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ABSTRACT

Seamlessly merging real and virtual reality, Augmented Reality (AR) is a promising technology that offers novel ways to use IS outside the office. For a company it is hard to determine whether to put R&D efforts into such an innovative technology. Developing methods to model, describe, assess and analyze such new technologies is a main challenge of the IS discipline. The purpose of this work is to support a decision concerning the adoption of an innovative technology. Yet, it is not known how the use of this technology would change business processes and also several uncertainties must be addresses. A three-step approach, dealing with these problems is proposed. To generate knowledge about how to use this technology scenarios are identified and analyzed within a framework. Furthermore, a decision model to estimate the impact of different investment decisions is established.

Keywords

Real Options, Augmented Reality, IS-Evaluation, Decision under Uncertainty

INTRODUCTION

Augmented Reality is a promising technology, merging real and virtual reality seamlessly. In doing this it offers the possibility to use IS outside the office. In this work we are investigating a possible introduction of AR into planning, erection and maintenance processes of nuclear power plants. While it is very exciting to deal with such an innovative technology it raises also many problems and uncertainties. For decision makers it is hard to determine if is reasonable to put R&D efforts into an innovative technology. One of the main challenges of the IS discipline is to develop appropriate methods in order to model, describe, assess and analyze the business value of new IS applications and technologies.

In this paper we present a case for an ex-ante evaluation of an innovative technology under uncertainty. To support a decision about investing into AR a three-step approach has been chosen. Scenarios for the use of AR are identified and analyzed. Furthermore a decision model is established in order to estimate the impact of an investment decision.

The remainder of this paper is structured as follows. First of all, basic principles of AR are explained. Then problems characterizing this case are addressed. One scenario for the use AR exemplifies our approach to deal with these problems. Next, a decision model for this case is developed. Finally the results are discussed and further prospects are given.

AUGMENTED REALITY

The term Augmented Reality denotes a field of research where real and virtual world are combined. Using e.g. a Head Mounted Display (HMD) with cameras attached, the user's normal view is augmented with virtual objects. Other visualization devices include Tablet PCs equipped with a video camera or, for stationary systems, video projectors. AR opens up astonishing possibilities to visualize all types of electronic information. For instance it can be used during minimal invasive surgeries. Ultrasound images acquired during the surgery can be displayed using a HMD to get an "x-ray view" into the patient. Other applications include industrial AR where for instance instructions for a difficult task are visualized, driving assistance where information is displayed in the wind shield and television where a moderator can be seen within a virtual studio. AR can also be seen as user interface. Using gesture recognition or another appropriate input device it can be used for mobile access to data.

While the possibilities AR could offer are promising it is still a quite young technology. Few experiences in everyday use have been made and no out-of-the-box solutions can be purchased, yet. Some technological problems have still to be solved. One of the most challenging problems is tracking. To embed the virtual objects properly into the real world the exact position and orientation of the visualization device has to be tracked. This is a difficult task, especially for wide area applications. Other problems include suitable display and input devices, power supply for mobile AR systems and authoring of content.

PROBLEM DESCRIPTION

The construction of nuclear power plants is a challenging business that must be done very carefully and has to meet high technological and legal demands. Due to these high requirements companies working in this domain are technological precursors for the whole building industry. This has for instance led to an early adoption of information systems, 3D CAD software and also first experiences with AR. Monitoring and documentation of the construction works, quality assurance and replanning during the construction works must be done with caution and take a lot of time. The basic idea of using AR to support these activities is to superimpose the real world with the CAD-model in order to identify differences between planned and real state. But also other possibilities to utilize AR in the construction of a power plant can be thought of. To support an investment decision an ex-ante evaluation of using AR had to be done, where beside a qualitative analysis also financial benefits had to be estimated.

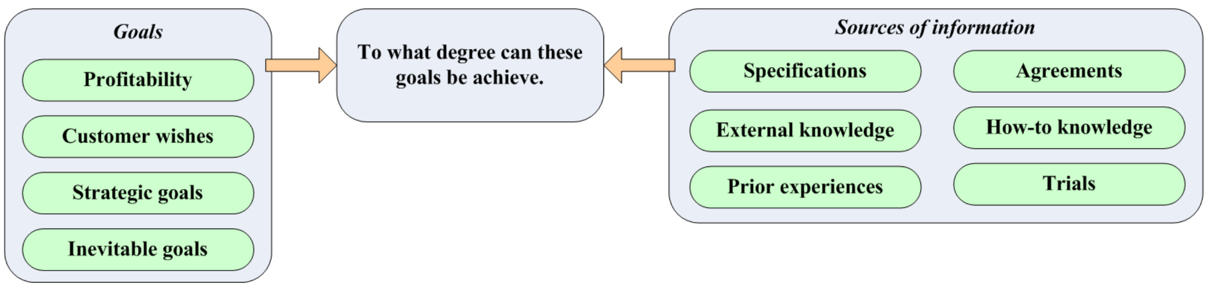

Figure 1. General framework of a value analysis

As discussed by Irani and Love(Irani and Love, 2002), ex-ante evaluation of IS is a non-trivial problem where an all-embracing generic appraisal technique might not be reasonable. In order to develop an approach suited for our case the differences to more conventional investments are pointed out. Figure 1 shows a very general and abstract framework of a value analyses. To be able to estimate the value of an investment the goals of a company are defined. This can be mere monetary goals, where capital budgeting methods like the Net Present Value (NPV) would be appropriate. Other goals of a company include strategic goals, customer wishes or inevitable goals like legal requirements. Various methods for estimating to which degree these goals are fulfilled by an investment have been proposed. For instance Zangemeister(Zangemeister, 2000) uses an integrated approach where he distinguishes between direct monetary, indirect monetary and non-monetarizable effects. Using analytic methods like the Analytic Hierarchy Process (Saaty, 1980) effects are weighted in respect to each other and consolidated to a single value. However, in general those methods treat uncertainty either not at all or very aggregate and endogenous.

The availability of information about the investment object and effects resulting from the investment is assumed implicitly. Possible sources of information include specifications of a product, agreements with the vendor of a customized product, prior experiences with similar investments, trials and external knowledge from consultants or literature. These sources of information are barely available for AR. Furthermore, for most investments it is known how the subject of the investment would be used or how it would change the current processes. To estimate to which degree an investment would help to achieve business goals it must be known how it would change the processes of the company. For AR, we do not have this how-to knowledge, yet. While some ideas exist how AR could be used, it has barley been in daily use and so it is still unknown how it will change the processes. So in addition to the uncertainty about how to monetarize and consolidate the effects of an investment we have also to deal with an uncertainty about how to use it. So the framework in figure 1 is modified to match our case what can be seen in figure 2.

Sources of information

As mentioned above, it is not possible to rely on usual sources of information. So other sources of information must be used to get an imagination of how to use AR. The two most important sources of information are technological and practical knowledge. The technological knowledge includes everything known about the technology. This includes hardware, software, algorithms, known problems, but also ideas how to use it, experiences from other companies and all related literature. Practical knowledge includes all knowledge about the environment where the use of the technology is considered. This includes for instance the current processes, problems, the organization, IT infrastructure and educational background of the employees.

For most technology investments the acquisition of technological knowledge is certainly a problem. The employees of a company will most probably not know much about a new technology. Literature research, consultants and knowledge transfer from other companies or universities are possible sources of technological knowledge. For this case technological knowledge is available from prior experiences with AR.

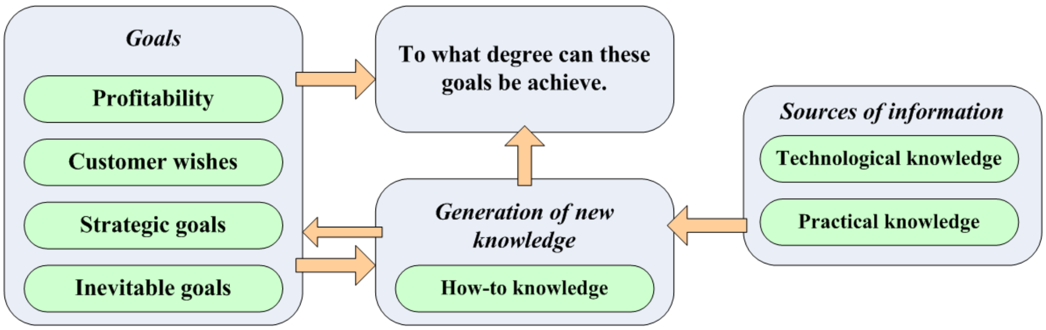

Figure 2. Modified framework of a value analysis

Goals

Another aspect that influences how a technology will be used are the goals of a company. For investment decision where a product is purchased the goals do not affect the characteristics of the product. Only the value of the product for the company is affected by the goals. However, for customized products or a still evolving technology the goals influence the characteristics. So the goals are another important input when acquiring how-to knowledge. The purpose of an investment is helping to achieve the goals of a company. So in most cases an investment does not have an impact on the goals. This can also be different for technology investments. When realizing the possibilities of a new technology this can result in grave changes to a company's goals. E.g. discovering how to use the internet as a new channel of distribution will certainly affect the strategic goals of a company.

Risks & Uncertainty

Several risks have to be considered when dealing with a new technology. Acceptance problems can lead to non-use. Some technological problems have still to be solved, whereas technological advances are difficult to predict. Technological problems could raise the costs or reduce the benefits.

It must also be kept in mind that this is a technology investment. No product is purchased but expenses on research and development (R&D) will occur. Experiences with the technology are made during R&D activities and so new, more substantiated predicts of costs, risks and benefits will be made. So the investment decision can be reconsidered after first experiences have been made. The R&D activities can be stopped if the expected profits are too low or the scope can be shifted if novel ways to utilize the technology are found. This is an important difference to an investment where a definite decision must be made.

So the following issues have to be addressed when trying to establish an appropriate decision model in order to assess the investment which is characterized by such a high degree of innovation:

- research uncertainty (this means the time to commercialization is uncertain),
- uncertainty about how to use the technology,
- reduction of these uncertainties over time by gathering new information and knowledge,
- flexibility to entry or stop R&D activities, as well as
- flexibility to scope or scale the application.

Considering these uncertainties it is obvious that a simple decision model can not cope with such a complex problem. So an additional qualitative analysis must be done in order to shed light on risks and chances.

Generation of new knowledge

The most important step is to generate how-to knowledge. Without knowing how the technology will be used it is not possible to predict cost savings, time savings, quality improvement or other benefits. An appropriate method to generate how-to knowledge is to develop scenarios for the use of the technology.

Based on these insights a three-step approach has been chosen. In the first step relevant scenarios have been identified. Subsequently the scenarios have been analyzed and based on a framework qualitatively and quantitatively evaluated. In the last step an appropriate decision model has been established in order to give decision makers the possibility to estimate the impact of their investment decision.

IDENTIFYING SCENARIOS

The first step is the identification of scenarios for the use of AR. This is related to the acquisition of practical knowledge. A total number of eight interviews and one meeting with several experts in the domain of plant construction were conducted. Unstructured interviews were used in order to understand the current processes, find possible applications for AR and identify risks and chances. Based on the first interviews the processes have been modeled using process chains. Modeling the processes helped to understand them and revealed gaps in the knowledge. After some scenarios have been identified, further interviews aimed at gathering more information concerning these scenarios.

Six different scenarios for the use of AR have been identified:

1. Inspection of clashes: If an item, like a pipe, is misplaced a clash with another item might occur. All clashes have to be inspected and documented.
2. Acceptance walk down: After the construction works are finished the correctness of the whole system must be verified.
3. Monitoring of the construction works: Throughout the whole erection of the plant the construction works must be monitored to discover problems.
4. Planning assistance: Replanning without an up-to-date CAD-model must be done during the construction works or for revamping of an existing plant.
5. AR for external construction companies: A lot of planning, monitoring and verification is also done by external companies.
6. Assistance of as-built modelling: To acquire a CAD-model that reflects the as-build state of the plant is a still unsolved problem.

ANALYSIS OF THE SCENARIOS

Framework for analyzing the scenarios

A framework to analyze all scenarios has been established. This framework can be seen in figure 3. First of all, current processes, background information and known problems are described. Based on this a scenario for the use of AR is developed. Costs and benefits of the scenario are identified and discussed. Possible technological, organizational and acceptance problems are taken into account. These risks have to be addressed as they can raise the costs or lower the benefits. To deal with non-technological risks the five most important perceived attributes affecting the rate of adoption of an innovation (Rogers, 2003) are examined. These are the relative advantage attributed to an innovation, compatibility, complexity, trialability and observability of an innovation.

While developing the scenarios it has shown that two different implementations of an AR system would be imaginable. This in on one hand an AR system which is relative independent from the IT infrastructure and on the other hand an extensive integration where AR can be used as a mobile interface to all kind of data. To present our approach a short summary of one scenario is given, which is the inspection of clashes.

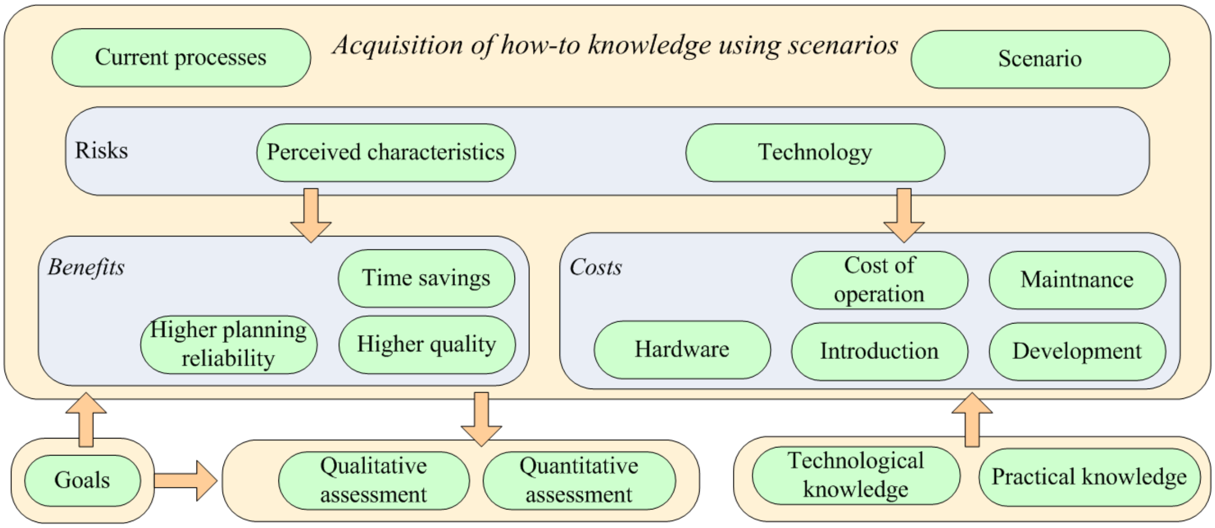

Figure 3. Framwork for the scenarios

Exemplary Scenario Analysis

Background & Current Processes

When an item, like a pipe or anchorage, is misplaced this can lead to clash with another item. A plant, including adjoining buildings, consists of about 30.000 items and so clashes are a common problem. Every clash has to be investigated and documented by an engineer from the planning department. This is a time-consuming task. Every time a clash occurs the construction workers report this to the planning department. All relevant documents have to be gathered and the clash has to be inspected. In some cases it is very difficult to discover the origin of a clash as a whole group of items may be misplaced.

Scenario

When a clash is discovered a photo is taken by the construction workers and sent to an engineer. The photo is superimposed with the CAD model. So the difference between planned state and real state can be seen in the photo. Some clashes can be handled using only this photo and so the time to visit the construction site can be saved. Otherwise all relevant documents are transferred to a Tablet PC which is taken to the construction site. There additional photos can be made and augmented using the Tablet PC. The Tablet PC holds all electronic documents concerning the items in this area and is also used to make the documentation.

Costs & Benefits

Costs for using AR independent from the information infrastructure can be expected as relative low as only few engineers would use AR. The AR set consist of a digital camera and a Tablet PC. Both are standard hardware which keeps costs low. When integrating AR into the information infrastructure, server and network hardware would be necessary and integration costs would arise. Costs for this would be much higher than for an independent solution.

To estimate the financial benefits, the number of clashes and time taken to investigate a clash was estimated based on experiences from previously built plants. About half of the time is taken by going to the construction site and managing documents before and after the inspection. So the highest benefits result from the possibility to inspect a clash in the office using only an augmented photo and the on-site use of electronic documents. Both would require an integration of the AR system into the IT infrastructure. Only minor time savings can be expected when using an AR system that is relative independent from the IT infrastructure. Using AR on-site seems interesting but only little time is saved as it would most probably not be used for all clashes.

Risks

Low risk can be expected from the perceived attributes. The engineers are responsible to do the investigation and so they have an advantage from using AR. They are familiar with 3D CAD and do already use digital cameras. So using AR is compatible with their existing practices. All of them have a higher education and they are familiar with computers. So the perceived complexity is relative low. AR can be tried out on a single clash and as it is a visual technology it is very observable. Ease of use is important as the engineers can decide on a case-by-case basis to use or not to use AR. If using AR is perceived as too laborious this can lead to non-use.

DECISION MODEL

After analyzing the costs, risks and benefits of the scenarios within the framework, a decision model had to be established in order to answer the question if an immediate R&D investment is economic rational or if it is better to postpone the R&D investment. Eventually, this means to calculate a critical value of estimated cash inflows generated by usage and the level of R&D expenses. To deal with a reduction of uncertainty over time the framework by McGrath (McGrath, 1997) which is based on Real Options is used. A technology investment is split up into development and commercialization of the technology. The value of commercializing a technology depends upon costs and benefits of the commercialization, which might be both subject of uncertainty. This uncertainty is reduced while the technology is developed. After development the commercialization is only done when it turns out to be profitable. So the expenses for development are the price of an option to commercialize the technology. The value of this option can be calculated using Real Options, a method based on financial options.

Deducted from the scenario analysis the following requirements have to be addressed by our decision model:

1. There are two exclusive deployment alternatives: A stand alone implementation and a highly integrated implementation
2. The cash flows generated by both options are uncertain, while the expenses for deploying and operating the technology are roughly predictable
3. Total R&D expenses are uncertain and therefore the point in time when the technology is productively usable is uncertain
4. Uncertainty resolves over time

Model Derivation

To begin with, a model for the cash inflows generated by both alternatives has to be adopted. These cash inflows are denoted with C for the integrated solution and C_l for the small solution and are assumed to be perpetual. Here C_l is a fraction n_l of C, hence $C_l = n_l C_l$. In order to take uncertainty into account a geometric Brownian motion

$$dC = m_C C dt + \sigma_C C dz_C , \quad C_l = n_l C ,$$

for C is assumed, whereas dz_C is a Gaussian random variable with a standard deviation of $dt^{1/2}$ (Wiener increments), m_C is the certain growth rate of C and may also be 0, σ_C is its standard deviation and can be seen as the measure of randomness and describes the expected deviation of C a year. Real option theory argues that under the assumption of completeness of markets for each risk factor an risk equivalent asset following the same geometric Brownian motion but with μ_C instead of m_C can be found (Trigeorgis, 2002). If there is no correlation between the market risk and the risk of C, then μ_C is equivalent to the riskless interest rate r. McDonald and Siegel(McDonald and Siegel, 1984) argue that m_C and μ_C do not have to be identical and therefore there might be a shortfall between them. This shortfall will be denoted here with $\delta_C = \mu_C - m_C$ and is e.g. equivalent to $r - m_C$ if all the risk in C is unsystematic.

The expenses for deploying the integrated alternative are denoted with I_C and respectively for the small alternative with I_l. Both are assumed to be predictable. Hence I_l can be calculated as a fraction n_k of I_C, i.e. $I_l = n_k I_C$. In order that the small option is economic meaningful $n_k < n_l$ is needed. If R&D succeeds then an option to acquire one of both alternatives comes into existence. Here the option provides the right to exercise this option at any time. The value of this option is calculated in the next section and will be denoted with $V = V(C, n_l, n_k, I_C)$.

Next, a model for the R&D expenses is required. The remaining R&D expenses until the technology is productively usable is here denoted with E. The cash outflow for R&D $I_R \in [0, I_{max}]$ lowers this remaining R&D expenses, whereas I_{max} is the maximal possible investment a year. Hence we attain $dE = -I_R dt$ if there is no uncertainty. In order to introduce uncertainty to this process a geometric Brownian motion

$$dE = -I_R dt + m_E E dt + \sigma_{E1} \left(E I_R \right)^{1/2} dz_{E1} + \sigma_{E2} E dz_{E2} ,$$

is also be assumed for E, whereas m_E is the expected growth rate of E and might be negative if there are exogenous R&D activities, dz_{E1} and dz_{E2} are Wiener increments as above and σ_{E1} and σ_{E2} are standard deviations. The two random terms represents the issue that a part of uncertainty may resolve exogenously and another part only if there are own research activities. This process is identical to the process proposed by Schwartz and Zozaya-Gorostiza(Schwartz and Zozaya-Gorostiza, 2003) for IS development projects. Following Schwartz and Zozaya-Gorostiza(Schwartz and Zozaya-Gorostiza, 2003) there may be also a high correlation between the increments especially between dz_{E2} and dz_C, which is denoted with ρ. With the same argumentation as above there might be a shortfall between the growth rate of a risk equivalent asset μ_E and m_E which is denoted here with δ_E. The decision is now I_R and lies in the interval $[0,I_{max}]$. The value of the total invest is here denoted by $F=F(E,C,n_l,n_k,I_R,I_C,t)$ and can be calculated from the following differential equitation

$$rF = \frac{\partial F}{\partial t} + (r-\delta_C)\frac{\partial F}{\partial C}C + \left((r-\delta_E)E - I_R\right)\frac{\partial F}{\partial E} + \frac{1}{2}\sigma_C^2 C^2 \frac{\partial^2 F}{\partial C^2} + \frac{1}{2}\left(\sigma_{E1}^2 I_R E + \sigma_{E2}^2 E^2\right)\frac{\partial^2 F}{\partial E^2} + \frac{1}{2}\left(\rho\sigma_C\sigma_{E2}CE\right)\frac{\partial^2 F}{\partial E \partial C}$$

with $\frac{\partial F}{\partial t} = -I_R$ and the boundary conditions

$$F(0,C,n_l,n_k,I_R,I_C,t) = V(C,n_l,n_k,I_C),\; F(E,0,n_l,n_k,I_R,I_C,t) = 0 \text{ and } \lim_{E\to\infty} F(E,C,n_l,n_k,I_R,I_C,t) = 0 .$$

This differential equitation relies on real option theory as is shown e.g. by Trigeorgis(Trigeorgis, 2002). From this differential equitation also follows that F depends linearly on I_R (Schwartz and Zozaya-Gorostiza, 2003) and hence it can be easily shown that

$$I_R = \begin{cases} I_{max} & 0 < -1 - \frac{\partial F}{\partial E} + \frac{1}{2}\frac{\partial^2 F}{\partial E^2}\sigma_{E1}^2 E \\ 0 & else. \end{cases}$$

holds. In order to solve this differential equitation a numerical method such as finite-difference method is required. As this model has been already analyzed by Schwartz and Zozaya-Gorostiza(Schwartz and Zozaya-Gorostiza, 2003) but without the boundary option V, we only provide here a further discussion of the boundary option $V=V(C,n_l,n_k,I_C)$.

Solution and Analysis of the Boundary

It can be easily shown that under the assumptions the value of the integrated alternative is $C/\delta_C - I_C$ and of the small alternative is $n_l C/\delta_C - n_k I_C$ (Dixit and Pindyck, 1994). There are three threshold values of C. Below the lowest threshold C_l it is optimal to wait and observe how C evolves. Between C_l and the middle threshold C_m it is optimal to implement the small alternative, between C_m and the highest threshold C_u it is again optimal to wait and see how C evolves and above C_u it is optimal to implement the integrated alternative. Therefore $V(C,n_l,n_k,I_C)$ must be spilt into four parts, e.g.

$$V(C,n_l,n_k,I_C) = \begin{cases} V_1(C,n_l,n_k,I_C) & C < C_l \\ \frac{n_l C}{\delta_c} - n_k I_C & C_l \le C \le C_m \\ V_2(C,n_l,n_k,I_C) & C_m < C < C_u \\ \frac{C}{\delta_c} - I_C & C_u \le C \end{cases}$$

By using the fundamental differential equitation of the real option theory, V_1 as well as V_2 follows the following differential equitation:

$$(r-\delta_c)\frac{\partial V}{\partial C}C + \frac{1}{2}\sigma^2 C^2 \frac{\partial^2 V}{\partial C^2} - rV = 0$$

The general solution of this differential equitation is

$$V_1(C,n_l,n_k,I_C) = A_1 C^{\beta_1} + A_2 C^{\beta_2} \text{ and respectively } V_2(C,n_l,n_k,I_C) = B_1 C^{\beta_1} + B_2 C^{\beta_2},$$

whereas $\beta_{1/2}$ are the roots of $0=\frac{1}{2}\beta(\beta-1)\sigma_C^2+\beta(r-\delta_C)-r$ with $\beta_1>0$, $\beta_2<0$. For V_1 the values of A_1, A_2, C_l can be calculated by using the following boundary conditions

$$\lim_{C\to 0} V_1 = 0\,,\; V_1 = \frac{n_l C_l}{\delta_C} - n_k I_C \text{ and } \left.\frac{\partial V_1}{\partial C}\right|_{C=C_l} = \frac{n_l}{\delta_C}.$$

The last condition is the smooth pasting condition (Dixit and Pindyck, 1994). The first condition entails $A_2=0$. For V_2 the values of B_1, B_2, C_m, C_u can be calculated by using the boundary conditions

$$V_2\left(C_u, n_l, n_k, I_C\right) = \frac{C_u}{\delta_C} - I_C\,,\; \left.\frac{\partial V_2}{\partial C}\right|_{C=C_u} = \frac{1}{\delta_C}\,,\; V_2\left(C_m, n_l, n_k, I_C\right) = \frac{n_l C_m}{\delta_C} - n_k I_C \text{ and } \left.\frac{\partial V_2}{\partial C}\right|_{C=C_m} = \frac{n_l}{\delta_C}.$$

These four boundary conditions form a non-linear system of equitations, which has to be solved numerical for B_1, B_2, C_m, C_u. Table 1 provides a brief numerical simulation of miscellaneous parameter constellations. All calculations are done with a risk free interest rate r=7% and deploying expenses I_C=1000. The last column shows the net present value in the case the investment had been realized immediately.

σ_C	δ_C	n_l	n_k	C_l	C_m	C_u	*V(90)*	*NPV*
25%	6%	0.5	0.2	51.44	63.19	131.05	597.92	550
		0.6	0.25	53.58	87.11	140.00	650.60	550
		0.7	0.3	55.11	120.48	160.96	822.10	550
		0.7	0.25	45.92	130.32	171.22	931.18	550
	4%	0.5	0.2	0	0	59.66	1250.00	1250
		0.6	0.25	0	0	66.18	1250.00	1250
		0.7	0.3	50.31	68.33	122.71	1313.96	1250
		0.7	0.25	41.93	76.23	128.51	1342.30	1250
35%	6%	0.5	0.2	0	0	88.13	550	550
		0.6	0.25	0	0	97.25	550	550
		0.7	0.3	71.12	103.45	180.99	757.35	550
		0.7	0.25	55.313	146.51	217.25	1007.32	550
	4%	0.5	0.2	0	0	63.41	1250	1250
		0.6	0.25	0	0	71.82	1250	1250
		0.7	0.3	0	0	82.80	1250	1250
		0.7	0.25	0	0	82.80	1250	1250

Table 1. Numerical Simulations of miscellaneous parameter constellations

As the table shows, the option on both alternatives is only valid for moderate volatilities. This issue is at first glance counterintuitive since usually the option value increases with the volatility because it increases the upside potential while the downside risk is still limited. For the option under consideration this is not completely true, as the value of the small alternative in the option decreases significantly with higher volatilities. Furthermore for a high volatility and a small shortfall it is never rational to implement the smaller alternative.

In order to protect the anonymity of the considered firm the collected financial data are not provided here, but for example the calculated n_l n_k are 0.39 and respectively 0.13 which leads to threshold 42.86, 44.48 and 128.76 with volatility of 25%, r=7% and a shortfall of 6% and I_C=1000.

RESULTS & CONCLUSION

Our research has shown that using AR in the construction of power plants promises interesting possibilities. On the basis of scenarios we have identified several applications for AR. We established a framework in order to systematically analyze the scenarios. We have generated how-to knowledge and also knowledge about chance, risks and requirements. The availability of this knowledge is crucial in order to make a substantiated decision about an investment.

Estimating costs and benefits using NPV is not easy and may lead to wrong decisions if uncertainty and flexibility is not sufficiently taken into account. To allow for a more sophisticated analysis the requirements for a decision model have been pointed out and an appropriate decision model has been proposed. This decision model addresses uncertainty as well as flexibility to start and stop R&D activities and flexibility to scale the technology in usage.

Obviously, a shortcoming of the decision model is the treatment of the cash inflows for both alternatives as fully positively correlated. This might or might not be true. In order to enhance the model in a next step, the processes of the cash inflows should be allowed to be separate processes which might be not fully correlated.

Although, initially the only motivation of this research was to estimate the financial value of the investment, it has shown that the qualitative scenario analysis using our framework was as important as establishing a financial decision model. In particular, when dealing with innovative technologies, the awareness about uncertainty and the generation of knowledge about chances, risks and ways to use the technology are essential for well-founded decision making.

REFERENCES

1. Dixit, A. K. and Pindyck, R. S. (1994) Investment under uncertainty, Princeton Univ. Press, Princeton, NJ.
2. Irani, Z. and Love, P. (2002) Developing a frame of reference for ex-ante IT/IS investment evaluation, *European Journal of Information Systems*, 11, 1, 74-82.
3. McDonald, R. and Siegel, D. (1984) Option Pricing When the Underlying Asset Earns a Below-Equilibrium Rate of Return: A Note, *Journal of Finance*, 39, 1, 261-265.
4. McGrath, R. G. (1997) A Real Options Logic for Initiating Technology Positioning Investment, *Academy of Management Journal*, 22, 4, 974-996.
5. Rogers, E. M. (2003) Diffusion of Innovations, 5 Ed., Free Press, New York.
6. Saaty, T. L. (1980) The Analytic Hierarchy Process, McGraw-Hill, New York.
7. Schwartz, E. S. and Zozaya-Gorostiza, C. (2003) Investment Under Uncertainty in Information Technology: Acquisition and Development Projects., *Management Science*, 49, 1, 57-70.
8. Trigeorgis, L. (2002) Real options: Managerial flexibility and strategy in resource allocation, MIT Press, Cambridge, Mass. et al.
9. Zangemeister, C. (2000) Erweiterte Wirtschaftlichkeitsanalyse (EWA), 2 Ed., Wirtschaftsverlag NW, Dortmund/Berlin.