that an adaptive pathway consists of contingency plans for contingency plans. That is, when a contingency plan fails, a new contingency plan is activated to adjust the strategy. A way of combining this concept with DAP is to develop different options for when an adaptive policy needs to be reassessed. Which option is activated depends on the reason why the policy failed. Using adaptation pathways could make the CBA of an adaptive policy clearer and more accurate, since, when a contingency plan fails the total policy does not need to be fully reassessed. Instead a new contingency plan would be activated with costs and benefits that can be estimated (thus making it possible to estimate the costs of the reassessment plan). Of course, many questions still remain concerning this idea (for instance, how to account for the costs of developing an adaptive policy, and when should one update the adaptation pathway), and more research is needed on the subject. However, at first glance it appears promising.

With respect to the generalization of the results presented here, the question is to what extent do the results apply to other megaprojects? For aviation-related megaprojects, we believe that the insights provided by this research can be generalized, since the main uncertainty (demand) for the Schiphol case is the main uncertainty for other airports in Europe and elsewhere. This research showed that, when dealing with uncertainty in demand, an adaptive policy results in a better cost–benefit performance than a static policy. A difference between the Schiphol case and the case for most other European airports is that other European airports have less strict regulations concerning noise and emissions. For Schiphol the adaptive policy respected the regulations in the Netherlands concerning noise. If these regulations were less strict, we believe that the adaptive policy would perform even better, since the capacity of the airport would not be restricted so quickly.

The adaptive approach and the approach to CBA presented in this paper need not be restricted to airport strategic planning. They are applicable to megaprojects with characteristics similar to those in our case study. The megaproject being considered in the case study is being built in a volatile environment (due to the strict regulations concerning noise, emissions, and third-party risks) with a lot of uncertainty in demand. One of the reasons for the poor cost–benefit performance of megaprojects is an overestimation of demand (Cantarelli, 2011; Flyvbjerg et al, 2003; 2005). This implies that a lot of megaprojects fail because they cannot cope with futures for which the demand is different from what was forecast. Our research shows that an adaptive policy could prevent these cost overruns, since the construction of the megaproject would start only when it becomes clear that the estimated demand is indeed becoming a reality. On the other hand, static policies take these demand forecasts as reliable predictions, leading the megaproject to suffer huge losses when the forecasts are not correct. Thus, this research suggests that DAP is to be preferred over the static policy-making approach for megaprojects that are being built in an environment where there is deep uncertainty in demand. But, to create more fundamental knowledge about situations in which adaptive policies are to be preferred over static policies, more evidence is needed and more cases need to be studied.

In addition to applying our approach to more cases, there is a need for more-realistic case studies. Proponents of the static policy-making approach (eg, those who do master planning) claim that their ‘static policies’ are actually adapted to changing situations through ad hoc policy changes. Whether this improves the cost-benefit performance of a static policy is unclear and needs to be researched. Another future research topic is how to monetize a reassessment. In our research, we chose to see all investments as lost when the reassessment is activated. It would be better to think in advance about what could cause a reassessment plan to be activated and, depending on the cause, have plans available that describe which parts of the old policy could still be used. As mentioned above, one way of doing this would be to use the concept of adaptation pathways (Haasnoot et al, 2011; 2012). How to combine adaptation pathways with DAP is currently being researched (Haasnoot et al, 2013).

Overall, despite the fact that we cannot be sure that DAP can improve the cost-benefit performance of large infrastructure projects in all situations, this research shows that, compared with static policy making, DAP is a promising way to plan such projects.

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