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Consideration of uncertain future demand and decision flexibility in the determination of intervention programs for buildings

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Foreword

The management of buildings involves determining the levels of service required from buildings and executing interventions to ensure that these levels are provided. Interventions are required because both the levels of service required from, and provided by, buildings change over time. The former is because of desired changes in use, e.g. the type of equipment housed by the building is changed, and the latter is because of deterioration, e.g. the ability of a building to keep out rain is compromised due to cracks in the façade.

Building managers are increasingly using computer support to help determine optimal intervention programs, i.e. when to execute interventions on their buildings, and which interventions to execute. These computer systems are relatively well equipped to help determine the intervention programs if the level of service to be provided is known and the only reason for intervention is deterioration. They are relatively poorly equipped to help determine the intervention programs when the level of service to be provided might change, and there is substantial uncertainty related to that change. In these situations, qualitative methodologies are often used.

To bring the building management community forward on this issue, Ms. Miriam Esders developed a methodology built on state-of-the-art methods to determine optimal intervention programs for buildings when there is substantial uncertainty with the level of service to be provided in the future. Ms. Esders shows clearly how her methodology works when compared to a traditional methodology using a simple example. She then shows how her methodology could work in the real world, simultaneously showing that the challenges of simplifying the real world in a meaningful way, so that the methodology can be used, can be overcome.

Through her work, Ms. Esders clearly shows that, with her methodology, building managers can take into consideration large uncertainties with respect to the level of service to be provided in the consideration of intervention programs to be followed for their building portfolios. She also shows that this can be done objectively, quantitatively and with explicit consideration of the ability of managers to change their minds in the future if circumstances changes. Even if there is substantial difficulty in estimating what will happen in the future, or the probabilities with which the many possible futures will occur, the use of her methodology leads to substantial insights into what may happen in the future, and as to the type of building that will be required to provide the possible required levels of service. This is a substantial improvement to the qualitative, and in many situations unsystematic, way, many building managers now develop intervention programs for the buildings in their building portfolios.

Ms. Esders' work as a whole will greatly help bring the building management community forward in developing improved computerised systems to support the development of intervention programs that will increase the net-benefit obtained from buildings. Additionally, however, her work is of interest to anyone who develops algorithms to determine optimal intervention programs for multiple objects, e.g. bridges, tunnels, locks, in situations where there is substantial uncertainty with respect to the level of service to be provided.

Through her work, Ms. Esders has demonstrated that she has the ability to conduct work rigorously at a high academic level, and make contributions to the state-of-the-art in a new emerging field of research. On behalf of the Institute for Construction and Infrastructure Management at the Swiss Federal Institute of Technology, Zürich, I thank her for her thorough and constant investment to this topic, as well as, for both her professional and personal qualities.

Zürich, 28.02.2017 Professor Dr. Bryan T. Adey

Abstract

One task of building managers is to ensure that their buildings function as required over a defined period of time, while the ability of buildings to meet demands changes over time due to two reasons: (1) The change of the ability of the building to meet fixed demands, normally through deterioration, and (2) the change of demands for the building. Building managers want to determine what they should do with their buildings at present to maximize their net-benefit in the long term. This requires determining the intervention to be executed immediately and estimating the ones that might be executed in the future, i.e. determining an intervention program. This decision making process is supported through the modelling of deterioration and the determination of the optimal intervention program.

The used models and methods often do not consider the uncertain future demands on the buildings. Although the assumption of non-changing demands is convenient from a mathematical modelling point of view, it is rarely true in the real world. Uncertain changes in demand make it undesirable to attempt to evaluate intervention programs now and then determine exactly which one to follow over the remaining planning horizon. Instead, uncertain changes in demand can make it desirable to find flexible solutions that consider the possibility to postpone decisions on the actual intervention program to implement to a later moment when more information will be available. Taking into consideration this flexibility of management to decide which intervention program to follow is believed to be a cornerstone of any method to be used to determine optimal intervention programs in management systems where there is uncertainty with respect to future demand.

To make a decision about whether to introduce decision flexibility in intervention planning, it is necessary to evaluate the benefits that the flexibility can bring to the building management, in light of the uncertainty it is exposed to. In conditions characterized by high uncertainty, interventions programs developed with consideration of decision flexibility enable building manager to adapt the system to new information and thus avoid losses or even seize opportunities.

The main objective of this research is to investigate how to consider the decision flexibility of the decision maker in the determination and evaluation of intervention programs with consideration of the uncertainty in future demand and to identify a method that can support a decision maker in the determination and evaluation of such intervention programs.

In this thesis, a Real Options Method for the evaluation of intervention programs with consideration of decision flexibility under uncertainty in changes in demand is presented and applied to a simple example of a fictive office building and a real world example, a clinic of a Swiss university hospital. This method is based on Real Option Analysis and Decision Tree Analysis. To identify eligible intervention projects where the consideration of decision flexibility is relevant, a methodology for the identification and evaluation of intervention projects with consideration of decision and building flexibility is presented and applied to the real world example.

The Real Options Method for the evaluation of intervention programs with consideration of decision flexibility and the methodology for the identification and evaluation of intervention projects with consideration of decision and building flexibility are applied by analysing the situation, building adequate models of the uncertain key parameters, establishing the static and dynamic evaluation models, identifying possible intervention projects, and evaluating these intervention projects with the method for the evaluation of intervention programs with consideration of decision flexibility. The decision flexibility about the interventions to be executed

over the investigated time period is the focus of this thesis. For the real world example, however, three different design alternatives are also considered, providing different levels of decision flexibility over the investigated time period. This design flexibility can also be evaluated with the presented method for the evaluation of intervention programs with consideration of decision flexibility.

The ramifications of the results from the application of both the method and the methodology are analysed. The use of the method for the determination and evaluation of intervention programs with consideration of decision flexibility shows that the method allows for appropriate consideration of decision flexibility and, therefore, can lead to an increased benefit for building managers. The expected net benefits and optimal intervention program determined with the method with consideration of decision flexibility are closer to reality, and thus enable better budget planning. The application of the method on this example showed that the Real Options Method required more effort than the Traditional Method without the consideration of decision flexibility before and during the evaluation for the definition of the flexible decision making, the definition of the consequences of the decision making at these decision points and values over the investigated time period, and the calculation of the probabilities of execution for each possible time and value where a decision of execution is beneficial.

The method with consideration of decision flexibility does not lead to better intervention programs for all components of a building, and thus should only be applied if management flexibility is a possibility, the uncertainty of key parameters is high, and the intervention costs are high compared to the benefits.

The use of the methodology for the identification and evaluation of intervention projects on the real world example shows that it can be applied to a real world situation and can deliver meaningful results. It strongly relies on stakeholder knowledge and requires good and extensive stakeholder communication throughout the complete process. Considerable simplifications regarding the selection of key parameters and models must be made throughout the process, to keep the complexity at a manageable level, though the methodology can be adapted to take in the level of complexity that is required for different projects.

The results from the application of the method on the simple and the real world example show that, even though the expected net benefits from the evaluation with the method with consideration of decision flexibility are higher than the ones from the Traditional Method, the difference is small for the given examples, within the error margin of the input parameters, which does not justify the additional effort required to consider the flexible decision process. This small difference is mainly due to the reduced impact that the uncertainty considered in the examples have on the expected net benefits of the intervention program, but it is a result that is only possible to obtain through an adequate evaluation method as presented in this thesis. In such a situation, the decision maker can make a choice of which intervention program to follow, either with or without consideration of decision flexibility. Also, during early steps of the methodology, a test can be made whether the considered case will have a significant impact.

Future research should also consider a deeper analysis of the probabilistic models used for the evaluation of intervention programs, which were in this thesis based on simplifications. Based on the given classification of influence factors, changes in demand, and effects, suitable methods for the modelling of changes in demands in connection with the changes of connected influence factors should be identified and tested for application. The consideration of decision flexibility in the construction of intervention programs is not applicable for all building components, as the application is only beneficial under certain conditions. It can be assumed that many of the intervention programs constructed for a complete building are determined without the consideration of decision flexibility, resulting in inflexible intervention programs. Thus, the method and methodology with consideration of decision flexibility investigated in this thesis have to be applied in the context of the management of related building components without consideration of flexibility.

Zusammenfassung

Eine Aufgabe von Gebäudemanagern ist es sicherzustellen, dass ihre Gebäude über einen definierten Zeitraum wie gefordert funktionieren. Die Fähigkeit von Gebäuden, gegebenen Anforderungen zu genügen, nimmt mit der Zeit aus zwei Gründen ab: (1) Die Veränderung der Fähigkeit des Gebäudes, gegebene Anforderungen zu erfüllen - normalerweise aufgrund von Verfall - und (2) die Veränderung der Anforderungen an das Gebäude.

Gebäudemanager wollen bestimmen, was sie heute mit ihren Gebäuden tun sollten, um ihren langfristigen Nettonutzen zu optimieren. Dies erfordert die Bestimmung jener Massnahmen, die sofort durchgeführt werden sollen, sowie die Abschätzung der Massnahmen, die in der Zukunft durchgeführt werden sollen, d.h. die Bestimmung eines Massnahmenprogrammes. Dieser Entscheidungsprozess wird unterstützt durch die Modellierung zukünftiger Umstände und die Bestimmung des optimalen Massnahmenprogrammes.

Die verwendeten Modelle und Methoden berücksichtigen selten die unsicheren zukünftigen Anforderungen an das Gebäude. Obwohl die Annahme von unveränderten Anforderungen von Vorteil für die mathematische Modellierung ist, trifft dies selten in der Realität zu. Bei unsicheren Veränderungen von Anforderungen ist es nicht wünschenswert, Massnahmenprogramme bereits jetzt zu bestimmen und genau festzulegen, welches Programm über den verbleibenden Zeitraum durchgeführt werden soll. Stattdessen ist es wünschenswert, bei unsicheren Anforderungen flexible Lösungen zu finden, welche die Möglichkeit berücksichtigen, Entscheidungen über das tatsächliche Massnahmenprogramm auf einen späteren Zeitpunkt zu verschieben, wenn mehr Informationen zur Verfügung stehen. Die Berücksichtigung dieser Flexibilität des Managements hinsichtlich der Entscheidung, welches Massnahmenprogramm durchgeführt werden soll, wird als grundsätzliche Basis jeder Methode gesehen, die zur Bestimmung optimaler Massnahmenprogramme verwendet werden sollte, wenn Unsicherheit über zukünftige Anforderungen besteht.

Um entscheiden zu können, ob Entscheidungsflexibilität in der Planung von Massnahmen berücksichtigt werden muss, ist es notwendig, den Nutzen dieser Flexibilität im Gebäudemanagement unter Berücksichtigung der zu berücksichtigenden Unsicherheiten zu bewerten. Wenn Massnahmenprogramme unter Berücksichtigung von Entscheidungsflexibilität ermittelt werden, kann der Gebäudemanager in Situtationen mit grossen Unsicherheiten ein System an neue Informationen anpassen und so Verluste vermeiden beziehungsweise günstige Gelegenheiten ergreifen.

Das Hauptziel dieser Forschungsarbeit ist es, die Berücksichtigung der Entscheidungsflexibilität des Gebäudemanagers in der Ermittlung und Bewertung von Massnahmenprogrammen unter Berücksichtigung von Unsicherheit in zukünftigen Anforderungen zu untersuchen und eine Methode zu identifizieren, die den Gebäudemanager in der Ermittlung und Bewertung solcher Massnahmenprogramme unterstützen kann.

In dieser Dissertation wird solch eine Realoptionsmethode zur Ermittlung und Bewertung von Massnahmenprogrammen unter Berücksichtigung von Entscheidungsflexibilität bei Unsicherheiten in Anforderungsänderungen vorgestellt und auf ein einfaches Beispiel eines fiktiven Bürogebäudes und auf das reale Beispiel einer Klinik des Universitätsspitals Zürich angewendet. Diese Methode basiert auf der Realoptionsanalyse und der Entscheidungsbaumanalyse. Um Massnahmenprojekte zu identifizieren, bei denen die Berücksichtigung von Entscheidungsflexibilität relevant ist, wird eine Methodik zur Identifikation und Bewertung von Massnahmenprojekten unter Berücksichtigung von Entscheidungs- und Gebäudeflexibilität vorgestellt und auf

das reale Beispiel angewendet.

Die Realoptionsmethode zur Ermittlung und Bewertung von Massnahmenprogrammen unter Berücksichtigung von Entscheidungsflexibilität bei Unsicherheiten in Anforderungsänderungen und die Methodik zur Identifikation und Bewertung von Massnahmenprojekten unter Berücksichtigung von Entscheidungs- und Gebäudeflexibilität werden auf das reale Beispiel angewendet, indem die Situation analysiert wird, adäquate stochastische Modelle von unsicheren Schlüsselparametern erstellt werden, statische und dynamische Bewertungsmodelle ermittelt werden, mögliche Massnahmenprojekte identifiziert werden und diese Massnahmenprojekte mit der Methode zur Ermittlung und Bewertung von Massnahmenprogrammen unter Berücksichtigung von Entscheidungsflexibilität bewertet werden. Obwohl die Entscheidungsflexibilität über die durchzuführenden Massnahmen über den definierten Zeitraum im Mittelpunkt dieser Arbeit stehen, werden im realen Beispiel auch drei verschiedene Designalternativen vorgestellt, die jeweils unterschiedliche Stufen von Gebäudeflexibilität aufweisen und somit unterschiedliche Stufen von Entscheidungsflexibilität ermöglichen. Diese Gebäudeflexibilität kann ebenfalls mit der gegebenen Methode zur Ermittlung und Bewertung von Massnahmenprogrammen unter Berücksichtigung von Entscheidungsflexibilität bewertet werden.

Die Schlussfolgerungen aus den Ergebnissen der Anwendung der Realoptionsmethode und der Methodik werden analysiert. Das Verwenden der Methode zur Bewertung von Massnahmenprogrammen unter Berücksichtigung von Entscheidungsflexibilität zeigt, dass die Methode die adequate Berücksichtigung der Entscheidungsflexibilität zulässt und damit zu einem erhöhten Nutzen für den Gebäudemanager führt. Der erwartete Nettonutzen und das mit der Methode ermittelte Massnahmenprogramm entsprechen eher der Realität und machen so eine bessere Budgetplanung möglich. Die Anwendung der Methode erfordert zusätzlichen Aufwand für die Definition der flexiblen Entscheidungsfindung, die Definition der Konsequenzen dieser Entscheidungen an den gegebenen Zeitpunkten und Werten der Schlüsselparameter über den untersuchten Zeitraum sowie die Berechnung der Durchführungswahrscheinlichkeiten für die möglichen Zeitpunkte und Werte der Schlüsselparameter, wenn das Durchführen einer Massnahme von Vorteil ist. Die Methode führt nicht für alle Gebäudekomponenten zu besseren Massnahmenprogrammen und sollte somit nur angewendet werden, wenn Entscheidungsflexibilität möglich, die Unsicherheit für Schlüsselparameter hoch und Massnahmenkosten im Vergleich zum möglichen Nutzen hoch sind.

Die Verwendung der Methodik zur Identifikation und Bewertung von Massnahmenprojekten unter Berücksichtigung von Entscheidungs- und Gebäudeflexibilität auf das reale Beispiel zeigt, dass die Methodik angewendet werden kann und relevante Ergebnisse liefert. Dabei hängt die Methodik stark von Stakeholderwissen ab und erfordert gute und ausführliche Kommunikation mit den Stakeholdern über den gesamten Prozess. Über den gesamten Prozess müssen erhebliche Vereinfachungen, bezüglich der Auswahl der Schlüsselparameter und der Modelle, vorgenommen werden, um die Komplexität auf einem akzeptablen Niveau zu halten, wobei die Methodik an das gewünschte Komplexitätsniveau des betrachteten Projekts angepasst werden kann.

Die Anwendung der Realoptionsmethode und der Methodik auf das einfache und das reale Beispiel zeigt, dass die Massnahmenprogramme unter Berücksichtigung von Entscheidungsflexibilität einen grösseren erwarteten Nettonutzen haben können als diejenigen, die ohne Berücksichtigung von Entscheidungsflexibilität ermittelt wurden. Der Unterschied der Nettonutzen mit und ohne Berücksichtigung der Entscheidungsflexibilität ist bei den Beispielen klein, er liegt im Fehlerbereich der Eingangsparameter, was nicht den erhöhten Aufwand für die Berücksichtigung der Entscheidungsflexibilität rechtfertigt. Dies ist hauptsächlich auf den geringen Einfluss der Unsicherheiten, die in den Beispielen berücksichtigt wurden, zurückzuführen. Diese Erkenntnis kann jedoch nur durch die Anwendung einer angemessenen Bewertungsmethode gewonnen werden, so wie sie in dieser Arbeit präsentiert wird. Auf Basis dieses Ergebnisses kann der Entscheidungsträger fundiert entscheiden, welchem Massnahmenprogramm er folgen möchte, mit oder ohne Berücksichtigung von Entscheidungsflexibilität. Auch kann in den frühen Schritten der Methodik der Einfluss der Unsicherheit im betrachteten Fall grob bewertet werden.

Zukünftige Forschung sollte eine tiefere Analyse der stochastischen Modelle beinhalten, die für die Ermittlung und Bewertung der Massnahmenprogramme verwendet und in dieser Arbeit vereinfacht wurden. Geeignete Methoden zur Modellierung von Anforderungsänderungen in Verbindung mit Änderungen der verbundenen Einflussfaktoren sollten, basierend auf der vorgestellten Klassifikation von Einflussfaktoren, Anforderungsänderungen und ihrer Auswirkungen, identifiziert und für die Anwendung getestet werden. Die Berücksichtigung von Entscheidungsflexibilität in der Bestimmung von Massnahmenprogrammen ist nicht anwendbar für alle Gebäudekomponenten, da die Anwendung nur unter bestimmten Bedingungen von Nutzen ist. Es kann angenommen werden, dass viele Massnahmenprogramme für ein komplettes Gebäude ohne Berücksichtigung von Entscheidungsflexibilität ermittelt werden, und somit auch unflexible Massnahmenprogramme erstellt werden. Daher müssen die Methode und die Methodik unter Berücksichtigung von Entscheidungsflexibilität unter Berücksichtigung von unflexiblen Massnahmenprogrammen in angrenzenden Gebäudekomponenten angewendet werden.

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Chapter 1

Introduction

1.1 Background and motivation

One task of building managers is to ensure that their buildings function as required over a defined period of time. This is a challenging task, particularly because the ability of buildings to meet demands[1] changes over time. Two reasons stand out:

1. The change of the ability of the building to meet current demands, which normally decreases as elements and connections between elements deteriorate.
2. The change of demands on the building, for example new laws concerning the energy consumption of buildings, which causes the building to become gradually obsolete[2].

Building managers can execute interventions[3] on the building elements to meet the required demands. If there were no constraints, such as budget constraints or the constraint to minimize the interruption of building operation, interventions would be executed in short time intervals, to ensure that the condition of all building elements remains close to the required level. However, such constraints exist and lead to the necessity for the building manager to find optimal intervention programs. An intervention program (IP) is a list of interventions to execute over a defined period of time, with the actual time and type of the intervention, with the highest expected net benefit over the investigated time period, considering the given constraints.

To determine when to intervene on buildings[4] and what intervention is to be done, building managers are increasingly supporting their decision making process through the use of computerized infrastructure management systems (IMS)[5][6]. The most advanced of these systems support the decision making process through the modelling of deterioration and changes in demand and the determination of the optimal intervention program to restore the building to a condition in which it can continue to, or can again, provide the presently required service level. Changes in demand, however, have been considered less widely than deterioration in most of these systems.

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[1] In this context, the required service level of a building results from demand situations, e.g. the demand for more and better living space results in the required service level in the form of apartment size and layout. Changes in demand will result in changes of the service level on buildings (compare appendix E).

[2] Changes in demand in this context include all key parameters that lead to the choice of different optimal intervention programs, i.e. all factors that (1) lead to a change of boundary conditions of the optimisation or (2) different goals of optimization or (3) introduce new candidate solutions.

[3] Interventions on buildings are herein defined as actions, which (1) keep a building and its components in a state to meet the initial demands, herein referred to as maintenance interventions, or (2) which adapt the building and its components to new demands, herein referred to as modification interventions (compare appendix D.1.5).

[4] See definition of a building in appendix D.1.1.

[5] IMS are software tools that determine quantitative intervention programs, i.e. intervention programs that give the exact time and type of interventions for a system to be taken in a given planning horizon. On the object level, IMS consist, on a very high level, of (1) a component for the prediction of system performance by deterioration modelling, (2) one for choosing possible interventions when required, and (3) one for the modelling of the effect of the taken interventions. These components produce different programs, which have to be evaluated with the help of an adequate optimization algorithm.

[6] Infrastructure or building management encompasses the process described in figure D.3 in appendix D.1.2.

Changes in demand are relevant in the determination of optimal intervention programs. A recent study by Sarja et al. (2006) found that changing demands are the cause of refurbishment in 26% of all cases, and in 50% of all cases when the buildings or infrastructures were demolished. It is suggested that the percentage is even higher for the renewal of components or modules, such as technical equipment.

It can be concluded that the change of demands is an important factor in the life cycle of a building and should be considered in the determination of optimal intervention programs, as modifications are often major interventions that affect maintenance interventions, which are counteracting deterioration, strongly.

While the modelling of deterioration of building elements over longer periods of time, and thus the prediction of an elements condition with both deterministic and probabilistic models, is considered extensively in research and practice, such models for predictions for the changes of demands on a building have not been used widely in the context of the determination of intervention programs, but rather in the context of business investment. There is often considerable uncertainty associated with the key parameters leading to changes in demand. This uncertainty is one reason for this lack of consideration of demand changes in the determination of intervention programs, even though a wide variety of probabilistic models is available for uncertain processes, and even in use for the modelling of deterioration.

Uncertainty about changes in demand make it undesirable to attempt to evaluate intervention programs now and then determine exactly which one to follow over the remaining investigated time period. It can be assumed that a building manager will adapt his or her decision about the execution of interventions over the investigated time period, e.g. when demands change, should it be beneficial; thus, the possibility needs to be considered, that the decision about the actual intervention program to follow can be postponed to a later moment, i.e. whether or not an intervention is to be executed now or not.

Taking into consideration this flexibility in decision making about the execution of interventions, which allows for more information to be considered at a later date, is believed to be a cornerstone of any method to be used to determine optimal intervention programs where there is uncertainty with respect to future demand. Existing IMS do not take such flexibility in decision making into account, i.e. the determination of optimal intervention programs is done under the assumption of intervention programs that are not changed over the investigated time period.

The evaluation of a set of decisions under uncertainty about the state of nature has been done before; the main methods for this purpose investigated in this thesis are (I) the Real Options Analysis (ROA) and (II) Decision Tree Analysis (DTA)[7]. These evaluation methods have been used for the evaluation of numerous engineering design and investment projects. There have also been a number of examples where these evaluation methods have been used for the evaluation of interventions for specific infrastructure objects (Haddad et al., 2011a,b; Koide et al., 2001; Santa-Cruz and Heredia-Zavoni, 2009). The focus of these publications, however, has been on the flexibility of the infrastructure or buildings themselves, which has to be distinguished from the decision flexibility in intervention programs[8].

In summary, the following main points can be made:

1. Changes in demand should be considered in the determination of intervention programs, as they can have considerable impact on the expected net benefits of an intervention program, which the building manager uses to pick the optimal intervention program.

2. Changes in demand should be considered probabilistically in the context of the determination of intervention programs as their outcomes are uncertain.

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[7] ROA and DTA and their relation are explained in more detail in appendix D.4.

[8] Flexibility in decision making in intervention programs: Decision flexibility, i.e. the decision about the exact time and type of an intervention is not fixed today but can be postponed to a later point in time. Flexibility of a building or building flexibility: Property of the building and its elements, defining how easily they can be modified and thus to what extent flexible decision making about interventions is possible (always assuming that modifications are easier or cheaper than tearing down the complete building).

3. Due to the uncertainty in changes in demand it can be assumed that building managers will be flexible in their decision making about interventions, i.e. the exact intervention program is not known from the beginning.
4. This flexibility of decision making of the building manager needs to be considered in the determination of intervention programs.
5. Flexibility in decision making about interventions and flexibility in buildings can be evaluated with either (i) Real Options Analysis or (ii) Decision Tree Analysis.

1.2 Aims

The main objective of this research is to investigate how to consider the decision flexibility of the decision maker in the evaluation of intervention programs with consideration of the uncertainty in future demand and to define a method that can support a decision maker in the evaluation of such intervention programs. This was done by

1. identifying relevant classes of uncertain changes in demand,
2. identifying and applying a methodology for the identification of
    (a) the most relevant uncertain scenarios for future demand and
    (b) suitable possibilities for flexible decision making about interventions with corresponding building flexibility

    for a specific building case, the methodology for the identification and evaluation of intervention projects with consideration of decision and building flexibility,
3. investigating possible ways of determining and evaluating the decision flexibility and building flexibility with Real Option Analysis and Decision Tree Analysis, and apply a suitable method, either from Real Option Analysis or Decision Tree Analysis, to determine and evaluate optimal intervention programs with consideration of decision flexibility of the building manager with regard to intervention programs and with consideration of uncertainty in future demands and constraints on the service level of the building, and
4. analysing the ramifications of the results from the application of the
    (a) methodology for the identification and evaluation of intervention projects with consideration of decision and building flexibility on a real world example and
    (b) the presented method for the determination and evaluation of intervention programs with consideration of decision flexibility on both a simple example and a real world example,

    also with regard to their possible use in existing methodologies for building management and intervention management systems.

1.3 Research significance

The research significance of this thesis is defined by the following points:

1. The systematic methodology for the identification of relevant uncertainties in future demand, the decision flexibility about the interventions to execute and the corresponding building flexibility supports the building manager in making better decisions about modification interventions.

2. The impact of flexible decision making on intervention programs can be estimated, and optimal intervention programs with consideration of decision flexibility and changes in demand can be determined with the application of Real Option Analysis or Decision Tree Analysis.
3. Negative impacts from uncertainty can be reduced with the consideration of decision flexibility in intervention programs and building flexibility.

1.4 Limitations

The following limitations apply to this work:

1. Flexibility in decision making was considered for interventions becoming necessary due to changes in demands, not deterioration, even though there can be considerable uncertainty about the deterioration of buildings and their elements over an investigated time period.
2. This work does not include a comprehensive collection and classification of relevant demand changes in the determination of intervention programs, the influencing key parameters or the resulting effects on the service level of a building; thus, a detailed modelling of the relationships between these factors was also not included.
3. This work does not include a comprehensive investigation of all costs and benefits, monetary and other, that can be used for the evaluation of a modification intervention program due to changes in demand, as it exists e.g. for the evaluation of maintenance intervention programs for highway infrastructure.

1.5 Organisation of the thesis

After the introduction of the thesis topic in chapter 1, the thesis is structured as follows to reach the aims described in section 1.2:

Chapter 2 provides a review of the state of research and the state of practice in the area of determination of intervention programs as well as the evaluation of flexibility in building design and decision making and identifies the research gap.

- First, the state of research and state of practice in the determination of intervention programs due to deterioration are presented for buildings and other infrastructure.
- Second, the state of research and state of practice in the determination of intervention programs due to changes in demand are presented for buildings and other infrastructure.
- Third, the state of research and state of practice in the evaluation of flexible decision making in interventions and flexible building design with the real options analysis is presented.
- Finally, the discussion and conclusion show the findings of this review.

The goal of chapter 3 is to present the methodology for the identification and evaluation of intervention programs with consideration of flexible decision making and design. This methodology consists of eleven steps.

- In steps 1 to 2, the desired service level and the key parameters are determined.
- In steps 3 to 5, adequate models to predict the likelihood of future scenarios of the key parameters are selected.
- In steps 6 and 7, a set of possible models for the evaluation of the service level are discussed and selected.

- In steps 8 and 9, possible renewal projects are identified, i.e. combinations of decision flexibility with regard to interventions and increased design flexibility of the building.
- In steps 10 and 11, the evaluation of intervention program with consideration of uncertainty and flexibility in decision making is prepared and executed.

The goal of chapter 4 is to show the proposed method for the determination and evaluation of intervention programs with consideration of uncertainty and flexibility in decision making, based on existing models and methods.

- First, an overview with necessary components is shown.
- Second, possible stochastic models to be used in the method are described.
- Third, a traditional method for comparison with the necessary steps of the methods is presented.
- Fourth, the mathematical formulations used in the method with consideration of decision flexibility is described.
- Finally, possible decision situations and intervention program types are presented.

The goal of chapter 5 is to demonstrate the effect of using the method presented in chapter 4 in the determination of intervention programs on a simple example of a fictive office building.

- First, the simple example is described.
- Second, the model of the uncertain key parameter is described.
- Finally, the results and their variation in a sensitivity analysis are presented and discussed.

The goal of chapter 6 is to show that the proposed evaluation method with consideration of uncertainty and flexibility presented in this thesis can be applied to a real world situation. The real world example considers the clinic of nuclear medicine of the university hospital Zurich. The eleven general steps presented in detail in chapter 3 are executed.

- First, the situation is analysed in steps 1 and 2, models of the key parameters are determined in steps 3 to 5 and a static and dynamic evaluation of the service level are established in steps 6 and 7.
- Second, possible renewal projects are identified in steps 8 and 9.
- Third, these renewal projects are evaluated, with the method presented in chapter 5, i.e. with consideration of decision flexibility in the determination of intervention program in steps 10 and 11.
- Finally, the results of the real world example are presented, discussed and investigated further in a thorough sensitivity analysis.

A summary, the discussion of the content of the thesis, overall conclusions, and the outlook of this work are provided in chapter 7.

For those who are unfamiliar with the field, a background section has been included in appendix D. This background section provides the basic definitions in infrastructure management and the construction of intervention programs. The goal of this appendix is to put the content of this thesis in the right context.

- First, the basics for the intervention management of buildings will be defined, especially the terms intervention strategy and intervention program.
- Second, the terms risk and uncertainty will be specified, and the content of this work will be positioned with regard to these terms.

- Third, the definition of flexibility in the context of intervention programs will be elaborated, and its relevance will be explained.
- Finally, general attributes of methods and models that can be used in the evaluation of flexible intervention programs will be presented.

Chapter 2

State of research and state of practice

The consideration of both deterioration and changes in demand are relevant when determining the intervention programs for buildings and their components, and there is often uncertainty associated with both deterioration and changes in demand. Further, it was elaborated that decision flexibility exists for a building manager with regard to decisions about interventions to be executed over an investigated time period.

In this chapter, the topic of this thesis is set in context with existing work in research and practice with regard to the determination of intervention programs for buildings and other infrastructure with consideration of uncertainty and the evaluation of engineering problems with consideration of decision flexibility.

First, current methods for the determination and evaluation of intervention programs for buildings and other infrastructure are presented, considering both deterioration, changes in demand and constraints. The focus lies here on methods in which uncertainty in the predictions of future deterioration and changes in demand are considered, i.e. methods using probabilistic models for these parameters. Second, as decision flexibility is not considered in the construction of intervention programs in the current publications, the state of research in the use of methods for the evaluation of decision and design flexibility in building and infrastructure design and management was investigated. The vast majority of these publications consider Real Option Analysis (compare appendix D.4). Finally, the findings from this review are summarised, and conclusions are drawn with regard to the goal of this thesis.

2.1 Methods for the determination of intervention programs for buildings and other infrastructure

This section shows a selection of publications considering the current methods for the determination of intervention programs for buildings and other infrastructure relevant to this thesis, considering both deterioration and changes in demand and constraints. The focus lies on methods using (1) consistent models for the prediction of future deterioration and changes in demand (not only expert opinion) with the goal to capture all relevant scenarios, and the consideration of uncertainty through probabilistic models, and (2) quantitative evaluation methods for finding the optimal intervention programs, e.g. mathematical programming. These two aspects, however, could not always be considered, especially for methods in which intervention programs due to changes in demand were constructed.

2.1.1 State of research

2.1.1.1 Deterioration

There is a great body of methods for the determination of intervention programs for buildings and other infrastructure with consideration of deterioration processes. Original methods for the determination of intervention programs for buildings and other infrastructure were based on deterministic models of the deterioration influencing the costs and benefits over the life cycle, i.e. the key parameters they depend on were assumed to be known with certainty. Examples for such methods for buildings are e.g. Mendes Silva and Falorca (2009); Flores-Colen and de Brito (2010), who use deterministic deterioration curves, adjusted according to the identified mechanisms leading to the deterioration, and determine intervention programs for building components that minimize life cycle costs whilst sustaining a minimum acceptable quality.

Building on these methods based on deterministic models, a great number of researchers realised the necessity to consider uncertainties in the prediction of the state of nature in the planning of interventions, and proposed methods with probabilistic models to address the uncertainties associated with engineering and construction projects (Kobayashi and Kuhn, 2007; Woodward, 1997) to be used for the determination and evaluation of intervention programs.

Markov models are often used for modelling the deterioration of buildings and other infrastructure: Lounis and Vanier (2000), for example, use the performance prediction based on a Markov model and determine the optimal intervention program with a multi-objective cost-benefit optimization for a roofing system. Lacasse et al. (2008) use the same method for a facade system. Zhang (2006, a) and Zhang and Gao (2010) use Markov models to model the change of the condition of buildings in a building network and determine intervention programs for these networks with integer programming and linear programming.

Monte Carlo simulation is also a model often used for modelling the deterioration of buildings and other infrastructure: Marseguerra and Zio (2000) use Monte Carlo simulation for the estimation of reliability, costs and revenues in the operation of industrial plants and use a genetic algorithm to optimize component maintenance periods and the number of repair teams. Borgonovo et al. (2000) use Monte Carlo simulation for the prediction of deterioration of the components of a production plant, and determine the desired intervention program by determining the optimal fixed intervention interval leading to lowest costs for repair, downtime and maintenance. Bocchini and Frangopol (2011) use Monte Carlo simulation to simulate the service states of bridges and the effect of maintenance interventions, and determine the optimal preventive intervention programs for these bridges in a network with a multi-objective genetic algorithm, resulting in a Pareto frontier of optimal solutions for the decision maker to chose from.

2.1.1.2 Change of demand and constraints

While the major body of methods used in the determination of optimal intervention programs in building management considers the deterioration of materials, components and structures, efforts have been made to determine intervention programs explicitly under the consideration of changes in demand and constraints. Most of these methods rely only on expert's opinion, sometimes for both predicting the change in demand and constraints, resulting in deterministic scenarios for these predictions, and the determination of intervention programs to follow, e.g. (Taillandier et al., 2009, 2011).

There are some methods using Monte Carlo simulation for the prediction of changes in demand and constraints: Booth and Choudhary (2013), for example, model uncertain energy savings after interventions for improvement of the energy efficiency of a set of buildings with Monte-Carlo simulation and Bayesian regression. Out of the set of candidate intervention programs, consisting of single interventions and determined by expert opinion, the intervention program with the best expected multi-attribute utility (energy savings, resulting in lifetime financial savings, emission reduction, temperature takeback, installation costs) is chosen as optimal. Borgonovo et al. (2000) use Monte Carlo simulation not only for the deterioration but also the obsolescence of components of a production plant. Intervention programs are determined by finding the optimal fixed intervention interval leading to lowest costs for repair, downtime and maintenance by choosing the interval leading to the best cost-benefit ratio.

2.1.2 State of practice

Probabilistic models and methods for the determination of intervention programs for buildings are also used in practice, often as part of infrastructure management systems, or IMS.

The Canadian Institute for Research and Construction and Public Works and Government services initiated the BELCAM project[1]. The resulting IMS combines (1) an condition assessment module, (2) a Markov model for the prediction of deterioration (Vanier et al., 2001; Lounis et al., 1999) and (3) a multi-objective optimization method that uses compromise programming for this optimisation (Lounis and Vanier, 2000).

The software tool EPIQR[2] combines (1) a framework for a quick survey of the a building's condition, (2) a database with possible interventions in repair, refurbishment and retrofit interventions, their effects on building condition and their costs, (3) a tool for the prediction of improvement for the energy situation and the indoor environmental quality for each intervention, (4) a software to model deterioration of building components probabilistically with Markov models, and (5) the MEDIC tool to simulate the future building condition and calculate the costs resulting for the intervention strategies. The intervention strategy to follow is selected by expert's opinion, based on the aforementioned simulations (Caccavelli et al., 1999; Flourentzou and Roulet, 2002). INVESTIMMO is a software, based on EPIQR, for the determination of intervention strategies for large portfolios of residential buildings. The user can create and evaluate several intervention strategies with a cost analysis, which considers changes in the building's physical and functional state due to deterioration, future deterioration of building elements, occupants' quality of life, energy and water consumption, and the environmental impact from a building's operation and retrofit interventions, reduction of operating costs and the overall time effectiveness of the investment (Balaras et al., 2005).

The European project TOBUS[3] considers in its assessment module for a building's condition deterioration, obsolescence, energy consumption and indoor environmental quality, using condition states for obsolescence. TOBUS offers a module for the determination of very simple intervention programs, which provides the decision maker with a tool to build and change interventions manually and the necessary information. TOBUS does not offer any algorithms for selecting the optimal intervention programs but only supports the expert decision maker in the choice of intervention programs. The decision maker is supposed to start from one intervention program and alter it according to the information he gets from TOBUS. TOBUS shows the condition of each element, its interaction with other elements, and the costs related to the chosen intervention program. The tool highlights contradictions between interventions on elements (Wittchen and Brandt, 2002; Flourentzou et al., 2002; Caccavelli and Gugerli, 2002).

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[1] The BELCAM project is "the Building Envelope Life Cycle Asset Management" project, which is aimed at helping building owners and facilities managers predict the service life of the building envelope and its components - a critical aid for managing their property inventory."(Canada, 2012)

[2] EPIQR stands for "Energy performance, Indoor Environmental quality and retrofit". The European Union launched the project EPIQR with the goal to develop a software tool for architects and other involved decision makers to make integrated decisions about refurbishment and modification interventions on residential (apartment) buildings with a minimum of complexity and effort.

[3] TOBUS has been initiated by the European Commission in the frame of the JOULE II programme. The aim of TOBUS was to develop a decision support tool for the assessment of relevant requirements for modification of office buildings and the estimation of the costs related to possible interventions to meet these requirements (Caccavelli and Gugerli, 2002).

2.2 Methods for the evaluation of decision and design flexibility in building and infrastructure design and management

Real Option Analysis and Decision Tree Analysis were applied widely to engineering projects for buildings and other infrastructure to consider decision and design flexibility. The following section shows the state of research in the use of ROA and DTA in decision making about the timing and/or type of interventions on buildings and other infrastructure. The vast majority of these publications describe the use of ROA. In the next section, a selection of current publications describing the use of ROA and DTA to determine the best design of buildings to facilitate future modifications due to changes in demand is presented.

2.2.1 Intervention management of buildings and other infrastructure

In the following section, publications in which ROA and DTA were used to determine time and/or type of interventions on buildings and other infrastructure objects are presented. Menassa (2011) and Rexrode J. and Menassa C. (2010) use ROA to evaluate the two investment possibilities to execute energy retrofit interventions on existing building now or at a later time and if to execute the intervention in one or two stages, under uncertainty of expected benefits and other key parameters from energy retrofits (an example for sustainable retrofit intervention is the installation of solar panels). Ashuri et al. (2011) use ROA to evaluate different building designs regarding the ease of sustainable retrofit interventions (installation of solar panels) over the life cycle of buildings, i.e. the building flexibility, under uncertainty. A binomial lattice is used to model the uncertain development of the energy price over time.

Lethanh and Adey (2014a) use a ROA to determine optimal intervention windows for railway infrastructure, where interventions were to be coordinated between multiple rail managers. The building manager has the decision flexibility to decide in the intervention window if to execute an intervention or not, considering uncertainty about the state of the railway infrastructure in the intervention window. Optimal intervention windows were selected according to their expected value at t=0. The expected values of two different intervention strategies were also compared. Santa-Cruz and Heredia-Zavoni (2009) use ROA to evaluate the decision flexibility to decide about executing interventions, maintenance intervention, decommissioning or doing nothing, on offshore oil platforms during a single intervention window, which is defined by an inspection of the platform. The Black Scholes method is used for evaluation of this decision flexibility under consideration of uncertainty about the state of the platform in the intervention window. The expected value from this evaluation is used to decide which interventions should be prepared to be executed upon inspection, i.e. in the intervention window. Koide et al. (2001) use ROA to evaluate two rehabilitation interventions today on a steel girder bridge under consideration of possible future interventions on the bridge. The decision today is made between a major rehabilitation and a minor repair. They assume that further repair or replacement decisions can be made after a legal inspection every two years over the investigated time period. The decision about these future interventions depends on the state of the bridge at time t. The uncertainty in the state of the bridge over the investigated time period is modelled with a probability density function at every inspection point.

2.2.2 Design of buildings and other infrastructure to facilitate modifications

Several examples exist where the ROA was used to evaluate the flexible designs of buildings and other infrastructure to facilitate modifications in the future. A selection is shown in this section. Greden and Glicksman (2004) use ROA to evaluate the flexible design of a laboratory building space that can be constructed in a way so that a conversion into office space is easy (flexible) or expensive (inflexible). The uncertain parameters are the future rent price and the actual dates of the change. This work is based on (Greden and Glicksman, 2005), where ROA is used to evaluate different design alternatives facilitating the installation of mechanical cooling in a building to save energy. Monte Carlo simulation is used to model the system's technical performance under future uncertainty in the market price of rent, timing, amount of space needed, and the number of renovations. Kalligeros and de Weck (2004) present a framework for the evaluation of designs for modular commercial buildings under market uncertainty which need to be adapted to changing market demands. In (Guma and de Neufville, 2008) the ROA is used on the evaluation of four major building projects with consideration of adding five or more stories to each building in the future with uncertainty in market demand for space, using Monte Carlo simulation.

Zhao and Tseng (2003) use the ROA to determine the best foundation size for a parking garage structure that might have to be adapted to new demand situations in the future by adding more parking levels, using a trinomial tree to model the uncertainty in future demand in parking space. de Neufville et al. (2006) use ROA for a similar example of a parking garage that is to be enlarged if needed, using Monte Carlo simulation for generating random scenarios for the demand development and to evaluate a flexible and inflexible design. Fawcett et al. (2015) apply ROA to the evaluation of the design of a highway with consideration of uncertainty of the rate of traffic growth and the discount rate. Seven designs for the roadway were evaluated, under consideration of six modifications that can be executed should the traffic demand cross given thresholds in the future.

There are many other examples of the use of ROA in evaluating designs of infrastructure objects facilitating future modifications. A good reference for further reading is Martins et al. (2013), who give a comprehensive overview of the state of research in the use of real option analysis on infrastructure projects with corresponding examples.

2.3 Discussion and conclusion

It can be seen from the review of the state of research and the state of practice that

- there are traditional methods (without the use of Real Option Analysis) for the determination of intervention programs for buildings and other infrastructure for choosing optimal intervention programs (time and type of intervention) for buildings, also considering uncertainties by modelling underlying parameters (deterioration, changes in demand and constraints) probabilistically - however, these methods assume in their optimization that intervention programs are inflexible (even though they mention that interventions can be adapted later),

- in these traditional methods where the changes in demand and constraints are considered, candidate and optimal intervention programs are often not determined systematically, i.e. often, the optimal IPs are chosen through expert opinion,

- there are many applications of ROA and DTA in building modification. Most of them focus , on the differences in value of design solutions (Flex/Inflex) today, not on possible timing of interventions in the future. The given sources suggest different methods for valuing a building's flexibility and its components to be modified to new requirements over the lifetime of the building, and

- there are a few publications about the application of ROA and DTA in this context that focus on the timing of interventions using a method from the Real Option Analysis, and focusing on specific time windows for execution.

Further research is possible about the use of the ROA and DTA to evaluate optimal maintenance and modification intervention programs for buildings, with the investigation of the determination of the preferred timing of execution of the interventions and the corresponding scenarios, under consideration the probability of changes of demand and the ability of decision makers to change their decisions in the future if beneficial. Possible outputs from the use of such a method from the ROA or DTA and the comparison of the results to the results of traditional methods will be investigated in greater detail.

Chapter 3

Methodology for the identification and evaluation of intervention projects with consideration of decision and building flexibility

The general methodology for the identification and evaluation of intervention and design projects with consideration of decision and building flexibility (MIP) presented in this chapter is based on the approach by de Neufville and Scholtes (2011), i.e. the five-step process for the estimation of the distribution of future possibilities, the identification of candidate flexibilities, and the evaluation and choice of flexible design options. The steps by de Neufville and Scholtes (2011) were adapted to fit the context of intervention projects and the application of the Real Option Method for the identification and evaluation of intervention programs with consideration of decision flexibility. Mainly, step 8 and 9 were added to ensure that possible interventions and flexibility in decision making are considered in addition to the design flexibility, and in step 11, the decision flexibility about the time and type of intervention to be exeucted over the investigated time period can be evaluated with the Real Option Method. The methodology presented in this chapter was adapted and published in (Esders et al., 2015) and applied to a real world example (see paper in appendix G).

An intervention and design project (IDP) is herein defined as the combination of intervention programs with decision flexibility and a related increase in building flexibility by design to facilitate this flexible decision making, if necessary. The presented methodology can be divided in three main parts:

1. Identify and model the system key parameters
2. Identify possible IDPs
3. Evaluate the possible IDPs

These three main parts are presented in more detail in tables 3.1, 3.2 and 3.4. The evaluation of intervention and design projects in step 11 was the focus of this thesis. The other steps of the methodology can be followed at different levels, from using very simple qualitative methods to using very detailed quantitative methods and assumptions, e.g. including the use of statistical methods for the interpretation of historical data and making forecasts, as demonstrated by (Cryer and Chan, 2008), and for the identification of ways to modify facilities, as demonstrated by (Hu and Poh, 2011). The choice of level depends on the amount of time, effort and availability of the building manager and the requirements of the investigation.

3.1 Identify and model system key parameters - Steps 1 to 7

This methodology was applied to a real world example, which is presented in detail in the publication by (Esders et al., 2015). Steps 1 to 7 in table 3.1 describe how the model system and key parameters are identified and analysed, and how the appropriate stochastic models for the key parameters can be found.

Table 3.1: Methodology MIP - Steps 1 to 7

Part	No.	Step	Comment
Model system and key parameters	1	Assess service level provided by and expected from building	This step is done to obtain a general overview of how the building is expected to function over the investigated time period. The expected function is defined in the level of service (LOS). This is to be done with taking into consideration how all of the elements in the building work together. It often requires the involvement of stakeholders of the building regarding their demands and processes in the building.
	2	Identify key parameters	In this step all parameters whose values have a non-negligible probability of changing, in a way that will have a large effect on the ability of the building to provide an adequate LOS, are to be identified. It is often useful to think of the processes that might lead to this changing, e.g. increases in fuel prices, the desire to have larger apartments. Thought then needs to be given as to which ones should result in a change to the building.
	3	Analyse past evolution of values of possible key parameters	This step involves the collection and investigation of historical data for the most important key parameters to gain insight into which possible future scenarios may occur and with what likelihood.
	4	Analyse changes in trends	If there are changes in the trends observed in past data, the reasons why they have occurred and the factors that led to this need to be identified. This information needs to be used in the identification of such trend changes in possible future scenarios and in how likely they are.
	5	Select models to predict likelihood of future scenarios	In this step models are selected based on the data, and the ability to use them to make future predictions is evaluated. The latter is done by verifying the ability of the selected models to make past predictions.
	6	Establish static model	An evaluation framework for system's service level as a function of the key parameters is established. If it is assumed that the values of the key parameters can be predicted precisely, this is a static model. The development of an appropriate model requires an understanding of how the building provides an adequate LOS, as well as how the system's service level is affected by a myriad of economic, environmental and social factors.
	7	Establish dynamic model	The static model is to be extended to represent the possible variations in the selected uncertain key parameters, the interactions between them and their influence on the system's service level.
			If desired, the effect of variations in the values of the key parameters of the static model on future benefit are tested using a sensitivity analysis. The parameters with the largest effect on future benefit are to be included in the dynamic model, keeping in mind the amount of work associated with the evaluation of each scenario and the level of detail required in the analysis.
			Once the key parameters to be used are decided, the ranges of these parameters are to be determined and the uncertainty associated with their values needs to be modelled.

3.2 Identify possible intervention and design projects - Steps 8 and 9

In steps 8, possible changes in operation and use are identified first. In step 9, possible interventions and flexible design alternatives are determined.

Table 3.2: Methodology MIP - Steps 8 and 9

Part	No.	Step	Comment
Identify intervention and design projects	8	Identify possible ways in $t > 0$ to change the building use or operation so that new LOS could be provided	In this step, possible changes to building use and operation are determined to adapt the building to different future scenarios with the potential to maximize net benefits. The determination of building use and operation often requires the definition of new LOS, and explicit consideration of how it could change over the investigated time period. This step involves considerable brainstorming and discussions with the stakeholders of the building and process specialists.
	9	Identify possible renewal projects at $t = 0$	In this step, possible interventions over the investigated time period need to be defined to enable the above determined changes to improve facility use and operation. Then, special consideration should be given to the definition of possible interventions at $t = 0$, which are referred to here as renewal projects. The sub process is shown in table 3.3.

Table 3.3 shows the sub-process of step 9 in detail.

Table 3.3: Sub-process of Step 9 in Table 1: Identify possible projects

Sub-step	Description	Comments
9.1	Identify details of changes in building use and operation in $t > 0$	The changes in building use and operation over the investigated time period are to be structured so that it is easy to identify both the possible effects on the building (i.e. with regard to interventions and operation) to maximize net benefit and the time that these should be done.
9.2	Identify necessary interventions and operations on building in detail in $t > 0$	The necessary interventions and changes in operation on the building are determined and organized in IPs and operation plans respectively, based on the general possible changes identified in the previous sub-step. These IPs include all interventions required to ensure that the general changes in use and operation will work and are planned in sufficient detail.
9.3	Construct possible renewal projects at $t = 0$	The proposed renewal project is checked to see if it is well fitted to the possible future scenarios. In particular, it is checked to see if it is robust or flexible. Part of this process includes envisioning if the future possible changes to the building would be better done now, or if the building could be built differently now so that it would be easier to make the changes in the future if they were required.
9.4	Pre-screen possible projects	A pre-screening is done to eliminate possible projects that are rather clearly not going to result in a maximisation of net benefit, i.e. either not flexible enough or robust enough. It is done to reduce the analysis effort in future steps. It can be done in many different ways. One is using a simple ranking based on expert opinion, and another is by defining a few basic criteria, and ranking these. The criteria can be weighted. If weighted, the sum of the multiplication between the score and weight will give the total score and will give insight into the most likely ways to change the building to maximise net benefit. As this ranking is rather approximate, it is advisable to set a threshold where one can say which possibilities are to be considered further and which ones not.

3.3 Evaluate possible intervention and design projects- Steps 10 and 11

Table 3.4: Methodology MIP - Steps 10 and 11

Part	No.	Step	Comment
Evaluate intervention and design projects	10	Estimate additional costs and benefits of each ID project in t > 0	In this step, the costs and benefits in each unit time for each investigated way to improve building use and operation and way to change the building are estimated. This is done for each investigated future, i.e. for each possible building use and operation scenario and all possible values for the key parameters. This step is to be done without consideration of probabilities of occurrence of each possible future or the ability of the building manager to change plans based on newly obtained information in the future.
	11	Estimate total additional net benefits of each project at t = 0	In this step, the cumulative costs and benefits of each identified possibility taking into consideration the probabilities of occurrence of the values of the key parameters in the future and the ability of a manager to change plans based on newly obtained information in the future. They are to be estimated relative to a reference project to modify the building. The method for determination and evaluation of intervention programs with consideration of decision and building flexibility (DEM) is applied here.

In step 11, the method for determination and evaluation of intervention programs with consideration of decision and building flexibility, which is described in the following chapter 4, is used. Thus, this step is the one described in greatest detail.

Chapter 4

Real Options Method for evaluation of intervention programs with consideration of decision flexibility

This chapter presents a method from the Real Option Analysis and Decision Tree Analysis[1] for the determination and evaluation of intervention programs with consideration of decision flexibility. In the method for intervention programs with consideration of decision flexibility, Real Option Analysis or Decision Tree Analysis, respectively, are used depending on the situation, i.e. using the risk-adjusted approach or not. For reasons of simplicity, the method will be called ROM. In this chapter, the method and its components are described in more detail. Some sections were published as described in (Esders et al., 2016).

4.1 Components

The method for the evaluation of intervention programs with consideration of decision flexibility requires the following components, which are also depicted in figure 4.1:

1. The modelling of one or multiple uncertain parameters with appropriate discrete stochastic models for the prediction of uncertain key parameters over the investigated time period.
2. A definition of how decisions are made over the investigated time period. This includes especially
   (a) the timing of the decisions
   (b) the type of decision making, e.g. according to an optimisation or when a threshold is transgressed.
3. Event trees or lattices, with the definition of nodes for possible values of the uncertain parameters, their probability of occurrence and the connection of these nodes.
4. The calculation of the costs and benefits used as the basis of decision making[2].
5. If required, the additional modelling of other input, e.g. the physical situation or maintenance planning.
6. The recursive decision making through the nodes of the combined lattice or tree according to the decision making defined above.

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[1] The Real Options Analysis is an extension of the Decision Tree Analysis. In appendix D.4, this difference is elaborated on further.

[2] Even though the examples in this thesis consider the monetary costs and benefits in the evaluation, also non-monetary components can be considered in this method, e.g. the environmental or social impacts of a decision. This depends on the preference and perspective of the decision maker.

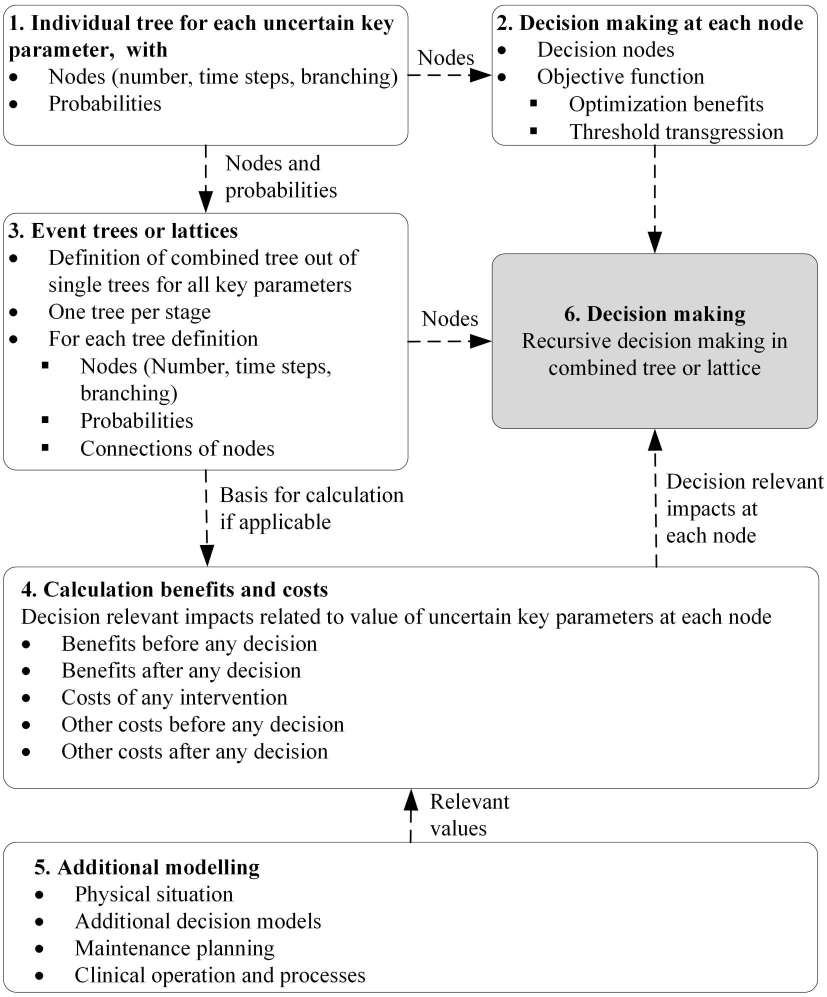

Figure 4.1: Components of evaluation method

4.2 Stochastic models for uncertain key parameters

Key parameters that influence the benefit of intervention programs and therefore decision making in the determination of intervention programs and that are uncertain can be modeled with probabilistic methods to make predictions about their future development. Different stochastic processes can be used to model these uncertain parameters, depending on the use of the model and the desired result of the evaluation. A selection of three processes (as also presented in Dixit and Pindyck (1993)) used in this work, that can be represented as binomial lattices, are presented in this section[3]:

- Geometric Brownian Motion (Suitable for manifest processes)
- Mean-Reverting Process (Suitable for manifest processes)
- Poisson Jump Process (Suitable for latent processes)

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[3] There are other popular processes that can be used in this context, e.g. the Markov process or the Levy process.

4.2.1 Geometric Brownian motion

The Geometric Brownian motion (GBM) is appropriate for non-negative parameters with exponential growth rates. The same input as for the Brownian motion is used, however, a log-normal distributed time variant is used. Other than the Brownian motion, this log-normal distribution cannot become negative, a property that is true for many processes in the evaluation of intervention programs in general, such as the oil price or the demand for a product, making the GBM widely applicable (Chow et al., 2011).

$$dS/S = \mu_s dt + \sigma_s dz \tag{4.1}$$

4.2.2 Mean reverting process

A mean reverting process, also called Ornstein-Uhlenbeck process, is suitable for modelling parameters with a tendency to vary around a mean value. The required input is, next to the mean value, $\overline{S}$, and the volatility, σ, a mean reversion parameter, k, defining how strong this tendency is to return to the mean value (Hahn and Dyer, 2008; Bastian-Pinto et al., 2009; Chow et al., 2011).

$$dS/S = k(\overline{S} - S)dt + \sigma dz \tag{4.2}$$

The expected S in t+1 depends on the value of S in t, and on its difference to the mean value $\overline{S}$; the bigger this difference is, the more likely S will return towards $\overline{S}$ in t+1. Thus, the increments of S are not independent from each other (Dixit and Pindyck, 1993).

4.2.3 Jump process

A jump process, also called a Poisson process, is used to describe significant changes in input parameters of known or uncertain size, so-called “events”, e.g. the success of research and development. According to Dixit and Pindyck (1993), λ denotes the mean arrival rate of such an event of the size u, i.e. the probability of the occurrence of event is λdt.

$$dq = \begin{cases} 0 & \textit{with probability } 1 - \lambda \, dt \\ u & \textit{with probability } \lambda \, dt \end{cases} \tag{4.3}$$

This leads to the definition of the stochastic process of S as follows (Dixit and Pindyck, 1993), with $f(S,t)$ and $g(S,t)$ being known functions:

$$dS/S = f(S,t)dt + g(S,t)dq \tag{4.4}$$

4.2.4 Representation of stochastic processes as binomial lattices

Stochastic processes can be represented in discrete-time step models, i.e. in trees or lattices, with a discrete number of possible outcomes in each year t. An example is given in the following figure 4.2, where the development of price S, e.g. as a Geometric Brownian motion, is given as a binomial, reconnecting lattice. Each connection of two paths i in the lattice is herein defined as a node, e.g. S_i. The paths i are defined by up-movements u, with a probability of p, and down-movements d, with a probability of $(1 - p)$. The path leading to node S_{uu} for example is defined by two up-movements, i.e. i_{uu}.

In addition to its computational tractability the use of a binomial or multinomial tree or lattice gives an attractive representation of the possible values of the key parameters (Dixit and Pindyck, 1993), which helps to increase transparency in the decision-making process (Kalligeros, 2010).

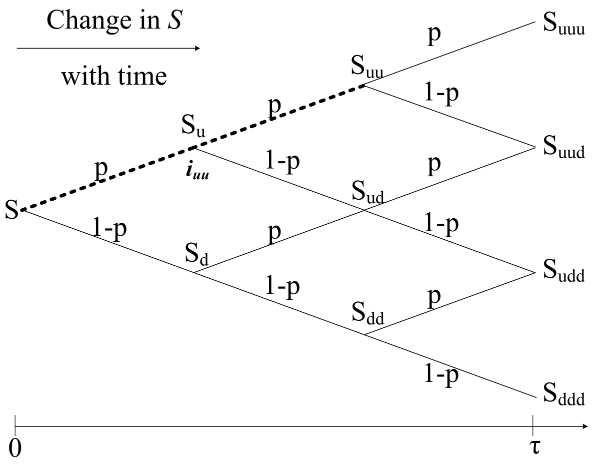

Figure 4.2: Binomial lattice with S and nodes N

4.2.5 Consideration of two uncertain key parameters

Often, the consideration of two or more uncertain key parameters is necessary. Copeland and Antikarov (2001) present the quadrinomial approach for the consideration of two uncorrelated uncertain key parameters that are modelled each in binomial lattices, an approach that was used in the real world example in chapter 6.

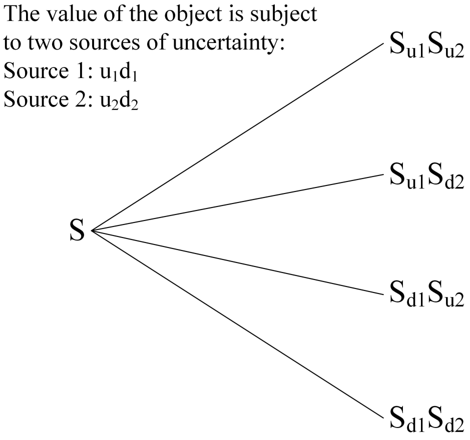

Figure 4.3: Quadrinomial lattice (adapted from (Copeland and Antikarov, 2001))

Assuming that these two key parameters are uncorrelated, the risk-neutral and the real probabilities can be combined following the equations (Copeland and Antikarov, 2001):

$$\begin{aligned} p_{u1u2} &= p_{u1} \cdot p_{u2} \\ p_{u1d2} &= p_{u1} \cdot p_{d2} \\ p_{d1u2} &= p_{d1} \cdot p_{u2} \\ p_{d1d2} &= p_{d1} \cdot p_{d2} \end{aligned} \tag{4.5}$$

4.2.6 Calculation of expected net benefits based on uncertain key parameter

In this context, not the values of the uncertain key parameter, S, are directly relevant to decision making, but the expected net benefits (ENB), R, that result from the yearly benefits, B, which in turn result from the value of the uncertain key parameter S^4. Figure 4.4 (a) shows

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[4] The yearly benefits can include monetary and non-monetary impacts, depending on the perspective and preferences of the decision maker.

the probabilistic model of one key parameter S in a binomial tree, each node n representing one possible value of S. As can be seen from figure 4.4, future scenarios are the paths that immediately follow each node n, with a certain probability q. $B_{i_{n_t}}$ in figure 4.4 (b) are the yearly net benefits depending on the value of S. Therefore, the expected net benefits in figure 4.4 (c), R_{n_τ} that can be gained in the following years t will be the sum of benefits yearly $B_{i_{n_t}}$ from all paths i_{n_t} departing from node n multiplied with their probabilities until the end of investigated time T, which can be represented by the following equation:

$$R_{n_{\tau_R}} = \sum_{t=\tau_R+1}^{T} \left(e^{-r(t-\tau_R)} \sum_{n_t=1}^{N_t} \sum_{i_{n_t}=1}^{I_{n_t}} \left(q_{i_{n_t}} \cdot B_{i_{n_t}} \right) \right) \tag{4.6}$$

Here, the notation τ_R is referred to as the decision time interval, the selected discount rate, r, and q is the joint probability of path i_{n_t} leading to node n_t. For example, if considering in figure 4.4 (a) the node S_u for the calculation of $R_{S_u,\tau}$, then the probability q that leads to the path over node S_{uu} to the node S_{uud} (dashed path in figure 4.4 (a)) with B_{uud} is $q = p \cdot (1 - p)$.

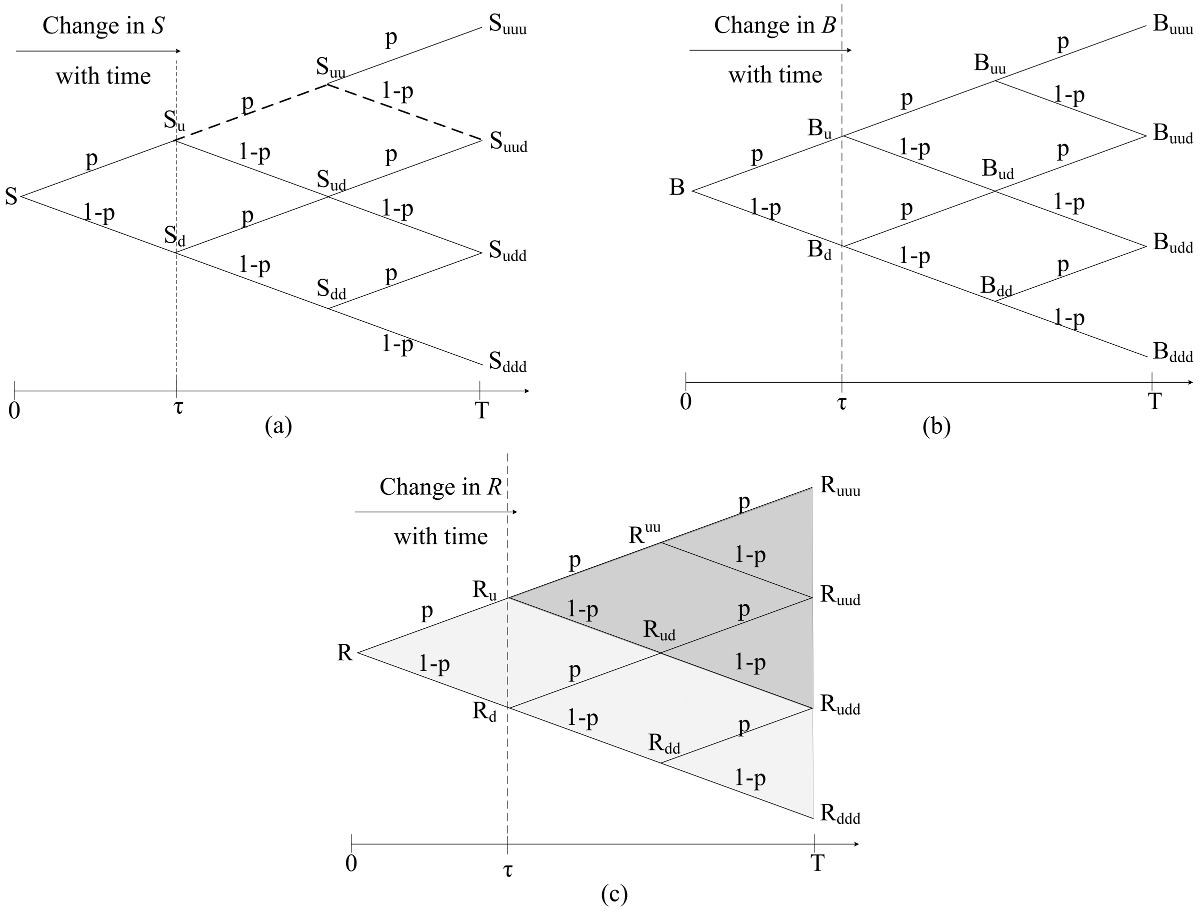

Figure 4.4: (a): Uncertain key parameter S, (b): Yearly benefits B, (c): Expected net benefits R in binomial tree (R is the sum of yearly benefits in the light grey cone, R_u is the sum of yearly benefits in the dark grey cone)

4.3 Traditional Method without consideration of flexibility in decision making

To show the validity of the method for the evaluation of intervention programs with consideration of decision flexibility, a comparison of the results of this method with consideration of decision flexibility with the results of a traditional method without the consideration of decision flexibility is necessary. The Traditional Method (TM) used in this thesis has been described in numerous literature before and is summarised in the following section. With the traditional method , it is assumed for the valuation of IPs that all possible IPs are known at the decision time t = 0 and that the building manager chooses the optimal intervention program among all possible IPs at t = 0, i.e. decision flexibility to postpone a decision to a later point in time is not considered.

4.3.1 Mathematical formulation of the Traditional Method

The mathematical model used in the TM in this thesis is described with the following equations. The interventions to execute and when they should be executed are determined at $t = 0$, taking into consideration the probable values of one uncertain key parameter, i.e. their expected values, throughout the investigated time period, by discounting them back to t = 0 and summing them up (as described for example in (Trigeorgis, 1998)). The objective function is:

$$argmax_{\tau_{TM}} \left\{ X(\tau_{TM}) \right\} \tag{4.7}$$

i.e. choose the time τ_{TM} to execute an intervention of a specific type that results in the maximum expected net benefits. The value of $X(\tau_{TM})$ is the cumulative expected net present benefits for all yearly benefits estimated for the entire investigated period $[0, T]$, and it can be estimated using the following equation:

$$X(\tau_{TM}) = R_0 + e^{-r\tau_{TM}} \left(\sum_{n_{\tau_{TM}}=1}^{N_{\tau_{TM}}} R^+_{n_{\tau_{TM}}} - C_{\tau_{TM}} \right) \tag{4.8}$$

where R_0 are the reference expected net benefits for the entire period $[0, T]$, i.e. for the case that no intervention is executed over the complete time period, and τ_{TM} in this equation is referred to as the time to execute the intervention, $C_{\tau_{TM}}$ is the cost of an intervention at time τ_{TM}. $N_{\tau_{TM}}$ is the total number of nodes at time τ_{TM}, and R^+_n are the additional expected net benefits that could be generated after any particular node due to the execution of the intervention. R^+_n is calculated depending on the chosen stochastic model for the uncertain utility over the investigated time period. In the calculation of $X(\tau_{TM})$, the probabilities of each R^+_n needs to be considered. If considering multiple interventions, e.g. one type can be executed multiple times or two types of intervention can be executed sequentially, then $X(\tau_{TM})$ has to be calculated for each possible combination of intervention type and execution time τ_{TM} in order to find the optimal.

4.3.2 Steps of the Traditional Method

The expected net benefits from a IP, determined with the TM, are determined by performing the steps shown in table 4.1.

Table 4.1: Steps evaluation with the Traditional Method without consideration of decision flexibility

Step	Description
1	Determine the costs and benefits as a function of the values of the uncertain key parameters over the investigated time period (T)
2	Develop a static model of the system, i.e. determine the values of the key parameters to be considered possible over the investigated time period
3	Develop a dynamic model of the system, e.g. using a binomial lattice, where the values of the uncertain parameters move in equal units up and down after calculating the probabilities of having each of the values of each of the key parameters S at the beginning of each time interval (p)
4	Estimate the expected net benefits of a reference IP
5	Estimate the additional yearly net benefits for each t in which it is possible to execute an intervention
6	Calculate the expected net benefits over the investigated time period for each node n of each IP, under consideration of the probabilities of occurrence of each node n, discounted to and compared at t = 0 and chose the IP with the maximum expected net benefits

This section was published in (Esders et al., 2016).

4.4 Real Options Method with consideration of decision flexibility

4.4.1 Mathematical formulation of the Real Options Method

The mathematical model used in the Real Options Method for the evaluation of intervention programs with consideration of decision flexibility is described in the following equations. The Real Options Method has been published in numerous literature, e.g. in (Kodukula and Papudesu, 2006; Menassa, 2011) and has been adapted here for the evaluation of intervention programs with consideration of decision flexibility.

This mathematical formulation applies for both ROM EO and ROM AO (which are explained more detail in section 4.4.3), while the decision in ROM EO can only be made at decision nodes in the last possible, i.e. only one, time interval, and in ROM AO is possible at decision nodes in selected time intervals before the last. In the method for the evaluation of intervention programs with consideration of decision flexibility, the total expected net benefits at $t = 0$ are calculated using following equation:

$$X_{\tau_{DI}}(t=0) = R_0 + e^{-rt} \cdot \sum_{\bar{n}_t=1}^{\overline{N}_t} X^{+}_{\bar{n}_t}(t) \tag{4.9}$$

where, τ_{DI} is the end of the decision time interval and t is the time in $[0,\ \tau_{DI}]$ in which the decision to execute an intervention can be made. The values of $X^{+}_{\bar{n}}(t)$ are determined by applying the following equation to the final nodes of last possible time interval at τ_{DI} in both the ROM EO and ROM AO context (according to (Kodukula and Papudesu, 2006; Menassa, 2011))

$$X^{+}_{\bar{n}}(\tau_{DI}) = max\left[0; R^{+}_{\bar{n}_{\tau_{DI}}} - C_{\tau_{DI}}\right] \tag{4.10}$$

In the European option (ROM EO) context, $X^{+}_{\bar{n}}(t)$ is determined only in the final nodes and then used in equation 4.9 to determine $X_{\tau}(t)$ at $t = 0$. In the American option (ROM AO) context, the decision is possible in the time intervals before the last and thus, $X^{+}_{\bar{n}}(t)$ can be determined (according to (Kodukula and Papudesu, 2006; Menassa, 2011)) in decision nodes before the last by applying

$$X^{+}_{\bar{n}}(t) = max\left[e^{-r\cdot dt}\left[p \cdot X^{+}_{\bar{n},up}(t+dt) + (1-p) \cdot X^{+}_{\bar{n},down}\right]; R^{+}_{\bar{n}_t} - C_t\right] \tag{4.11}$$

where $X^{+}_{\bar{n},up}$ are the additional expected net benefits from executing an intervention in the time interval following t at the node with the increasing value of S, and thus $R(up)$, and $X^{+}_{\bar{n},down}$ are the additional expected net benefits from executing an intervention in the time interval following t at the node with the decreasing value of S, and thus $R(down)$. $R^{+}_{\bar{n}_\tau}$ are the additional expected benefits from executing an intervention only at the node $\bar{n}$. When an intervention is executed, positive benefits can be gained. Again, the probabilities of $R^{+}_{\bar{n}_\tau}$ relative to $X_{\tau_{DI}}(t=0)$ need to be considered.

Applying equation 4.11 in recursive calculation from time T to 0, the expected net benefits at t = 0 can be expressed under the consideration of optimal decision-making at each decision node n in any t. It can be seen that the expected net benefits of the reference case, R_0, are not considered in the optimisation at each decision node described in equation 4.11, but finally in the total expected net benefits at $t = 0$ (equation 4.9). If considering multiple interventions, e.g. one type can be executed multiple times or two types of intervention can be executed sequentially, $X^{+}_{\bar{n}}(t)$ of each possible intervention after t and following node $\bar{n}$ has to be considered in the optimisation in equation 4.10 and equation 4.11 (Esders et al., 2016).

4.4.2 Steps of the Real Options Method

The expected net benefits from a IP, determined with the method for the evaluation of intervention programs with consideration of decision flexibility, are determined by performing the steps given in table 4.2, which are similar to those used by others (Arnold and Crack, 2000; Kodukula and Papudesu, 2006). This section was published in (Esders et al., 2016).

Table 4.2: Steps evaluation with method for the evaluation of intervention programs with consideration of decision flexibility

Step	**Description**
1	Determine the costs and benefits as a function of the values of the uncertain key parameters over the investigated time period (T)
2	Develop a static model of the system, i.e. determine the values of the key parameters to be considered possible over the investigated time period
3	Develop a dynamic model of the system, e.g. using a binomial lattice, where the values of the uncertain parameters move in equal units up and down after calculating the probabilities of having each of the values of each of the key parameters S at the beginning of each time interval (p)
4	Estimate the expected net benefits of a reference IP
5	Estimate the additional yearly net benefits for each t in which it is possible to make a decision for each possible IP
6	ROM EO: Calculate the additional expected net benefits, i.e. additional to the one of the reference IP, of each possible IP for each possible node n in one time t in which decisions can be made and chose the one with the maximum expected net benefits for each node n; then discount this expected net benefits back to t = 0, considering the probabilities of occurrence of all possible node n with values of S at decision time t
	ROM AO: Calculate the additional expected net benefits, i.e. additional to the one of the reference IP, of each possible IP for each possible node n for each possible time t in which decisions can be made. then, starting with the latest possible decision time t, chose the IP with the maximum expected net benefits for each node n in that decision time t; then discount this expected net benefits back to t − 1 and again chose the IP with the highest expected net benefits for each possible node n at time t − 1, considering the probabilities of occurrence of all possible nodes n with values of S at decision time t, relative to t − 1. repeat this backward calculation until time t = 0

4.4.3 Types of evaluation with the method for the evaluation of intervention programs with consideration of decision flexibility

The method for the evaluation of intervention programs with consideration of decision flexibility includes two types based option types introduced in the Real Option Analysis[5]:

1. ROM EO – the European option type, where a decision is to be made at one specific point in time in the future, or at the last possible time interval, and
2. ROM AO – the American option type, where decisions are to be made at multiple specific points in time in the future, or at the last possible time interval and in the intervals before.

For both types, it is not assumed that the building manager chooses the intervention program to follow, herein referred to as optimal intervention program (OIP), at t = 0, but merely the intervention at t = 0 that is most likely to be part of the optimal intervention program. In both ROM EO and ROM AO, it assumed that decisions about interventions at times t > 0 are made when the uncertainty related to the values the key parameters has decreased, i.e. when the building manager knows more about the actual value of the key parameter than she did at decision time t. The possible values of the key parameter are represented as nodes n in the binomial tree. It can be seen that in both types of options, there is not one optimal intervention program at time t but an optimal set of IPs, and the intervention selected at t = 0 will belong to all IPs in that optimal set. As the key parameter develops probabilistically, optimal intervention programs are selected with a certain probability. In this thesis, the optimal set of IPs determined with the method with consideration of decision flexibility is equally referred to as optimal intervention program (section published in (Esders et al., 2016)).

4.5 Decision situations

For the determination of possible intervention programs, it is necessary to define the possible execution times over the investigated time period, which also has to be defined. The combination of investigated time period and possible decision times is herein defined as decision situation for one or several interventions, e.g. the two different decision situations in table 4.3.

Table 4.3: Decision situations

No.	Description	Decision times (years)
A	In this situation the building manager can decide to execute an intervention at the end of any 1-year time interval between now and one time step before the end of the 10-year time period (a decision in year 10 would lead to not executing the decision as no yearly benefits can be generated afterwards). this situation is one without constraints	0, 1, 2, 3, 4, 5, 6, 7, 8, 9
B	Here, the building manager can decide to execute an intervention at any time during the first 5 years of the 10-year time period but not afterwards. It is one where due to planned interventions on other nearby buildings nothing can be done beyond a specific point in time	0, 1, 2, 3, 4, 5
C	Here, the building manager can decide to execute an intervention now or in 5 years but at no other time. It is one where effort is being made to combine interventions on the building to reduce the impact on the users of the building	0, 5

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[5] For further explanation of options of the European and American option type, refer to section 4.6 and ROA literature, e.g. Trigeorgis (1998).

4.6 Probabilities and time of execution as part of the intervention programs

Intervention programs are defined as a list of interventions to execute over a defined period of time, determined under consideration of the actual state of nature and the constraints over the investigated time period. Thus, in this context, the possible times of execution of each intervention are of interest. The optimal intervention programs for each method and situation are the ones that yield the highest expected net benefits at t = 0.

4.6.1 τ_{TM} for the TM

For traditional methods, the time of intervention, τ_{TM} is the optimal planned time of execution as defined at t = 0. Because the decision is assumed to be made at t = 0, the assumed probability of execution, $q^{ex}_{\tau_{TM}}$, at each possible time t_{TM} is 1.

4.6.2 Nodes and probabilities of execution for the ROM

The core of using the ROM for the determination and evaluation of intervention programs with the consideration of uncertainty in demand is the determination of when and under which conditions, i.e. for which values of the uncertain key parameter, interventions are expected to be executed. The discrete attributes of the binomial lattice used in this thesis allows for the identification of the nodes where execution takes place according to equations 4.10 or 4.11, i.e. if the maximum expected benefits at any node can be generated by executing an intervention.

An example is given in the following figure 4.5, where the execution nodes, i.e. nodes where an execution of an intervention are beneficial, are highlighted with a frame (S_{uuu} and S_{uud}).

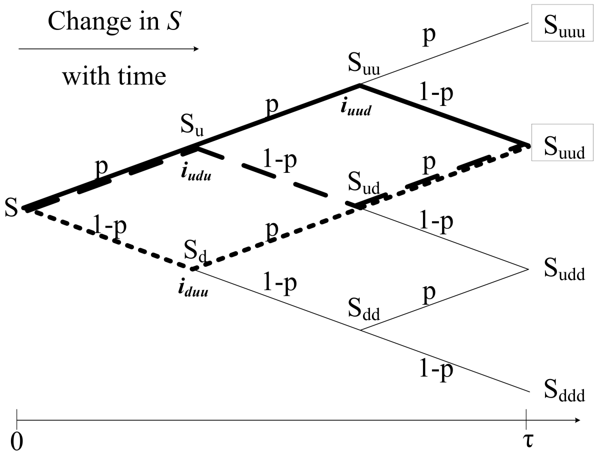

Figure 4.5: Binomial lattice with nodes of S where execution is beneficial with frame

The probability of execution results from the probability of the execution node(s), i.e. the probability of uncertain parameter S reaches the value of S_{uuu} and S_{uud} respectively where an execution is beneficial. The probability of a single node, generally defined by the time t and its position n in the lattice, i.e. as node n_t relative to another node $n^\star_t$, is the sum of the probabilities q_i of all paths i leading from $n^\star_t$ to n_t. If the binomial lattice in figure 4.5 represents a Geometric Brownian motion, for node S_{uud}, there are three paths from node S in t=0: Path i_{uud}, with two up- and one down-movement, path i_{udu}, with one up-movement, one down-movement and one up-movement, and path i_{duu}, with one down- movement and two up-movements. If the probability of an up-movement is p and the probability of a down-movement is $(1-p)$, then the probability $q_{S_{uud}}$ of node S_{uud}, relative to t=0, is $q_{i_{uud}} + q_{i_{udu}} + q_{i_{duu}} = p \cdot p \cdot (1-p) + p \cdot (1-p) \cdot p + (1-p) \cdot p \cdot p = 3 \cdot p^2 \cdot (1-p)$.

If the lattice represents the Geometric Brownian motion, the probability of each node in the lattice can be calculated by the following general equation (adapted e.g. from (Copeland and Antikarov, 2001)):

$$q_S(n, |t, p) = \frac{t!}{(t-n)!n!} p^{t-n} (1-p)^t \tag{4.12}$$

where n is the number of the node counted from the top of the lattice, starting at $n = 0$, and t is the number of time steps to the node, starting at $t = 0$. For the representation of other stochastic processes as lattices, the probabilities for each node have to be calculated with less elegant methods.

4.6.3 τ_{EO} and probability of execution for the ROM EO

τ_{EO} for the ROM EO, is herein defined as the best possible time of execution to decide about the execution. This optimal time τ_{EO} is selected by calculating the expected net benefits for all possible τ_{EO} according to equations 4.9 and 4.10 and selecting the one with the highest expected net benefits. Using equation 4.10 at each node in τ_{EO}, the execution nodes can be identified, with an example in figure 4.6.

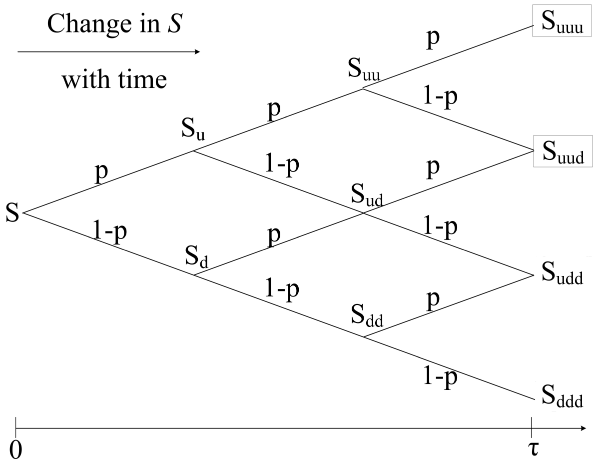

Figure 4.6: ROM EO with example execution nodes in frames

For this example, the optimal τ_{EO} is t=3 and the execution nodes are nodes S_{uuu} and S_{uud}. S_{uuu} is defined by n=0 and t=3, S_{uud} is defined by n=1 and t=3. Thus, the node probabilities are $q_{S_{uuu}} = p^3$ and $q_{S_{uud}} = 3 \cdot p^2 \cdot (1-p)$ respectively (according to equation 4.12). The sum of all node probabilities of the execution nodes is the total probability $q^{ex}_{\tau_{EO}}$ of execution for this τ_{EO}.

4.6.4 τ_{AO} and probability of execution for the ROM AO

τ_{AO} for the ROM AO, is the earliest time where the probability of execution is non-zero. The ROM AO considers that decisions cannot only be made in one τ_{AO} but at several times over T, e.g. in the fictive and the real world examples here are at every time step dt. In a recursive calculation all possible nodes of execution are determined over T, always considering possible optimal decisions at a later τ_{AO}. As the intervention is only possible once over the investigated time period, but the recursive calculation from equation 4.11 does not consider possible optimal execution at preceding nodes only at subsequent nodes, such interactions have to be considered in an additional step. It is assumed that the decision maker will execute an intervention at the earliest possible time, i.e. as soon as an execution is beneficial compared to not executing according to equation 4.11. If execution of preceding nodes is possible, execution at a later node is not possible anymore in this context. Thus, it is necessary to check for each execution node if an execution is possibly optimal at a preceding node.

In a reconnecting lattice, one single node can be part of multiple paths i (compare S_{uud} in figure 4.5). Some of these paths can include a preceding node where an execution would be beneficial earlier. This is explained with the help of the example of nodes S_{uuu} and S_{uud} already shown in figure 4.6 for the ROM EO. For the ROM AO, these execution nodes in time τ are preceded by node S_{uu} in time $\tau - 1$.

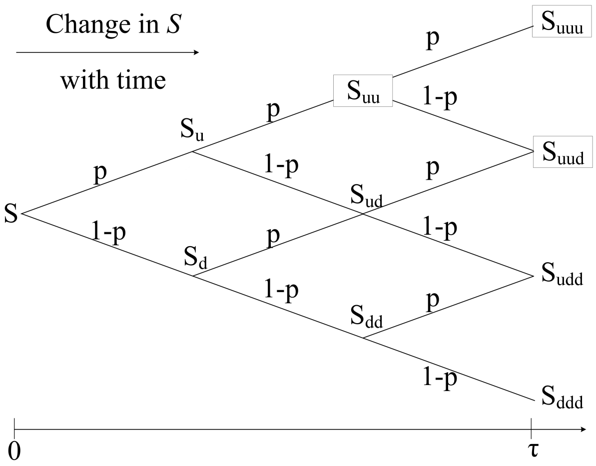

Figure 4.7: ROM AO with example execution nodes in frames

Only one path is leading to the possible execution node S_{uuu}, namely path i_{uuu} through the nodes S_u and S_{uu}. If earlier execution is possible at node S_{uu}, then execution is not possible at S_{uuu} if the building manager executes at the earliest possible node, even though execution is initially indicated through recursive optimisation according to equation 4.11. For the possible execution node S_{uud}, the situation is different, as there are three paths leading to that node, namely i_{uud}, i_{udu}, and i_{duu} (compare figure 4.5). Only path i_{uud} includes the earlier possible execution node S_{uu}. Thus, the probability of path i_{uud} has to be excluded when calculating the probability q_{n_t} of node S_{uud} to determine the *adjusted probability* $q_{n}{}^{a}{}_{t}$ of execution node S_{uud}.

In this case, the adjusted probability $q_{S}{}^{a}{}_{uud}$ is $2 \cdot p^2 \cdot (1-p)$, opposed to the general probability $q_{S_{uud}}$, which is $3 \cdot p^2 \cdot (1-p)$.

The sum of the adjusted probabilities $q_{n_t}^{a}$ of execution that are non-zero are summed up for each τ_{AO} and describe the *total probability of execution in* τ_{AO}, $q_{\tau_{AO}}^{ex}$. The *overall probability of execution of the considered intervention,* q_{AO}^{ex}, is the sum of the total probabilities of execution $q_{\tau_{AO}}^{ex}$ of each τ_{AO} over the investigated time period. τ_{AO} are thus the times over the investigated time period where the probability of execution are non-zero.

4.6.5 Staged interventions

Sometimes it is necessary to consider several subsequent interventions, i.e. one intervention can only be executed at the same time as or after the preceding intervention.

4.6.5.1 τ_{TM} for the TM for staged interventions

With the Traditional Method, the τ_{TM} for each intervention is determined according to equation 4.7, while considering all possible combinations of τ_{TM} of the individual interventions. The probabilities of execution of each intervention are 1, as for the single-stage intervention.

4.6.5.2 Nodes and probabilities of execution of staged interventions for the ROM

For the Real Options Method, equations 4.10 and 4.11 can easily be adapted to consider subsequent interventions by adding the additional expected net benefits from executing a subsequent intervention, e.g. I2, and thus $X_{n,I2}^{+}(\tau_{DI})$, to the additional expected benefits from intervention

I1, $R^{+}_{\tilde{n}_{\tau_{DI}}}$, and the subsequent intervention I2 in equations 4.10 and 4.11, resulting for example in equation 4.13 in both the ROM EO and the ROM AO context.

$$X^{+}_{\tilde{n},I1}(\tau_{DI,I1}) = max\left[0; R^{+}_{\tilde{n}_{\tau_{DI,I1}},I1} + X^{+}_{\tilde{n},I2}(\tau_{DI,I2}) - C_{\tau_{DI,I1}}\right] \tag{4.13}$$

$X^{+}_{\tilde{n},I1}(\tau_{DI,I1})$ are the additional expected net benefits from intervention I1 in the end of the decision interval for intervention I1, $\tau_{DI,I1}$. $X^{+}_{\tilde{n},I2}(\tau_{DI,I2})$ are the additional expected net benefits from intervention I2 in the end of the decision interval for intervention I2. $R^{+}_{\tilde{n}_{\tau_{DI,I1}},I1}$ are the additional expected benefits of the execution of intervention I1 in the end of the decision interval for intervention I1, $\tau_{DI,I1}$. $C_{\tau_{DI,I1}}$ are the execution costs of intervention I1 in time $\tau_{DI,I1}$. As above, in the European option (ROM EO) context, $X^{+}_{\tilde{n}}(t)$ is determined only in the final nodes and then used in equation 4.9 to determine $X_{\tau}(t)$ at $t = 0$.

For the determination of the τ_{EO} of two or more interventions, the expected net benefits $X_{\tau}(t)$ at $t = 0$ from equation 4.9 are calculated for all possible combinations of τ_{EO} for each intervention, always considering that only staged, i.e. subsequent, execution is possible.

In the American option (ROM AO) context, the decision is possible in the time intervals before the last and thus, $X^{+}_{\tilde{n}}(t)$ can be determined in decision nodes before the last by applying

$$X^{+}_{\tilde{n},I1}(t) = max\left[e^{-r\cdot dt}\left[p\cdot X^{+}_{\tilde{n},I1,up}(t+dt) + (1-p)\cdot X^{+}_{\tilde{n},I1,down}\right]; R^{+}_{\tilde{n}_t} + X^{+}_{\tilde{n},I2}(t) - C_t\right] \tag{4.14}$$

The probabilities of execution of a subsequent intervention, e.g. intervention I2, are *conditional probabilities*, q^c, i.e. conditional on the probabilities of execution of the preceding interventions, e.g. $q^{c,ex}(I2|I1)$ is the conditional probability that intervention I2 is executed if intervention I1 is executed before or at the same time. The approach for the calculation of these conditional probabilities is the same as for the calculation of the probabilities of single interventions in sections 4.6.2 to 4.6.4, with the difference that these probabilities are not calculated relative to S at $t = 0$, but can be relative to any preceding node $n^{\star}_{t}$ in the lattice, where the preceding intervention is executed. In the intervention program, the *joint probabilities* q^j of execution of the subsequent intervention are given, e.g. the joint probability $q^{j,ex}(I1, I2)$ is the probability of execution of intervention I2 given that intervention I1 was executed before or at the same time (see also Bayes' theorem on conditional and joint probabilities described in appendix D.4.1). If intervention I1 is the first possible intervention, its execution is not conditional on the execution of other interventions, and thus, only the execution probability $q^{ex}(I1)$ has to be calculated, as for a single-stage intervention.

For both the ROM EO and the ROM AO, the probabilities of execution of the first intervention are calculated the same way as for the single-stage interventions described in sections 4.6.3 and 4.6.4. The probabilities of execution of any subsequent intervention, e.g. $q_{\tau_{EO,I2}}$ are calculated first as conditional probabilities $q^c(I2|I1)$, i.e. conditional on the execution of preceding interventions, e.g. intervention I1, first, and then as the joint probabilities $q^j(I1, I2)$, before summing the joint probabilities up to calculate $q^{ex}_{\tau_{EO}}$, $q^{ex}_{\tau_{AO}}$and q^{ex}_{AO} (as was explained in sections 4.6.3 and 4.6.4).

Chapter 5

Simple example with fictive office building

The Real Options Method for the evaluation of intervention programs with consideration of decision flexibility[1], presented in the preceding chapter, was used on a simple example of an office building with the goals (1) to determine the optimal work program for this fictive building, (2) to test the applicability and (3) investigate possible results. An additional goal of this example was to show that a case exists where management's flexibility and its consideration with the ROM result in higher expected net benefits and different IPs than the IPs determined using the selected traditional method.

The effect of using a ROM to determine an optimal intervention program (OIP) is demonstrated in this example by comparing the optimal intervention programs determined using a traditional method and the ROM shown in the previous chapter. The application of the ROM on a simple example allows for better checking and comprehension of the process, results, and implications. This complete chapter was published in (Esders et al., 2016).

5.1 Description

In this example, the building manager wants to determine if the expected net benefits from the operation of a fictive office building can be improved by renovating it. The manager receives rent from the tenants of the building and has costs for heating it. The heating costs depend on the price of heating fuel, with which there is substantial uncertainty, and the total amount of heating required, which can be changed by improving the facade system. Based on the past volatility in the price of heating fuel it is expected that they could either increase or decrease significantly over the next 50 years. The facade can be improved by replacing the facade cladding, and thus the insulation, or by replacing the current insulation with improved ones. Improvement is here defined by the improvement of the heat transfer coefficient of both insulation and windows, so that less heat is lost. The manager wants to determine what should be done at t = 0 and if no intervention is executed then, when it will most likely be that she should execute an intervention and what type of intervention that would be, i.e. the OIP.

5.1.1 Building

The fictive office building has 20 levels of about 3.5 m floor level and a rectangular footprint with a usable floor space of $600m^2$ per level (30 m × 20 m). This results in total usable floor space of 12'000 m^2 and a facade area of 7'000 m^2. The facade system consists of facade cladding with the insulation, in the following referred to as insulation, and windows. The ratio of area of facade cladding to total facade area is 70% and the corresponding ratio of windows is 30%. The building characteristics are summarised in table 5.1.

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[1] The method for the evaluation of intervention programs with consideration of decision flexibility will be called ROM in the following text

Table 5.1: Building characteristics

Parameter	**Description**	**Units**	**Value**
A_H	Heated area	m^2	12’000
A_F	Facade system surface area	m^2	7’000
f_d	Fuel demand of heating system	l/kWh	0.1
c_r	Yearly rental income	$€/a \cdot m^2 A_H$	300
d_0	Initial heating demand per area of building with old facade	$kWh/a \cdot m^2 A_H$	75
c_f	Intervention costs for facade replacement per facade area	$€/a \cdot m^2 A_F$	40

The information required to enable the estimation of the expected net benefits are given in table 5.2. The volatility of the fuel price was derived from the historical data of heating fuel prices in Switzerland (as given by the Swiss Federal Statistical Institute) for the years 2002 to 2012.

Table 5.2: Costs, benefits and time parameters for operation of office building

Parameter	**Description**	**Units**	**Value**
B_{n_t}	Yearly net benefits $= I_t - O_t^{k_t} \cdot S_t$	€/a	-
I_t	Yearly rental income $=c_r \cdot A_H$	€/a	-
$O_t^{k_t}$	Yearly heating demand $=d_t^{k_t} \cdot A_H \cdot f_d$	€/a	-
S_0	Initial fuel price at t = 0	€/a	1
σ	Volatility of fuel price	-	0.3
ir	Risk-free interest rate per year	-	0.02
f	Inflation rate per year	-	0.02
dt	Time steps of binomial tree model	Years	5
T	Investigated time period for generation of yearly net benefits	Years	50

5.1.2 Decision situations

There are three possible decision situations, i.e. the possible times to decide about the execution of an intervention over the investigated time period.

Table 5.3: Decision situations

No.	Description	Decision times (years)
1	In this situation the building manager can decide to execute an intervention at the end of any 5-year time interval between now and one time step before the end of the 50-year time period (a decision in year 50 would lead to not executing the decision as no yearly benefits can be generated afterwards). this situation is one without constraints	0, 5, 10, 15, 20, 25, 30, 35, 40, 45
2	Here, the building manager can decide to execute an intervention at any time during the first 15 years of the 50-year time period but not afterwards. It is one where due to planned interventions on other nearby buildings nothing can be done beyond a specific point in time	0, 5, 10, 15
3	Here, the building manager can decide to execute an intervention now or in 15 years but at no other time. It is one where effort is being made to combine interventions on the building to reduce the impact on the users of the building	0, 15

5.1.3 Interventions and intervention programs

The four possible interventions are (1) replace the insulation, (2) replace the windows, (3) replace the facade system, i.e. replace the wall insulation and the windows together and (0) do nothing. These are summarised in table 5.4.

Table 5.4: Interventions

		Heating demand per area	**Yearly heating demand**	**Intervention costs per area facade**
		d_t^{kt}	O_t^{kt}	c_t^{kt}
Int.	**Description**	$(kWh/a \cdot m^2 A_H)$	(l/a)	$(€/m^2 A_F)$
0	Do nothing	75	90’000	0
1	Stage 1: Replace insulation only	35	42’000	200
2	Stage 2: Replace windows only additional to insulation	17	20’400	200
3	Replace complete facade system	17	20’400	400

The investigated IPs are constructed from these interventions and the three possible IP types are explained in table 5.5.

The interventions are assumed to take effect immediately; costs are incurred immediately, benefits from operation are generated in the time interval following the decision, in this case over 5 years. The multi-stage optimal intervention program using ROM EO was estimated by first determining the most beneficial time interval to have the ability to decide to replace the insulation (e.g. time interval 15), and then assuming that the insulation was replaced, determining the most beneficial subsequent time interval in which to have the ability to decide to replace the windows. This was done for all possible combinations (i.e. IPs) of execution of both stages. The IP with the highest expected net benefits was chosen as the optimal one. The multi-stage optimal intervention program using ROM AO was estimated by first determining the optimal intervention programs and their expected additional net benefits of replacing the windows (stage 2) for each possible time interval when the insulation (stage 1) could have be executed and any possible outcome of the uncertain key parameter (e.g. if the insulation is

Table 5.5: Intervention program types

				Number possible IPs		
				Situation		
No.	**Name**	**Short description**	**Long description**	**1**	**2**	**3**
1	Do nothing	Do nothing	No physical interventions are executed over the investigated time period		1	
2	Single - stage	Replace complete facade system	All IPs that have only one intervention (additional to the do nothing intervention) with that intervention being the replacement of the facade system (they include the do nothing IP). this intervention is possible only once over the investigated time period	10	4	2
3	Multi - stage	Replace facade in stages (insulation and windows)	All IPs that have two interventions (additional to the do nothing intervention), where the first intervention is the replacement of the insulation and the second is the replacement of the windows (they include the IP with doing nothing at all and the IPs with only replacing the insulation). the second intervention is only possible after or at the same time as the first. Both interventions are possible only once over the investigated time period	66	15	6

replaced in time interval 5 at a fuel price of 1.96 €/l, then the recommended IP would suggest to replace the windows in time intervals 20, 30 and 40). Then, the beneficial time intervals to have the ability to decide to replace the insulation (stage 1) were determined under consideration of the subsequent beneficial time intervals to be able to decide about the replacement of the windows determined before.

5.2 Uncertainty modelling

In the construction of a static model of the system, it is necessary to make clear the entire range of possible scenarios to be analysed. This is done by identifying the range of possible values of the key parameters at each t in the investigated time period, and determining how to divide these into a tractable number of scenarios. This usually means discretising the range of values within one unit of time. One possible way to do this is to use a binomial tree, i.e. the values of the key parameters at each instant in time can be modelled as being located on one of a finite number of values at each point of time, and the number of possible values increases with the number of time units. The evolution of the value of a key parameter is then given by:

$$dS/S = \mu_s dt + \sigma_s dz \tag{5.1}$$

where S is the value of the key parameter at the beginning of the investigated time period, μ_s is the drift of the value of the key parameter, σ_s is the volatility or standard deviation of the value of the key parameter, dt is an increment in time and dz is an increment of the standard Wiener process in dt that deviates around a mean of 0. In a binomial tree, each value S in time interval t branches to two possible values in time interval t + 1, namely $S_t \cdot u$ and $S_t \cdot d$, where u and d represent the amount that the key parameter can increase or decrease in each unit of time, respectively. If the values of the upward and downward movements are equal over time, the binomial tree forms a recombining binomial lattice, as shown in Figure 1(a). For each time interval, the value of the key parameter goes up with the probability p and down with the probability (1 − p). (a) Uncertain key parameter S, (b) yearly benefits B and (c) expected net benefits R in binomial tree (R is the sum of yearly benefits in the hatched cone, R_u is the sum of yearly benefits in the grey cone). The evolution over time of the values of the key parameters can often be modelled as geometric Brownian processes where it can be assumed that the values at t + 1 depend only on the values at t and that this can be modelled as random. In this case, the values of a key parameter going up and down can be determined by the following equations (Cox et al., 1979):

$$\begin{cases} u = e^{\sigma\sqrt{dt}} \\ d = e^{-\sigma\sqrt{dt}} \end{cases} \tag{5.2}$$

where σ is the volatility or standard deviation of the key parameter and dt is the size of the time interval. The risk-free probability of the value of S going up and down is determined by the following equation (derivation e.g. in (Dixit and Pindyck, 1993; Trigeorgis and Mason, 1987)):

$$p = \frac{exp(ir \cdot dt) - d}{u - d} \tag{5.3}$$

where ir is the risk-free interest rate. Using the risk-neutral probability instead of the real probability accounts for the underlying assumption that the building manager could also rent a different similar building and use this building for the same purposes as her own building (compare assumption in similar cases e.g. (Greden and Glicksman, 2004; Menassa, 2011)). Using the risk-neutral probability ensures that the results of the evaluation of the IPs have the same expected benefits as the renting opportunity; otherwise the building manager should simply rent a building from someone else.

5.3 Results

5.3.1 Results

The optimal intervention program of each type was found for each decision situation using each method. The results are shown in table 5.6. For each decision situation and IP type, the expected net benefits are given along with the relevant times of the recommended IPs:

τ_{TM} for the TM, the optimal planned time of execution at t = 0.

τ_{EO} for the ROM EO, the best time to decide about the execution.

τ_{AO} for the ROM AO, the earliest time where the probability of execution is non-zero.

Table 5.6 shows the expected net benefits and probabilities of execution of the optimal intervention programs according to the mathematical formulations of sections 4.3.1 and 4.4.1 for all situations, IP types and methods. The optimal intervention programs for each method and situation are the ones that yield the highest expected net benefits at t = 0.

Table 5.6: Results of simple example

				Recommended IP as probabilities of execution in interval $q^{ex}_{\tau_{EO}}/q^{ex}_{\tau_{AO}}$												**Expected net benefits in 10^6 €**	
				Intervals in years													
Sit.	**IP type**	**Method**	τ	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	Σ **(Prob)** $q^{ex}_{\tau_{EO}}$/ q^{ex}_{AO}	**Total**	**Diff. to IP 0**
0	Do nothing	All							No Execution						*0*	*109.70*	-
1	Single-stage	TM	τ_{TM}	1											*1*	*110.36*	*0.66*
		ROM EO	τ_{EO}				0.37								*0.37*	*111.00*	*1.30*
		ROM AO	τ_{AO}			0.17		0.08		0.09		0.09			*0.43*	*111.22*	*1.52*
	Multi-stage	TM insulation	τ_{TM}	1											*1*	*110.69*	*0.99*
		TM windows	τ_{TM}						No Execution						*1*	-	-
		ROM EO insulation	τ_{EO}			0.65									*0.65*	*111.06*	*1.36*
		ROM EO windows	τ_{EO}					0.19							*0.19*	-	-
		ROM AO insulation	τ_{AO}		0.41		0.10		0.10				0.05		*0.66*	*111.30*	*1.60*
		ROM AO windows	τ_{AO}						See table 5.7						*0.18*	-	-
2	Single-stage	TM	τ_{TM}	1											*1*	*110.36*	*0.66*
		ROM EO	τ_{EO}				0.37								*0.37*	*111.00*	*1.30*
		ROM AO	τ_{AO}			0.17	0.20								*0.37*	*111.13*	*1.43*
	Multi-stage	TM insulation	τ_{TM}	1											*1*	*110.69*	*0.99*
		TM windows	τ_{TM}		No Execution										*1*	-	-
		ROM EO insulation	τ_{EO}			0.65									*0.65*	*111.03*	*1.33*
		ROM EO windows	τ_{EO}			0.17									*0.17*	-	-
		ROM AO insulation	τ_{AO}	0.41			0.10								*0.51*	*111.20*	*1.50*
		ROM AO windows	τ_{AO}		See table 5.7										*0.07*	-	-
3	Single-stage	TM	τ_{TM}	1											*1*	*110.36*	*0.66*
		ROM EO	τ_{EO}				0.37								*0.37*	*111.00*	*1.30*
	Multi-stage	TM insulation	τ_{TM}	1											*1*	*110.69*	*0.99*
		TM windows	τ_{TM}		No Execution										*1*	-	-
		ROM EO insulation	τ_{EO}				0.37								*0.37*	*111.00*	*1.30*
		ROM EO windows	τ_{EO}				0.37								*0.37*	-	-

Table 5.7 shows the probabilities of execution for the multi-stage IP type for the evaluation with the ROM AO.

Table 5.7: Probabilities of execution for staged IP of ROM AO – situation 1 and 2.

τ_{AO} **of stage 1**	**Energy price**	$q^{ex}_{\tau_{AO}}$ **of stage 1**	τ_{AO} **of stage 2**	**Energy price**	$q^{ex}_{\tau_{AO}}$ **of stage 2**
	€/l	**(%)**		**€/l**	**(%)**
Decision situation 1					
5	1.96	41.11	15	7.48	6.9
5	1.96	41.11	30	14.63	1.4
5	1.96	41.11	40	14.63	1.8
15	1.96	9.95	25	7.48	1.7
15	1.96	9.95	35	7.48	0.8
15	1.96	9.95	45	7.48	0.9
25	1.96	9.64	35	7.48	1.6
25	1.96	9.64	45	7.48	0.8
40	3.83	5.04	45	7.48	2.1
Decision situation 2					
5	1.96	41.11	15	7.48	6.9
15	1.96	9.95	-	-	-

In figure 5.1, for TM and ROM EO, the different expected net benefits at t = 0 are shown for each possible decision interval t for decision situation 1. For the ROM AO, the decision can be made at each node of the binomial tree in each t so that the representation in separate decision intervals t is not possible; thus, only the maximum expected net benefits at t = 0 is shown for both IP types.

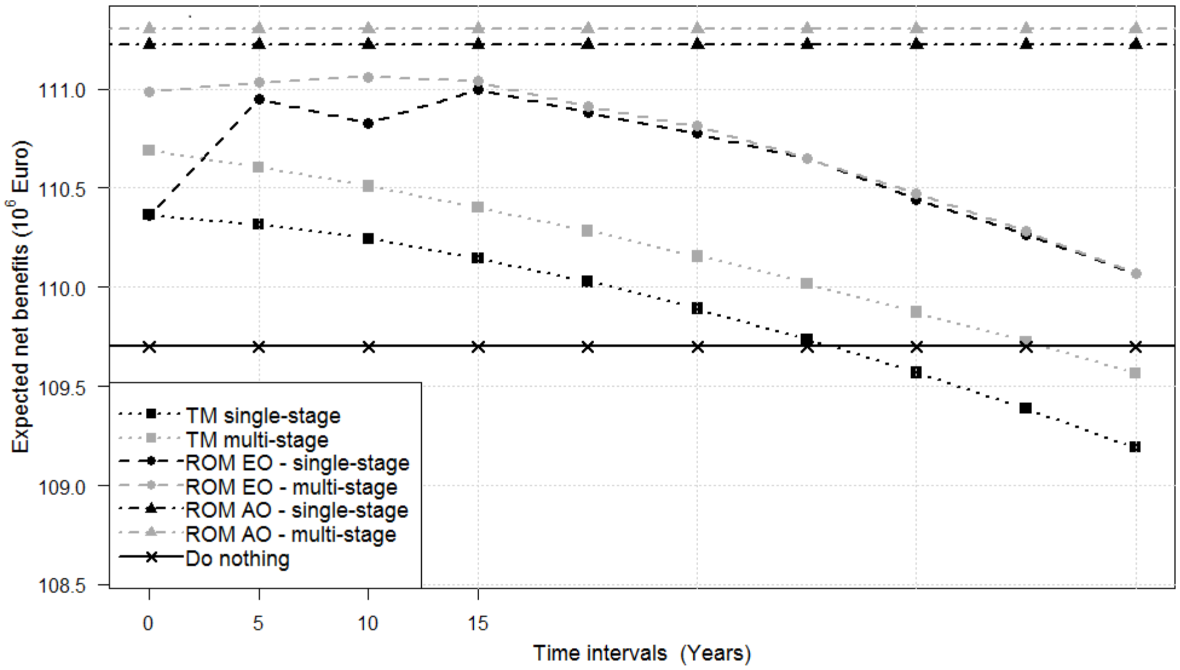

Figure 5.1: Expected net benefits for different τ_{TM} , τ_{EO} and τ_{AO} for situation 1 (decision in t = [0, 45]).

Table 5.6 shows the recommendation of the different methods for IPs that the building manager should adopt if she wants to maximise her expected net benefits. The expected net benefits of the do nothing optimal intervention program, 109.70 Mil. €, are the same determined with the TM and the ROM types, as no interventions are executed and the building manager has no flexibility to make decision in the future for this type of IP. Following the do nothing optimal intervention program yields the lowest expected net benefits at t = 0 of all optimal intervention programs. If the building manager has the possibility to execute an intervention in the future, i.e. OIPs of all other types, it can be seen that the use of different methods to determine optimal intervention programs results in different optimal intervention programs (table 5.8).

Table 5.8: Differences in expected net benefits for different methods, IP types and situations.

			Difference of expected net benefits (in 10^6 €) at t=0 between				
Sit.	**IP type**	**Method**	**ROM and TM**	**ROM AO and ROM EO**	**Single-stage and multi-stage type of IP**	**Sit.2 & 3 and Sit. 1**	**Sit. 3 and Sit. 2**
0	Do nothing	All			-		
1	Single-stage	TM					
		ROM EO	0.63				
		ROM AO	0.86	0.22			
	Multi-stage	TM - insulation			0.32		
		TM - windows					
		ROM EO - insulation	0.37		0.06		
		ROM EO - windows					
		ROM AO - insulation	0.61	0.24	0.08		
		ROM AO - windows					
2	Single-stage	TM				0.00	
		ROM EO	0.63			0.00	
		ROM AO	0.76	0.13		-0.10	
	Multi-stage	TM - insulation			0.32	0.00	
		TM - windows					
		ROM EO - insulation	0.34		0.04	-0.03	
		ROM EO - windows					
		ROM AO - insulation	0.51	0.16	0.07	-0.10	
		ROM AO - windows					
3	Single-stage	TM					
		ROM EO	0.63			0.00	0.00
		ROM AO				0.00	0.00
	Multi-stage	TM - insulation			0.32	0.00	0.00
		TM - windows					
		ROM EO - insulation	0.31		0.00	-0.06	-0.04
		ROM EO - windows					

For example, with decision situation 1, if the building manager

1. investigates the single-stage IP type and uses
    (a) the TM to evaluate her possibilities she will replace the complete facade at t = 0 and will expect net benefits of 110.36 Mil. €, i.e. additional expected net benefits of 0.66 Mil. € compared to the do nothing IP.
    (b) the ROM EO to evaluate her possibilities, she will do nothing at t = 0 and wait to obtain more information in the future to determine whether or not she should execute the intervention. The expected net benefits are 111.00 Mil. €, i.e. additional expected net benefits of 1.30 Mil. € compared to the do nothing IP. The additional expected net benefits at t = 0, compared to the results from the TM, are 0.63 Mil. €. In this case, the best time to decide about the replacement of the system is year 15, and therefore the best time to have the ability to decide to execute an intervention is in year 15 where the probability is 0.37. The default intervention is to do nothing, i.e. with a probability of execution of 0.63, the facade would never be replaced.
    (c) the ROM AO to evaluate her possibilities she will do nothing at t = 0 and wait to obtain more information in the future to determine whether or not she should execute the intervention. The expected net benefits are 111.22 Mil. €, i.e. additional net benefits of 1.52 Mil. € compared to the do nothing IP. The additional expected net benefits at t = 0, compared to the results from the TM, are 0.86 Mil. €, compared to the ROM EO they are 0.22 Mil. €. The time intervals in which there is a non-zero probability of executing the window intervention, if given the chance, are year 10, 20, 30 and 40, with probabilities of 0.17, 0.08, 0.09 and 0.09, respectively. The default intervention is to do nothing, i.e. with a probability of 0.57, the facade would never be replaced.

2. investigates the multi-stage IP type and uses
    (a) the TM, she will decide to replace the insulation at t = 0 but then to not replace the windows at all. This yields an expected net benefits of 110.69 Mil. €, i.e. additional net benefits of 0.99 Mil. € compared to the do nothing IP.
    (b) the ROM EO, she will do nothing at t = 0 and wait to obtain more information future to determine whether or not she should execute the intervention. The expected net benefits are 111.06 Mil. €, i.e. additional net benefits of 1.36 Mil. € compared to the do nothing IP. The additional expected net benefits at t = 0, compared to the results from the TM, are 0.37 Mil. €. The best time to be able to decide to replace the insulation is in year 10, when the probability of doing so is 0.65. Assuming the insulation is replaced in year 10 the best time to decide to replace the windows is in year 20 when the probability of doing so is 0.19. The default intervention is to do nothing, i.e. with a probability of 0.35, the insulation would never be replaced, and with a probability of 0.81, the windows would never be replaced, even if the insulation were replaced.
    (c) The ROM AO, she will do nothing at t = 0 and wait to obtain more information in the future to determine whether or not she should execute the intervention. The expected net benefits are 111.30 Mil. €, i.e. additional net benefits of 1.60 Mil. € compared to the do nothing IP. The additional expected net benefits at t = 0, compared to the results from the TM, are 0.61 Mil. €, compared to the ROM EO they are 0.13 Mil. €. The time intervals in which there is a non-zero probability of executing the insulation intervention if given the chance are years 5, 15, 25 and 40 with probabilities of 0.41, 0.10, 0.10 and 0.05, respectively. Assuming that they are executed at these times, the time intervals where there is a non-zero probability of executing the windows intervention if given the chance are shown in Table 8. They depend on the time when

> the insulation has been replaced and the energy price at that time. If, for example, the insulation has been replaced in year 5 at an energy price of 1.96 €/l fuel, the time intervals with non-zero probabilities for replacing the windows are years 15, 30 and 40, with probabilities of 0.069, 0.014 and 0.018, respectively.
>
> The default intervention is to do nothing, i.e. with a probability of 0.34, the insulation would never be replaced, and with a probability of 0.81 (compare Table 5.7), the windows would not be replaced, even if the insulation were.
>
> Table 9 shows that there are thresholds for the energy price above which the probability of execution is non-zero. For the first stage of the multi-stage IP type, these thresholds are 1.96 and 3.83 €/l, for the second stage, 7.48 and 14.63 €/l.

With decision situation 2, the results read the same as for decision situation 1, with the difference that the time period where decisions are possible is 15 years and not 45 years.

With decision situation 3, the building manager can only decide about interventions in year t = 0 or t = 15. The evaluation with the ROM AO is not applicable here, as with one decision interval (except t = 0), the results are identical to those from the ROM EO. If she investigates the single-stage IP type, and uses the TM, she will replace the complete facade at t = 0 and will expect net benefits of 110.36 Mil. €, i.e. additional net benefits of 0.66 Mil. € compared to the do nothing IP. If she uses the ROM EO, she will do nothing at t = 0 and wait to obtain more information in the future to determine whether or not she should execute the intervention. The expected net benefits are 111.00 Mil. €, i.e. additional net benefits of 1.30 Mil. € compared to the do nothing IP. The additional expected net benefits at t = 0, compared to the results from the TM, are 0.63 Mil. €. The best time to decide to replace the facade is in year 15, where there is a probability of 0.37 that it will be replaced if given the chance. The comparison between the expected net benefits at t = 0 of the single-stage IP types and the multi-stage IP types in Table 10 shows that the multi-stage IP types yield higher expected net benefits than the single-stage IP types for all three situations, e.g. for situation 1, 0.32 Mil. € if comparing expected net benefits between the two types with the TM, 0.06 Mil. € if comparing expected net benefits between the two types with the ROM EO, and 0.08 Mil. € if comparing expected net benefits between the two types with the ROM AO.

Finally, comparing the expected net benefits at t = 0 for the different decision situations, the results for the situations 2 and 3 are lower than for situation 1. Comparing the expected net benefits at t = 0 for the situations 2 and 3, situation 3 shows lower or equal expected net benefits.

This means, in this example, that using the ROM types results in different decisions of whether or not an intervention should be executed now and results in higher net benefits for a building manager.

5.3.2 Sensitivity analysis

Although it was found in the example that using the ROM types lead to different decisions at t = 0 and to different estimations of net benefits, it is not certain, based only on this information, to what extent their use makes a difference. This was investigated by varying the intervention costs (in ranges that can realistically be expected (Curschellas et al. 2011)) and volatility of the energy price (in a range from almost 0 (for the assumption of no uncertainty) to 0.5 (an increase if about 50% from 0.3)) to see the extent with which the use of the ROM results in different decisions and different expected net benefits. The ranges over which the values were varied are summarised in table 5.9. The values were varied one at a time, e.g. the volatility was held constant at 0.3 and the expected net benefits were estimated for varying intervention costs and each decision situation using each method, as described above.

Table 5.9: Values used in the sensitivity analysis

Varied	Minimum	Maximum	Increments	Figure
Intervention costs	100	700	50	Figure 5.2
Intervention costs	100	700	50	Figure 5.3
Volatility	0	0.5	0.05	Figure 5.4

5.3.2.1 Intervention costs

The extent that varying intervention costs change the expected net benefits, using each of the methods, can be seen in figure 5.2.

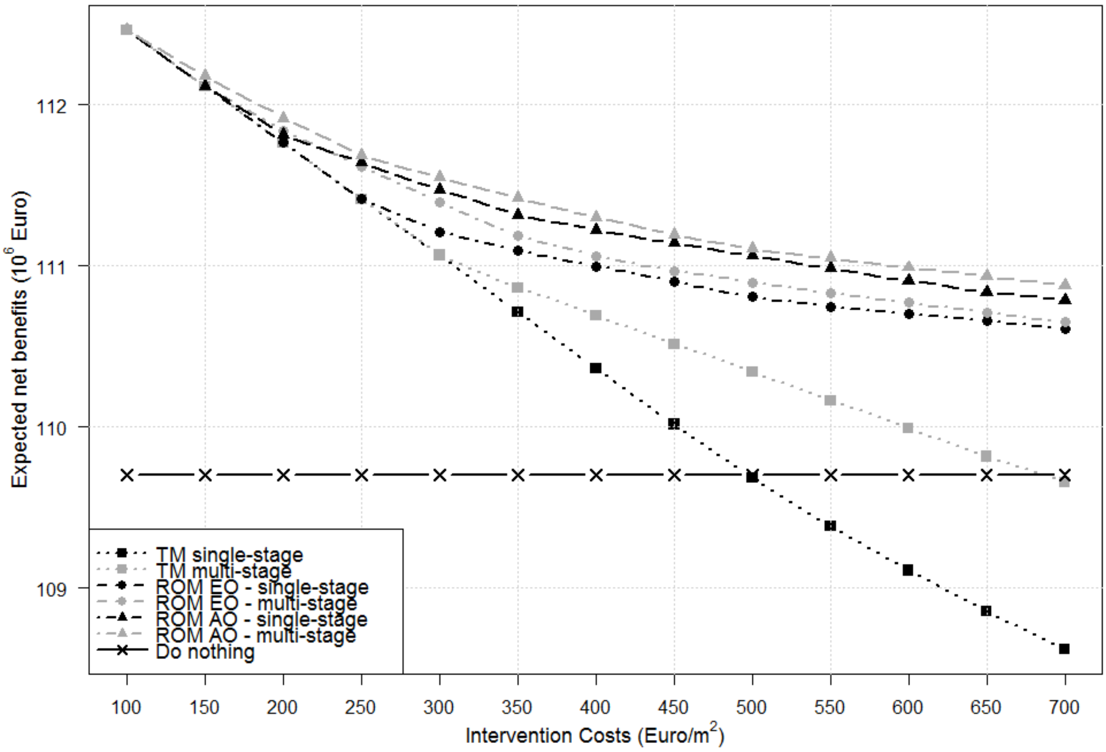

Figure 5.2: Decision situation 1: Expected net benefits at t = 0 as a function of intervention costs from 100 to 700 €/m^2

When the intervention costs are 0, the expected net benefits from ever executing an intervention are at their maximum, and the difference between the expected net benefits of executing an intervention at some point and doing nothing is high. The difference, however, with regard to the expected net benefits, between the methods is very small to almost 0 when the intervention costs are 0, i.e. all methods would recommend the same IP, in this case, to replace the complete facade at t = 0 (also compare figure 5.3).

It can be seen in figure 5.3 that for both the ROM AO and the TM, for intervention costs from 100 to 150 €/m^2 , the recommended IP would be to execute the intervention in year t = 0, thus leading no difference between the expected net benefits from the different methods. With intervention costs between 150 and 450 €/m^2 , the TM would recommend a IP with an execution in year t = 0 whereas the ROM AO would recommend a IP with waiting with the execution, first, to year t = 5, then even to year t = 10. Above intervention costs of 450 €/m^2 , even the TM would give the recommendation of the IP with waiting with the execution.

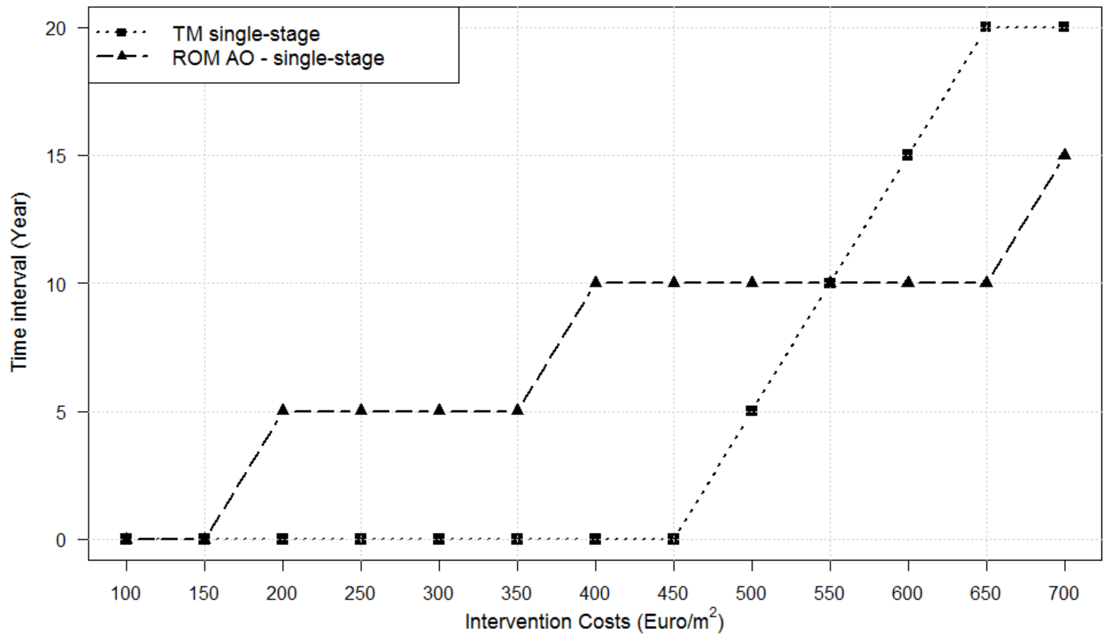

Figure 5.3: τ_{AO} for ROM AO and τ_{TM} for single-stage IP type in range of intervention costs from 100 to 700 €/m^2.

5.3.2.2 Volatility

With increasing volatility of the uncertain key parameter around the average scenario, the ROM types yield increasing expected net benefits for the preferred IPs while the expected net benefits with the TM remain the same (figure 5.4).

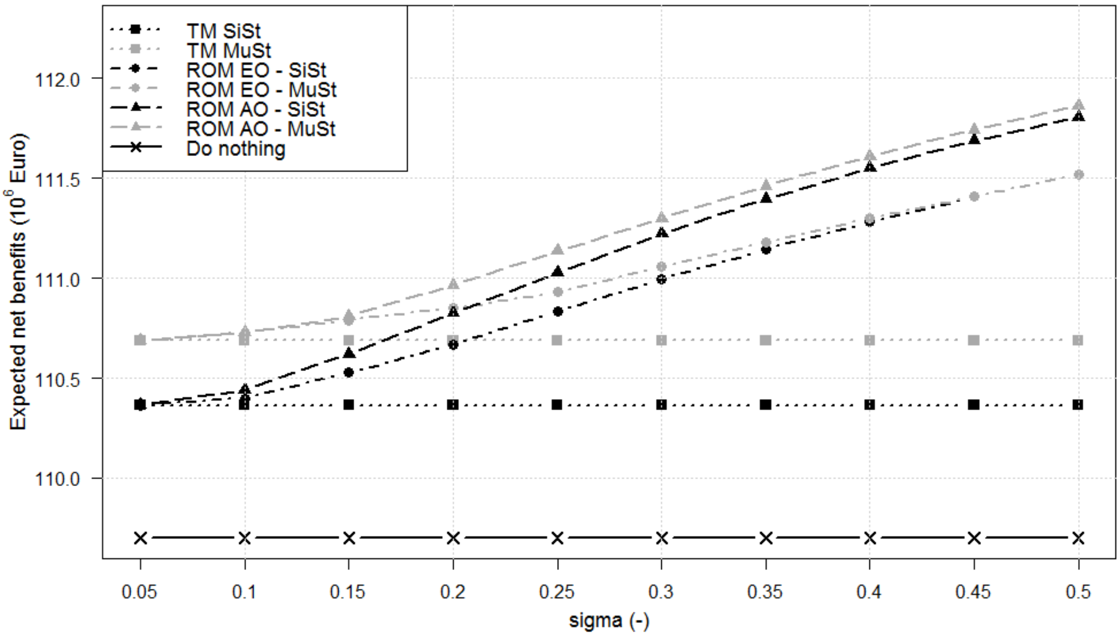

Figure 5.4: Expected net benefits at t = 0 applying the different methods of evaluation with increasing volatility of energy prices.

When the volatility is low, i.e. the key parameter can vary only close to the average scenario, the expected net benefits of all methods tend to the same value (while there remains a difference between the results of the single-stage and multi-stage IP type).

5.4 Discussion

The results of the chosen example of the facade replacement show that the application of the two ROM types result in different optimal intervention programs with different expected net benefits than the application of a TM in specific cases such as this one. The differences between the expected net benefits are with about 1% very small and potentially lie in the margin of error of the input parameters; however, the goals to show how the proposed ROM types could be applied on a realistic example, and which results can be expected, were reached. The following points can be discussed for this particular example.

ROM results in different estimates of expected net benefits than the TM

All three methods estimated that IPs that include an intervention are better than doing nothing over T, i.e. the optimal intervention program with interventions have higher expected net benefits than the doing nothing IP.

The IPs determined with the two types of ROM yield higher expected net benefits at t = 0 than the ones determined with TM; the reason for this is that the ROM types consider decision flexibility in executing interventions in the future.

The IPs determined with the ROM AO yield higher expected net benefits than the ones determined with the ROM EO, because ROM AO considers a higher degree of decision flexibility, i.e. more opportunities to exploit positive risk than ROM EO. The same argument applies to the fact that the multi-stage IP type yields a higher expected net benefits at t = 0 than the single-stage IPs. Situation 1 yields a higher expected net benefits at t = 0 than situation 2, and situation 2 a higher one than situation 3, because the manager has the least flexibility with decision situation 3, the most flexibility in decision situation 1.

The variation in the volatility of the key parameter (figure 5.4) shows that as the volatility approaches 0, the expected net benefits determined with all three methods approach the same value when t = 0. The reason is that, with low volatility of the key parameter, i.e. low uncertainty of the key parameter around the average value, there are fewer situations where it is beneficial to wait and decide about the execution of an intervention in the future. In other words, the benefit of using a ROM over a TM is lower with decreased uncertainty.

As volatility increases, the expected net benefits determined with the TM and the optimal intervention program remain the same, whereas with the ROM types, the expected net benefits increase. This is due to the fact that the higher the assumed volatility, the bigger the expected range of values for the uncertain key parameter, in this case the energy price, with higher and lower benefits in case of replacement. In the determination of the expected net benefits with the TM, the high and low benefits cancel each other out whereas with the ROM types, there are increasingly better opportunities to exploit positive risk.

ROM is better or at least as good as the TM

The results from the sensitivity analysis for the intervention costs suggest that the use of the ROM would always be better, or at least as good as, the TM, i.e. a building manager would always increase their expected net benefit at t = 0. The reason is that if there is one scenario where there is a possibility that a manager may change her mind about the execution of an intervention based on new information than there is information that cannot be captured appropriately in the TM.

Even if intervention costs are increased above a certain threshold, the expected net benefits for the ROM is always higher than the ones for the TM. They are never lower. Also, as intervention costs increase, the expected net benefits from the TM decrease, whereas the latter can even fall below the expected net benefits of the do nothing IP, while the expected net benefits of the ROM types approach those of the do nothing IP.

That way, the ROM consider IPs that exploit even the smallest chance of additional benefits compared to do nothing IP, thus approaching the expected net benefit of the do nothing IP but never going below. Even for high intervention costs, there might be situations where the key parameter has a value that results in benefits high enough to justify an intervention at a time $t > 0$.

ROM results in different IPs than TM

As the expected net benefits from the methods are different so are the IPs. This means that if a building manager uses different methods to estimate net benefits she will arrive at different recommended IPs. As the use of the ROM in most cases is a better reflection of reality, i.e. a building manager normally has substantial flexibility, then the use of the TM will result in not only different IPs but less net benefits!

The variation in the key parameter's volatility (figure 5.4) shows that above a certain volatility, the ROM make better recommendations for the IP, as the recommendation of the TM 'destroys' the possibility of higher expected net benefits by executing the intervention today instead of waiting for better information.

If the intervention costs exceed a certain value, the TM gives the same recommendation as the ROM, i.e. to do nothing, which leaves the possibility open to reconsider the situation later. The ROM types, however, state clearly that the situation should be reconsidered later and even gives hints on when an optimal time might be to reconsider, whereas the results from the TM indicate that it is best to abandon the whole project.

5.5 Conclusions

It has been shown that, when applying the ROM to this simple example, it can result in higher expected net benefits, and different IPs, than if a TM is used. This occurs because the ROM types take into consideration the fact that a building manager will evaluate in the future whether or not it is beneficial to execute an intervention and will make a decision to intervene only if it is beneficial. As the flexibility of a manager increases so does the improvement of the estimate with ROM, even if the optimal intervention program does not always change. In any case, the optimal intervention program determined using ROM is never worse than the one determined using the TM. The TM, which requires less modelling effort for the decision making and its consequences, no effort for the calculation of execution probabilities and no active reconsideration of IPs during the investigated time period and thus less management effort, is applicable in cases where

- it is clear that decision can only be made today,
- costs are low compared to benefit,
- the uncertainty of key parameters is low, or
- decision flexibility is low.

The two types of ROM require more modelling effort for the decision making and its consequences, more effort for the calculation of execution probabilities, and active reconsideration of IPs, and thus more management effort over the investigated time period. The expected net benefits and optimal intervention programs determined with the ROM types, however, are closer to reality, and thus enable better budget planning. They should be used in cases where

- decision flexibility is a possibility,
- the uncertainty of key parameters is high, or

- the costs are high compared to the benefits, always taking into consideration that if the costs are so high that the TM would recommend to do nothing, technically, all methods would recommend the same thing at t = 0, i.e. to do nothing. The ROM types, however, will show that there are possible times in the future where is might be beneficial to execute an intervention. This can be seen as that the ROM types recommend to reconsider in the future, whereas the traditional method recommends simply to never execute an intervention.

The European option ROM should be used if there is only one decision interval (either t = 0 or t > 0), e.g. through time constraints; such constraints can occur through contractual arrangements or through the interaction with interventions in connected buildings or building elements, if, for example a group of buildings is refurbished successively where one of the buildings must always serve as a spare area to accommodate the people or equipment displaced from the building being renovated. The American option ROM should be used if there is more than one possible decision time, i.e. as soon as there are two time intervals of which one is t > 0, and it is possible to make the decision at either of these. It applies to single properties, on which interventions can be planned independently.

The use of ROM to determine the time to intervene on buildings allows appropriate consideration of decision flexibility and, therefore, will lead to an increased benefit for building managers. In addition, its use may even lead to the creation of more decision flexibility and, therefore, further increased benefits. Examples of increased decision flexibility are the allocation of additional budget today which might or might not be used for interventions in the future or even by changing the building physically to facilitate interventions in the future which might not be possible otherwise.

Chapter 6

Real World Example - Clinic of nuclear medicine - University Hospital Zurich

In this chapter, the methodology for the identification and evaluation of intervention projects with consideration of decision and design flexibility (MIP), presented in chapter 3, and the Real Options Method for the determination and evaluation of intervention programs with consideration of decision flexibility (ROM), presented in chapter 4, were applied to a real world example of a clinic of the University Hospital Zurich (USZ). The main goal of this example was to investigate the applicability of the MIP and the ROM on a more elaborate, realistic - in parts fictive - example, as close as possible to an example in the real world. Several simplifications were made in the definition of the example to assist the demonstration of the method and the methodology in this thesis. The main simplifications are (a) the selection of the discrete probabilistic models for the uncertain key parameters and (b) the choice of the layout of the considered clinic of nuclear medicine. For the application of both method and methodology in the use of a real business case, these assumptions will have to be replaced by a deeper analysis.

The main goal of this example can be subdivided in more detailed goals, namely to show that

1. the ROM produces useful results, i.e. that the consideration of decision flexibility generates

    (a) other intervention programs and

    (b) higher expected net benefits

   than with the evaluation with a traditional method, i.e. without the consideration of decision flexibility, and

2. there are problems in the real world with

    (a) uncertain changes of the service level in the future (for example, operating costs and expenses)

    (b) the possibility to model the uncertain changes probabilistically in a discrete multinomial lattice,

    (c) the possibility to counteract these changes with expensive modification interventions that need to be avoided under certain circumstances,

    (d) the possibility to be flexible in the decision making about the time of these interventions,

    (e) the possibility to increase the flexibility of the current design of the premises through additional investments today with regard to the modifications in the future.

For this real world example, only the American Option type of the ROM was applied in addition to the Traditional Method, because it represented the actual decision making more precisely than the European option type: Decisions about the execution of the interventions were possible in every year over the investigated time period, and the decisions in each t depended on possible future decisions, i.e. the possibility to postpone the execution to a later t existed in reality. Section 6.1 of this chapter discusses steps 1 and 2 of the MIP for the analysis of the situation and the identification of relevant key parameters. Section 6.2 shows in steps 3 to 5 the determination of dynamic, stochastic models of these key parameters. In section 6.3, the static and dynamic evaluation models for the intervention programs are defined in steps 6 and 7. Section 6.4 describes possible modification interventions in the future and design variants for the building today in steps 8 and 9. In section 6.5 possible intervention programs are evaluated following steps 10 and 11 with the Traditional Method from chapter 4 (TM) and the method for the evaluation of intervention programs with consideration of decision flexibility (ROM), which was presented in chapter 4. In section 6.6, the results and the sensitivity analysis are presented and discussed, followed by the overall conclusions.

6.1 Description

The university hospital has to be refurbished and rebuilt respectively between today and 2060. The functionality of the hospital, i.e. the continuity of operation during this construction period is of high importance. The focus of this work lay on the analysis of the clinic of nuclear medicine (CNM) that is currently situated, together with the clinic of radiology, in the NUK building on the campus of the university hospital. The NUK building is one of the first buildings to be demolished in the hospital's refurbishment program, because it is contaminated with asbestos fibers, a fact that render any modification impossible. Thus, the CNM has to move at the next opportunity to a new building. The overall reconstruction of the hospital is roughly divided in Stage 1 (S1) and Stage 2 (S2). The CNM will move into a building of S1, E1 in figure 6.2. The assumption for this real world example is that the CNM will move to the new space in E1 in the next 2 years and that it is necessary now to define the required layout of the new rooms and the structural facilities of the new space.

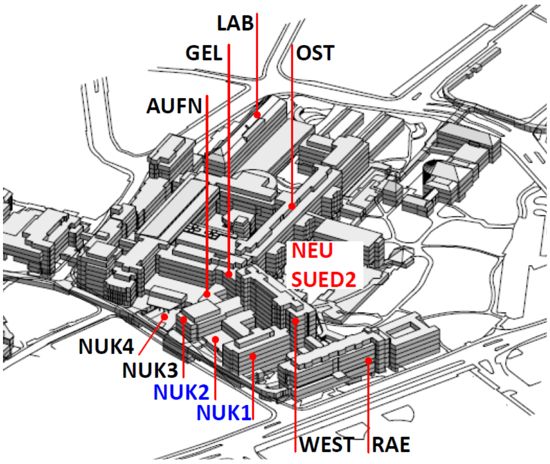

Figure 6.1: NUK building in the campus of the University Hospital Zurich (By courtesy of the USZ)

Figure 6.2: Master plan refurbishment and new construction of the university hospital campus with building E1 in orange (By courtesy of the USZ)

The focus of this example lies on the determination of intervention programs for modification interventions of the clinic, even though building designs with different levels of flexibility were investigated. Different designs were considered to show that, in this context, it could be helpful to improve the design to facilitate interventions and decision flexibility.

Table 6.1: Special devices used in clinic of nuclear medicine

Abbreviation	**Special devices used in CNM**
CT	Computertomograph
SPECT	Single-photon emission computed tomography
SPECT/CT	Combination of SPECT and CT
PET/CT	Combination of Positrone Emission Tomography and CT
PET/MR	Combination of PET and Magnetic Resonance imaging
Cyclotron	Particle accelerator (part of the radiopharmacy)

6.1.1 Step 1: Assess service level provided by and expected from building

With the help of the project manager and the head of the clinic and the head of the technical-medical staff, the process flows in the clinic for the different treatments and other processes and the resulting requirements on the existing building today were identified in several interviews and clinic inspections during operation. More information about the as-is state of the clinic's building was obtained through technical plans and information from the construction project manager. The CNM requires the space and facilities under special consideration of radiation protection in the building E1. The focus of the clinic of nuclear medicine lies on the diagnostic imaging and treatment using radioactive substances and materials. These imaging and treatment services require heavy technical equipment and "hot" rooms, i.e. rooms where radiation is released, either by the technical equipment or the substances that the patients are injected with (List of special devices in table 6.1).

Another important aspect is the radiopharmacy in the level U and V of the NUK building below the other rooms of the CNM. This radiopharmacy houses a particle accelerator producing radioactive substances, and laboratory rooms and equipment for the processing and handling of these radioactive substances for medical application. These substances are used both in the CNM and delivered to other clinics in Switzerland and Europe. Regarding the future rooms of the CNM, consideration has to be put to the length the substances have to be transported; the activity of the substances, i.e. their ability to emit sufficient radiation for the imaging, diminishes with time, sometimes after a few minutes. Thus, the radiopharmacy needs to be located close to the application and diagnosis rooms, where the patients are treated, ideally in the same building. The radiopharmacy should be located in basement rooms. The clinic is divided in seven departments: The PET center, cardiac imaging, the thyroid center, therapy, the conventional nuclear imaging, neuro-imaging, and the center for radiopharmacy. The PET center treats 90% of the patients of the clinic, with two up-to-date PET/CTs. The PET center has an external branch in the periphery of Zurich, i.e. a complete second PET center, situated in an industrial area, inconvenient to reach from the Zurich city center. This external PET center has two more PET/CTs and one PET/MR, while the latter is mainly used for research purposes and used far below capacity.

6.1.2 Step 2: Identify key parameters

6.1.2.1 Decision making, level of service and net benefits

To determine the relevance of the key parameters, a definition is necessary with respect to which criteria will be used to decide about modifications of the clinic rooms. The assumption is that decisions about modifications are made by the CNM. Together with the head of the clinic, the main goal of the clinic's operation was identified, namely to treat as many patients as possible, on the one hand to fulfill the hospitals aim of treatment and on the other side to generate income for the clinic. Also, the rejection of patients can lead to the founding of private clinics in the city of Zurich, which will be in competition to the CNM in the future and will lead to decreasing patient numbers for the CNM in the long term. Summarised, these are the two main criteria pertaining to the decision about modification:

1. Avoid loss of patients and ensure treatment of all patients
2. Operate the clinic economically

Level of service The required level of service is the capacity to treat patients, i.e. the number of patients that can be treated per year. The competitional advantage in this area of treatment is also to be considered, i.e. the goal is to lead the market in this treatment method in Switzerland and Europe respectively.

Net benefits The unit used to measure the benefit of a decision are the yearly cash-flows, here called the yearly benefit, and simplified assumed as $B = I - O$, where I describes the yearly income, and O the yearly operational costs of the clinic.

6.1.2.2 Relevant uncertain parameters

The identification of the relevant uncertain parameters for the future operation of the clinic required the expertise of the head of the clinic. From the different parts of the clinic, the PET center, and the treatments taking place in it, were chosen as the subject of further investigation. This choice was based on the fact that this part of the clinic treats 90% of the clinic's patient, thus generating the main part of the clinics income and revenue. Based on the expected net benefits and the service level, two relevant main scenarios concerning uncertain parameters were identified that could lead to significant changes in future net benefits and thus, to modification on the building in the future of the clinic:

1. **Change in patient numbers for an existing imaging application** which requires special equipment (PET/CT) and capacity on other stations of the patient path.
2. **Introduction of new imaging application** that requires new special equipment (PET/MR) and thus building modifications.

6.1.2.3 Structural objects in and adjacent to the PET center

Table 6.2 shows a complete list of building components that could be modified in case of changes in patient numbers in the clinic of nuclear medicine to increase the treatment capacity. The existing scanners (PET/CT) are assumed to be state of the art. The radiopharmacy, where the required substance, FDG[1], is produced, is assumed to have sufficient production capacity to accommodate even the highest increases in patient numbers encountered in this example.

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[1] a modified and radioactive labeled sugar

Table 6.2: Structural objects - Rooms, Infrastructure and devices - in the PET center

Name	Ind.	Room/ Function	Name	Ind.	Infrastructure	Name	Ind.	Device
Room 1	R1	Hot laboratory	Infrastructure 1	IF1	Ventilation	Device 1a	G1a	PET
Room 2	R2	Room for PET	Infrastructure 2	IF2	Electrical installation	Device 1b	G1b	PET/CT
Room 3	R3	Application room	Infrastructure 3	IF3	Load bearing capacity	Device 1c	G1c	PET/MR
Room 4	R4	Changing room patients (hot)	Infrastructure 4	IF4	Cooling pond	Device 2	G2	Particle accelerator
Room 5	R5	Sanitary facilities patients	Infrastructure 5	IF5	Cooling room			
Room 6	R6	Resting room	Infrastructure 6	IF6	Pipes to cooling pond			
Room 7	R7	Diagnosis room						
Room 8	R8	Changing room staff						
Room 9	R9	Lounge staff						
Room 10	R10	Sanitary facilities staff						
Room 11	R11	Administration rooms						
Room 12	R12	Radiopharmacy						
Room 13	R13	Technic room						

6.1.2.4 Problem summary and the value of flexibility

Based on the preceding chapters and the analysis presented in the appendix, the problem was formulated as follows: The PET center, which is part of the clinic of nuclear medicine, generates the majority of benefits for the clinic and is thus the most relevant part of the clinic. Further, the most likely scenario for the introduction of a new imaging application, the pre-screening for Alzheimer's, has a direct impact on the patient numbers in the PET center: This pre-screening requires the injection an FDG tracer and a scan on a PET/MR, very similar to the existing application for the localisation of cancer cells and tumors, which provides the biggest part of the patients currently treated in the clinic, and which requires the injection of FDG but a scan either on a PET/CT or PET/MR. This leads to the more detailed definition of the following two uncertain key parameters most relevant for the service provided by the CNM:

1. Number of patients for existing application for cancer localisation with PET/CT or PET/MR (**UP 1**)

2. Number of patients for new application for pre-screening for Alzheimer's with PET/MR (**UP 2**)

The development of both parameters over the investigated time period of 40 years is subject to uncertainty and can lead to significant modifications and thus costs, when certain thresholds of the treatment capacity are exceeded. Both parameters have the same effect, namely the regular or irregular[2] treatment of patients in the PET center with the FDG substance, with the difference that UP1 varies constantly while UP2 can lead to sudden jump in patient numbers when the research concerning the pre-screening is successfully finished and the treatment is approved by the Swiss health care system, i.e. covered by the standard Swiss health insurance. If the modifications for the expansion of the treatment capacity are not executed, it is possible that the PET center loses patients in the long-term and its position as an institution of cutting-edge treatment in this area.

6.2 Stochastic models and input parameters

The change in parameters UP1 and UP2, their steps and probabilities of change are modelled in discrete lattices. This allows for the analysis of future decision situations at different times and their evaluation using the method for the evaluation of intervention programs with consideration of decision flexibility.

6.2.1 Step 3: Analyse past evolution of values of possible key parameters UP1 and UP2

6.2.1.1 UP1: Number of patients for existing application for cancer localisation with PET/CT or PET/MR

As the actual historical data for UP1 from the clinic are not useful in their quality and quantity, the discrete model for UP1 was selected according to assumptions, which will be described in more detail in the next steps. The alternative to this would have been to create a model for the patient numbers based on external parameters, e.g. cancer rates or growth and demographic development of the Swiss population, with an approach similar e.g. to publications by Forró et al. (2012) and Fievet et al. (2015). This was, however, not done in this example, as the connection with the expected patient numbers for the PET center is very complex and would have required disproportionate additional effort to deliver meaningful results. Considering the goal of this example to show that the method presented in this thesis produces useful results, i.e. other intervention programs and higher expected net benefits than the Traditional Method, the decision was to continue with a probabilistic model based on adequate assumptions.

6.2.1.2 UP2: Number of patients for new application for pre-screening for Alzheimer's with PET/MR

A pre-screening for Alzheimer's is necessary to identify persons that are at risk of getting Alzheimer's. A vaccination, which has to be applied 15 years before the actual outbreak of Alzheimer's, can prevent this outbreak. The pre-screening is actually already possible with an existing tracer, the FDG, and requires a PET/MR, a device that is already available; however, the vaccination is still under development and has to be approved by the Swiss health care system, i.e. approved as a treatment reimbursed by a Swiss health insurance. At the same time, the pre-screening has to be approved as part of the treatment to be equally billable. Only when the Swiss health care system agrees to pay for the pre-screening, a significant jump in patient numbers for it can be expected for the clinic's PET center.

The high costs for the vaccination make the pre-screening necessary, as the health insurance will only pay for it for persons with a significant risk to fall ill with Alzheimer's. If the pre-screening is positive, patients at risk will then take a blood test that is far more expensive than the pre-screening to finally confirm the significance of the risk for Alzheimer's. Potential patients for the pre-screening are all persons between 40 and 50 years of age. 1'000 patients can at least be expected in the beginning with a significant increase when the application is established (according to the CNM). It can be assumed that the patient number reaches a plateau after the

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[2] Irregular treatment of patients requires costly evasive measures, which will increase the overall operational costs for the PET center significantly. They will be defined in detail in later sections.

initial rise, based on developments of patient numbers for other newly introduced applications in the clinic in the past. Obviously, there is no historical data concerning patient numbers for this particular application. Similar to UP1, a probabilistic model based on external parameters, such as demographic data for age relevant groups in Switzerland and Zurich could have been established. However, for the same reasons as for UP1, the probabilistic model for UP2 was built based on assumptions, which will equally be explained in later steps.

6.2.2 Step 4: Analyse changes in trends

6.2.2.1 UP1: Number of patients for existing application for cancer localisation with PET/CT or PET/MR

A change of the existing application for the localisation of cancer cells is not expected over the investigated time period (see appendix F.1.1 for discussion), i.e. the assumption is that the existing application for the localisation of cancer cells and tumors will remain the main treatment in the PET center with the highest patient numbers. However, the development of the actual patient numbers is uncertain. According to the management of the PET center, the existing application has been established at the clinic for 10 years and the patient numbers have reached today a plateau around the actual number of 4'700 patients per year. The existing application as such has been established for more than 30 years (Som et al., 1980).

6.2.2.2 UP2: Number of patients for new application for pre-screening for Alzheimer's with PET/MR

This scenario is a trend breaker itself, thus, no further trend breakers are considered. Similar to the existing application, it is assumed that the application for the pre-screening for Alzheimer's will be equally established as the existing treatment, over more than the investigated time period of 40 years.

6.2.3 Step 5: Select models to predict likelihood of future scenarios

As discussed in sections sections 6.2.1.1 to 6.2.1.2, sufficient historical data was not available for the patient numbers and the of other, external information would have added little additional value for significant additional effort. Thus, the models for the prediction of likelihood of future scenarios for both parameters and their parameters were selected based on assumptions.

6.2.3.1 UP1: Number of patients for existing application for cancer localisation with PET/CT or PET/MR

Currently about 4'700 patients a year receive the existing application on the PET/CTs today. The assumption is that the patient number will vary around this number of 4'700 over the investigated time period, but will not increase or decrease above or below a certain level. A significant increase in patient numbers for the existing treatment would require a massive increase in cases of carcinosis in the relevant demographic groups. This is assumed to be very unlikely over the investigated time period, as these significant increases would have to be caused by a significant increase in life expectancy or the introduction of a new source for carcinosis, e.g. nuclear radiation or toxins in the environment, both not to be expected in Switzerland or Europe. A significant decrease would also not be expected for the same reasons as for the increase. The head of the clinic recommended to assume a variation around the mean of 4'700 patients/year of not more than 2'000 to 2'500 for UP1. One possible way to represent this situation is to use the mean-reverting process, i.e. a process that does not deviate too far away from a possible mean (compare section 4.2.2). This mean reverting probabilistic model allows sufficient accuracy for this example and easy application in the representation as a binomial lattice. Figure 6.3 shows a selection of possible continuous scenarios of UP1 over the investigated time period (top) and the representation of these scenarios in a binomial lattice (bottom).

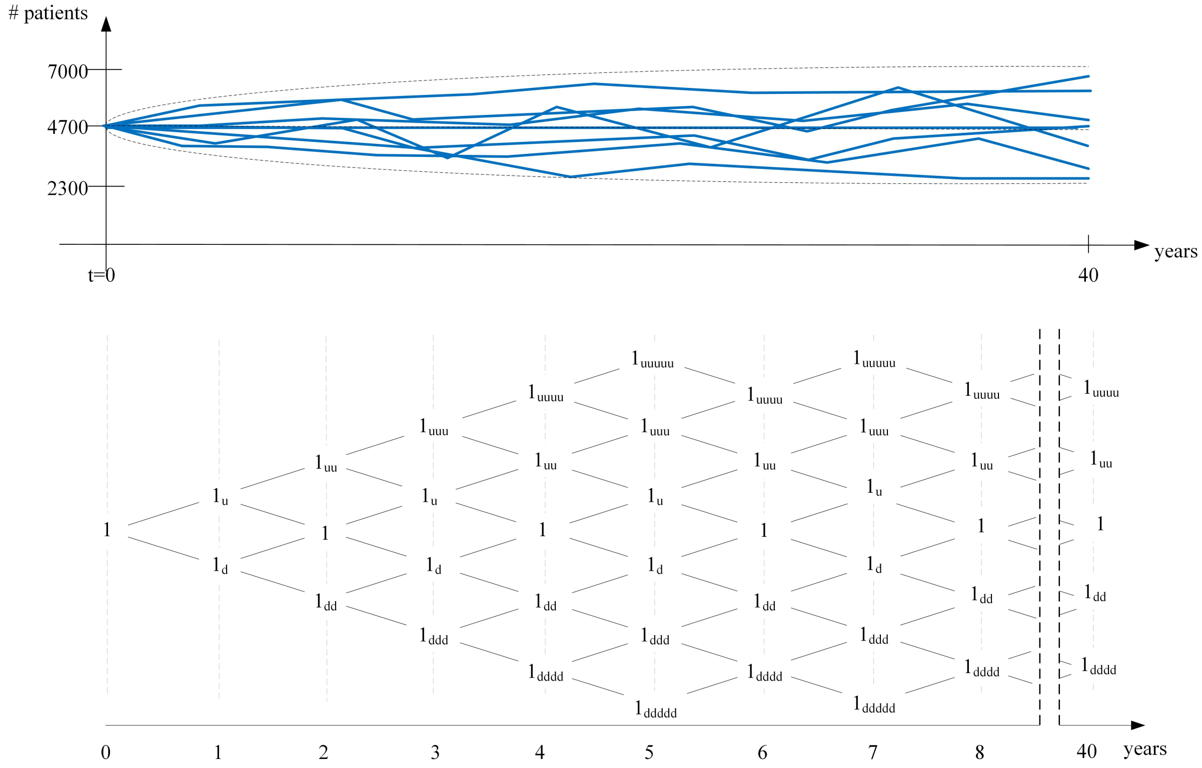


Figure 6.3: Representation of a continuous (top) vs. a discrete model (bottom) of the uncertain parameter P_{UP1} (Continuous model: Mean value, upper and lower boundaries of confidence interval as dashed lines, possible paths of the uncertain parameter as solid lines)

The necessary input for this lattice is shown in table 6.3.

Table 6.3: Input for mean-reverting process (Ornstein-Uhlenbeck-Prozess) for stochastic model of UP1 (Hahn and Dyer, 2008)

Name	**Calculation**	**Description**
$P^{+}_{log,t,UP1}$	$P_{log,t-1} + \sqrt{\Delta t}\sigma$	Natural log of up movement of patient number
$P^{-}_{log,t,UP1}$	$P_{log,t-1} - \sqrt{\Delta t}\sigma$	Natural log of down movement of patient number
$p_{t,UP1}$		Probability of up movement
$1 - p_{t,UP1}$		Probability of down movement

The assumption is that UP1 changes each year. The probability of an up movement of UP1, $p_{t,UP1}$, can be calculated as follows (according to Hahn and Dyer (2008)):

$$p_{t,UP1} = max\left(0, min\left(1, \left(\frac{1}{2} + \sqrt{\Delta t}\frac{k\left(\overline{P}_{log} - P_{log,t}\right) - \frac{1}{2}\sigma}{2\sigma}\right)\right)\right) \tag{6.1}$$

with the necessary input parameters in table 6.4. The variance σ and the reversion factor k were selected to guarantee that variation of about 500 patients per year and the upper and lower boundary of about 2400 patients more or less per year (as recommended by the head of the clinic) were not exceeded.

Table 6.4: Input parameter for calculation of input for mean-reverting process

Input Parameter	**Description**	**Unit**	**Value**
σ	Variance	-	0.1
Δt	Time increment	Years	1
k	Reversion factor	-	0.3
$\overline{P}_{log}$	Natural log of the mean of the patient numbers	Patients	log(4'700)
$P_{log,t}$	Natural log of the current value of the patient numbers at an upward node in t	-	-

6.2.3.2 UP2: Number of patients for new application for pre-screening for Alzheimer's with PET/MR

According to the head of the clinic, the demand for the pre-screening for Alzheimer's depends directly on the research success of the Alzheimer vaccination. The probability of research success for the vaccination is 80% (Source: CNM). The different scenarios for the possible increase can be represented by a jump process (Poisson process), with possible jumps in years 2, 4, 6 and 8 to account for the uncertainty in the timing of the research success for the vaccination. Even if the research is not successful in 2 years, there is still the possibility of a later success in case more time for the development is needed. Should the research in 8 years still not be successful, it can be assumed that it will not be afterwards, i.e. the probability of introduction is 0%.

The simplification here is that the number of patients will increase to a number of 2'000 additional patients and stay at that level until the end of the investigated time period (figure 6.4). This is a simplification, as it is more likely that the patient number starts at a lower number to increase to a plateau, similar to the patient numbers for UP1 (see discussion in appendix F.1.2).

The selected model of the Poisson process for UP2 can be represented in a binomial lattice, as shown in figure 6.4.

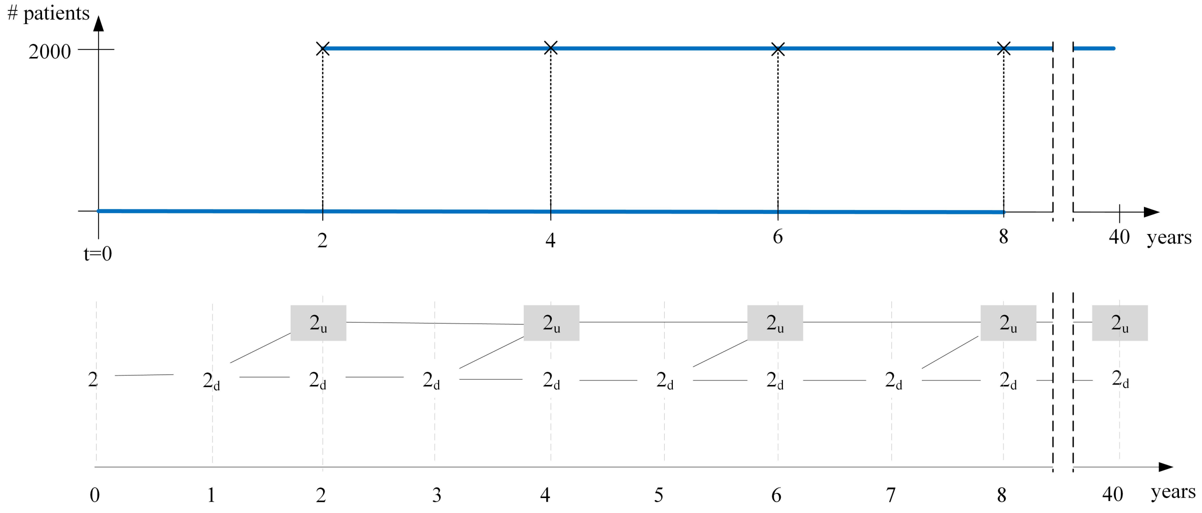


Figure 6.4: Representation of a continuous (top) vs. a discrete model (bottom) of the uncertain parameter P_{UP2} (Continuous model: Possible paths of the uncertain parameter as solid line, possible jumps in the values as dashed lines)

For this lattice, the following input was defined according to the information from the head of the clinic presented above:

Table 6.5: Input for Poisson process for stochastic model for UP2

Name	Values	Description
$P^{+}_{t,UP2}$	+2000 Patients	Additional number of patients after introduction of application
$P^{-}_{t,UP2}$	+ 0	Additional number of patients before introduction of application
$p_{t,UP2}$	0.8	Probability of introduction of application in the years t=2, 4, 6 and 8 (with the probability decreasing by 0.1 in each time step)
$1 - p_{t,UP2}$	0.2	Probability of no introduction of application in the years t=2, 4, 6 and 8 (with the probability increasing by 0.1 in each time step)
Δt	2	Time increment of change in years

6.2.3.3 Combination of discrete models of uncertain parameters UP1 and UP2

These two uncertain parameters 1 and 2 need to to form a combined lattice, as they both affect the number of patients for PET/MR and the patient path. Figure 6.5 shows that the combined lattice consists of the pairing of each node in the single lattice for UP1 (figure 6.3) with all nodes of the single lattice for UP2 (figure 6.4).

In year 1 for example, there are two possible outcomes for UP1, nodes 1u (UP1 up) and 1d (UP1 down), while there is only one possible outcome for UP2, 2d (UP2 down), as the introduction of the new application will only be possible starting in year 2. This leads to two combinational nodes in year 1: (1) 2d1u, (2) 2d1d. In year 2, however, there are three possible outcomes for UP1 (1uu, 1, 1dd) and two possible outcomes for UP2 (2u and 2d), leading to the following combinational nodes: 1uu2u, 1uu2d, 1ud2du, 12d, 1dd2u, 1dd2d. All other combinational nodes of the lattice can be formed in this manner. The combined lattice is, following the equivalent properties of the single lattices, recombining, i.e. the majority of nodes (except the nodes in the margins of the lattice) are part of several paths in the lattice.

The possible paths, i.e. the connections of each nodes with possible successors, in the combined lattice are represented by black lines. Node 1u2d in year 1, for example, has 2 nodes - 1uu2uu and 1ud2uu - in year 2 as successors (as an up move of UP2 cannot be followed by a down move), whereas node 1u2d has 4 nodes - 1uu2u, 1uu2d, 12u, 12d - as successors, as a change in UP2 is possible.

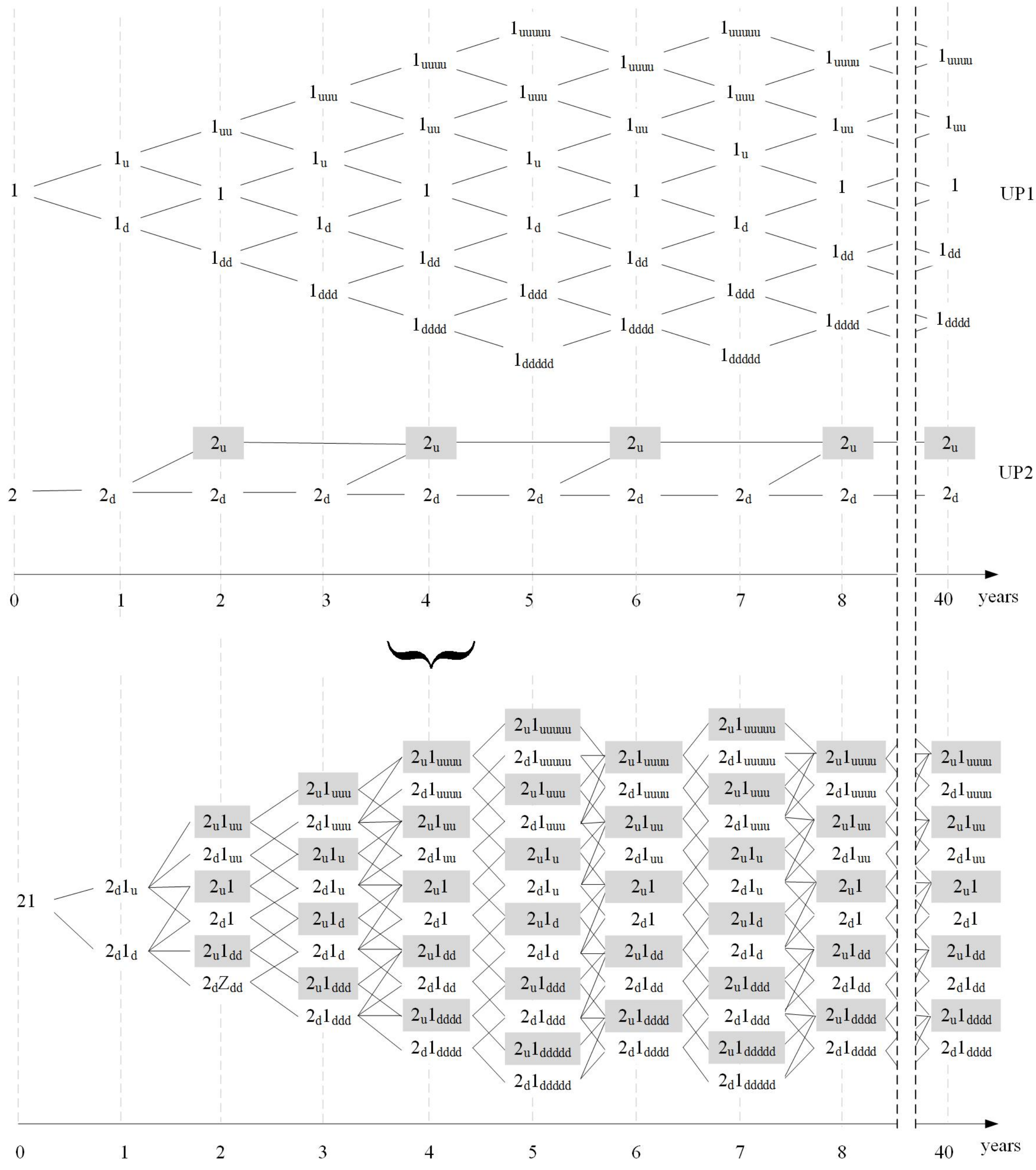


Figure 6.5: Discrete models of the uncertain parameters UP1 and UP2 and their combination in one lattice

6.2.3.4 Summary of extreme expected scenarios for the patient numbers to be treated in the PET center

Based on the chosen stochastic models in the previous chapters, a finite number of main scenarios can be identified, which can serve as the basis for the static and dynamic evaluation models in the next sections. For this purpose, it is useful to list possible extreme scenarios for both uncertain parameters (table 6.6) to determine possible scenarios for costs and benefits and possibly necessary interventions and consequences that need to be considered.

Table 6.6: Possible main scenarios for UP1 and UP2

No.	Main scenarios UP1	No.	Main scenarios UP2
1	Patient numbers remain on current level	a	Pre-screening is not introduced
2	Patient numbers increase to maximum	b	Pre-screening is introduced in 2 years
3	Patient numbers decrease to minimum	c	Pre-screening is introduced in 8 years

The combination of possibles scenarios of these two parameters can be seen in table 6.7 and figure 6.6.

Table 6.7: Combinations of main scenarios of UP1 and UP2

	1	**2**	**3**
a	1a	2a	3a
b	1b	2b	3b
c	1c	2c	3c

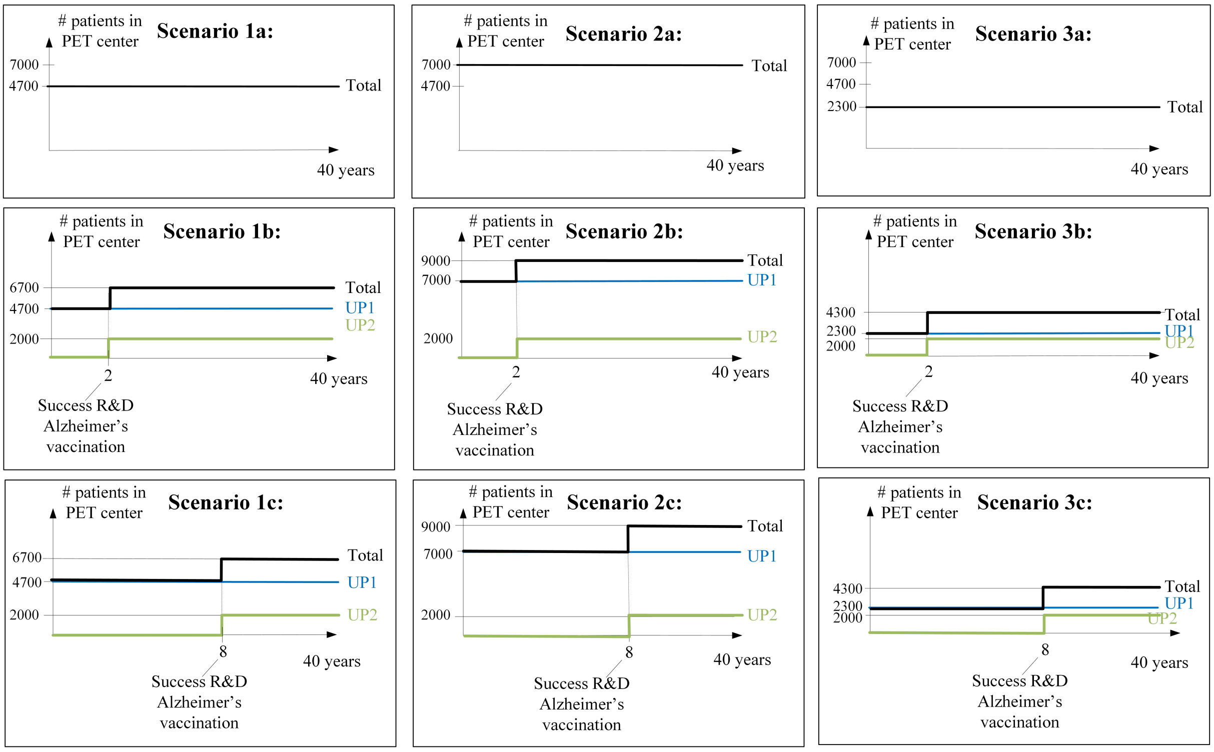


Figure 6.6: Combinations of possible main scenarios for UP1 and UP2

6.3 Evaluation models

6.3.1 Step 6: Establish static model

After the possible scenarios for the key parameters were defined in the previous steps, the detailed evaluation model for the benefit, according to which the optimal intervention program is chosen, is determined, i.e. the overall expected net benefits from the building operation have to be calculated.

The mathematical formulation is described by the following equations. The assumption is that all costs and benefits are discounted with a discount rate r to t=0. $R(t=0)$ are the expected net benefits of all yearly net benefits that are estimated for the investigated time period (0,T], and can be described as follows :

$$R(t=0) = \sum_{t=0}^{T} e^{-rt} B_t \tag{6.2}$$

where

$$B_t = P_t \cdot (I_{v,t} - O_{v,t}) - O_{f,t} \tag{6.3}$$

and the input parameters are defined in table 6.8

Table 6.8: Description and calculation of all impacts

Parameter	Description	Calculation
P_t	Number of treated patients at time t	-
$I_{v,t}$	Variable income from patient treatment	5'000 CHF/patient
$O_{v,t}$	Variable operational costs (per patient)	S. equation 6.15
$O_{f,t}$	Fixed operational costs	S. equation 6.17

6.3.2 Step 7: Establish dynamic model

In this step, the probabilistic models from steps 3 to 5 are integrated in the static model, so that the development of the benefits and costs can be dynamically displayed by time.

6.3.2.1 Dynamic evaluation model

The dynamic evaluation model takes into account now that the number of patients in year t, P_t, has not one value but follows a probability distribution according to the chosen discrete, probabilistic models of UP1 and UP2 (compare section 6.2.3 for details). Hence the expected net benefits must be calculated under consideration of these probabilities. The expected net benefits R_{n_t} at each node n in the combined lattice of UP1 and UP2 (represented in figure 6.5) are calculated (similar to chapter 4) and are the sum of the expected yearly net benefits, B_t, i.e. considering their probability of occurrence, relative to the considered node for a particular value of the uncertain key parameter in τ_R:

$$R_{n_{\tau_R}} = \sum_{t=\tau_R+1}^{T} \left(e^{-r(t-\tau_R)} \sum_{n_t=1}^{N_t} \sum_{i_{n_t}=1}^{I_{n_t}} \left(q_{i_{n_t}} \cdot B_{i_{n_t}} \right) \right) \tag{6.4}$$

where

The expected net benefits at time $t=0$ are calculated as follows (also considering interventions), and correspond to equation 4.8 in section 4.3.1 from the traditional evaluation method:

$$X(\tau_{TM}) = R_0 + e^{-r\tau_{TM}} \left(\sum_{n_{\tau_{TM}}=1}^{N_{\tau_{TM}}} R^{+}_{n_{\tau_{TM}}} - C_{\tau_{TM}} \right) \tag{6.5}$$

Table 6.9: Parameters for equation 6.4

Name	Description
T	Investigated time period
N_t	Number of nodes with possible values at time t
I_{n_t}	Number of possible paths leading to node n in time t
$q_{i_{n_t}}$	Probability of path i_{n_t} to node n at t
$B_{i_{n_t}}$	Yearly net benefit at node n at t

where

Table 6.10: Parameters for equation 6.5

Name	Description
R_0	Expected net benefits without any intervention at t=0
$N_{\tau_{TM}}$	Number of nodes with possible values at time τ_{TM}
$R^+_{n_{\tau_{TM}}}$	Additional expected net benefits at node n at time τ_{TM} after execution of an intervention
$C_{\tau_{TM}}$	Intervention costs at time τ_{TM}

6.4 Identify renewal projects

6.4.1 Step 8: Identify possible ways to change the buildings use or operation in t>0

The changes in use and operation can be defined as the change in number of patients that have to be treated in the PET center, for all possible main scenarios (and intermediate scenarios) that were described in the previous section (figure 6.6). Two significant changes in operation occur

1. if the total number of patients exceeds the current capacity of the clinic (5'000 patients)
2. if patients require the new application, the pre-screening for Alzheimer's, in the PET center

6.4.1.1 Change of operation 1 (CO 1): Total number of patients exceeds the current capacity of the clinic (5000 patients)

The capacity of the PET center is exceeded as soon as the capacity of one of the patient stations (see figure 6.7) is exceeded. For both applications, the patients have to follow linearly through all stations, i.e. if the capacity of one station is met, this station is a bottleneck for the complete process. The patient path for both applications, the existing application for the localisation of cancer cells and tumors and the new application, the pre-screening for Alzheimer's, can be seen in figure 6.7. Necessary side rooms are also depicted.

If the total number of patients exceeds the capacity of the PET center, an evasive measure (EM1) has to be taken to ensure treatment: Afternoon shifts can be introduced, as currently, patients are only treated in morning shifts until 2 pm. However, these afternoon shifts cause significant additional costs for an additional medical team and for a second production of tracers in the radiopharmacy.

6.4.1.2 Change of operation 2 (CO 2): Patients require the new application, the pre-screening for Alzheimer's, in the PET center

Currently, the scanners in the PET center are PET/CTs. The new application for the pre-screening for Alzheimer's, however, requires a PET/MR. The clinic of nuclear medicine has a branch in the periphery of Zurich, where a PET/MR is currently used for research in Alzheimer's.

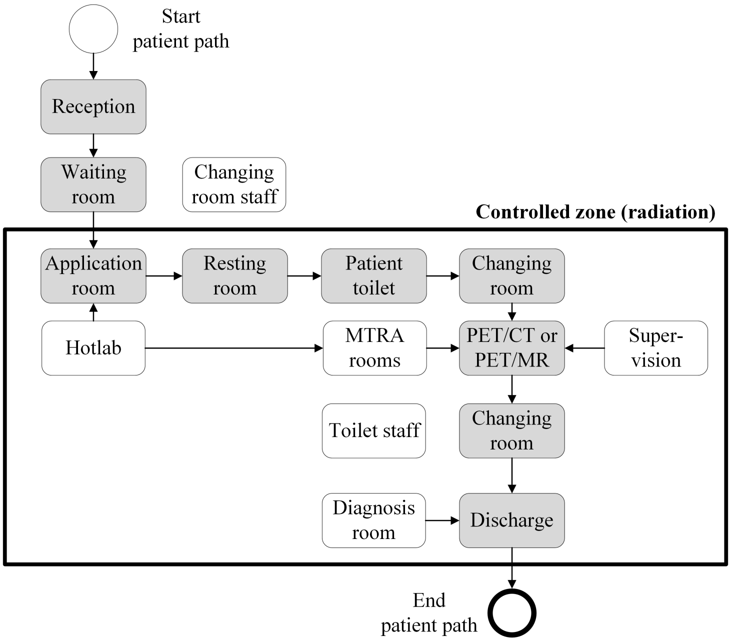


Figure 6.7: Patient path (grey fields) in PET center with adjacent rooms

This external branch of the clinic has also two more PET/CT and treats patients similarly to the considered PET center in university hospital in the city center. The currently available capacity of this PET/MR in the external branch is high. In case that demand for the new application for the pre-screening for Alzheimer's arises, before the main PET center on the university hospital campus in the city center has a PET/MR, an evasive measure (EM 2) is to send patients to the external branch for the pre-screening for Alzheimer's. However, the way to the premises of the external clinic branch is inconvenient for patients. Thus, it can be assumed that a ratio of the patients sent there will instead chose to go to one of the more attractive private PET centers in the Zurich area for the pre-screening. This leads to a loss of patients and thus income from their treatment.

6.4.2 Step 9: Identify possible renewal projects at t=0

To accommodate the considered changes in operation in the last section, possible modification interventions have to be identified. Together with possible changes to the current design of the clinic premises at t=0, the combination of these modification interventions and design changes will be referred to as a intervention and design project.

Possible modification interventions in $t > 0$ Interventions in $t > 0$ are necessary due to the two changes in operations described in the previous section. There are two main ways to accommodate these changes:

1. Install a PET/MR for the PET center in E1 in the clinic for nuclear medicine
2. Expand the treatment capacity of the bottleneck stations in the patient path

The rooms in table 6.11 were identified as bottlenecks in the patient paths and are a selection of the rooms in table 6.2 in step 2 of the methodology (section 6.1.2.3). Possible interventions to increase the capacity of patient care are listed in table 6.12.

The scans for the existing treatment, the cancer localisation, can be executed on both PET/CTs and PET/MRs, i.e. the additional PET/MR counteracts all changes in use. Interventions 1 to 4 need to be executed consecutively, i.e. intervention 2 is executed after or at

Table 6.11: Bottlenecks in patient path

Interv.	**Structural object**
1	PET/MR + room
2	Room 3 (Application room)
3	Room 6 (Resting room)
4	Room 7 (Diagnosis station)

Table 6.12: Description of possible interventions to increase capacity

Name	**Description**
I0	No intervention
I1	Additional PET/MR
I2	Additional application room
I3	Additional resting room
I4	Additional Diagnosis station

the same time as intervention 1. Also, due to the high costs of any intervention, it is assumed that each intervention can only be executed once over the investigated time period.

Possible layout variants in t = 0 The assumption is that the clinic of nuclear medicine will move to the new premises in building E1 of the new construction project of the university hospital. The assumption is that the building is planned today, with the possibility to change the design or layout to account for the chosen interventions 1 to 4. The actual plans for E1 do not exist yet. Thus, the following assumptions for the position of the clinic of nuclear medicine and the PET center in E1 were made, together with the clinic of nuclear medicine and the construction department of the university hospital:

1. The PET center should be located in the ground floor of E1, directly above the radiopharmacy in the level below, directly adjacent to the remaining departments of the clinic for nuclear medicine.
2. The layout of the ground floor is based on the master plan for the new construction of the university hospital buildings. The layout of the ground floor includes an inner courtyard (figure 6.8).

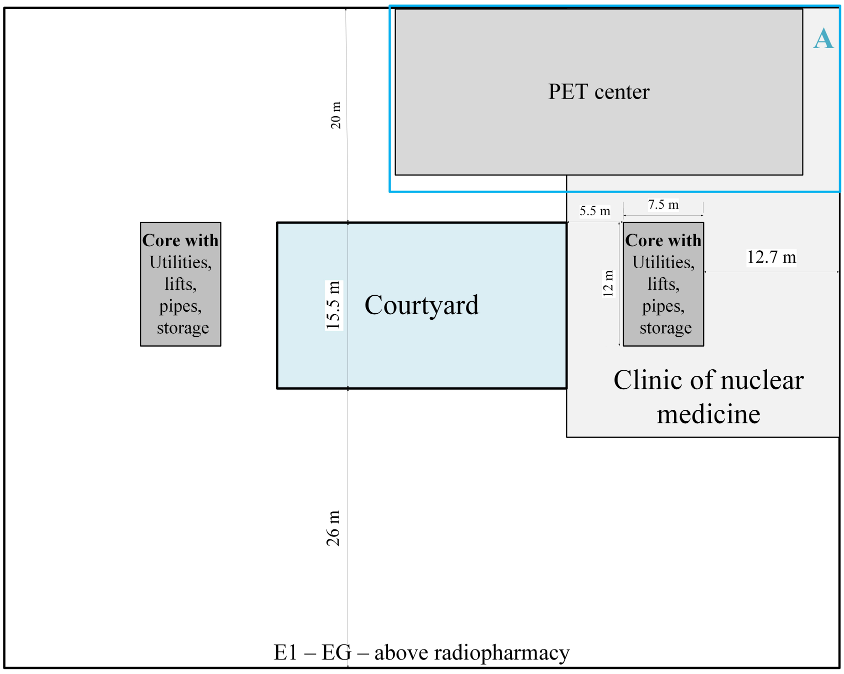
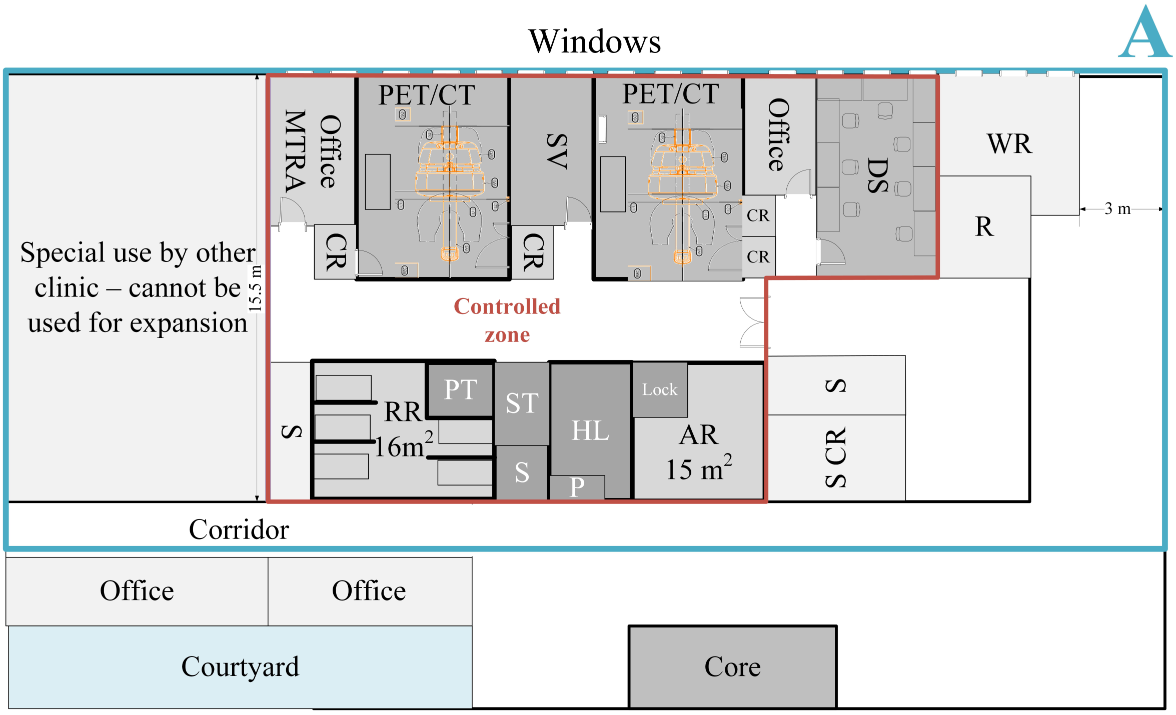


Figure 6.8: Floor plan ground floor - E1

Three possible designs at t=0 were chosen for the PET center. Because the differences affect mainly the floor layout, i.e. size and position of rooms, the three designs are called "layouts".

Basic layout - NoInitial The basic layout for the PET center can be seen in the following figure 6.9 and is optimized for the current requirements. The position of the PET center is in frame A.



R – Reception
WR – Waiting room
AR – Application room
RR – Resting room
PT – Patient toilet
CR – Changing room

PET/CT – PET/CT room
PET/MR – PET/MR room
TR – Technic room
DS – Diagnosis stations
SV – Supervision PET

HL – Hotlaboratory
ST – Staff toilet
SCR – Staff changing room
P – Pipes
S – Storage room

Figure 6.9: Layout 1 - NoInitial of the new PET center in E1 - optimised for current patient numbers - frame A from figure 6.8

Even though the NoInitial layout in figure 6.9 is already very flexible compared for example to the current PET center in NUK buildings[3], it is almost impossible to modify it with regard to interventions 1 to 4.

However, the NoInitial layout loses this flexibility with regard to interventions 1 to 4 due to two factors:

- **No load bearing capacity for PET/MR** - The expansion of the PET center by a PET/MR is only possible if the floor has the required load-bearing capacity, as a PET / MR weighs, with accessories in the equipment room, 15 t, much more than the maximum 4 t of the existing PET/CTs. If this load bearing capacity of the floor is not provided in the initial design, subsequent strengthening is difficult, expensive and almost impossible.
- **Additional area for PET/MR is not available** - The additional PET/MR requires a large additional area of more than 90 m^2, which cannot be cleared easily. This additional area would have to be taken from the adjacent clinic, as it cannot be expected that valuable

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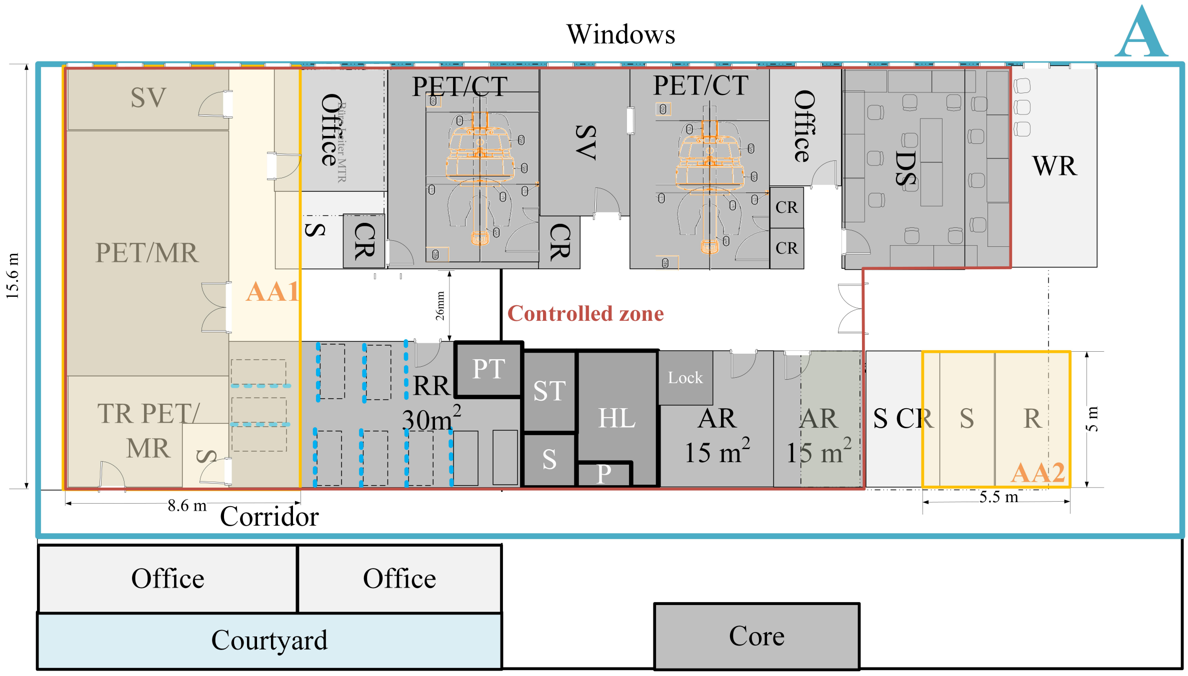
[3] The post and beam structure of E1 already brings great flexibility by load transfer through props and thus makes an open floor plan possible; walls can be added with little effort. The room arrangement along an open corridor makes expansions possible. The assumption of a suspended ceiling or a hollow floor brings great flexibility. Another point towards flexibility is the concentrated arrangement of hot spots, such as highly specialised technical rooms, in the heart, and the position of soft facilities like reception, staff changing rooms and storage rooms on the edge of the PET center, making the subsequent displacement of spaces possible.

space in E1 will remain unused. If the use of this area is highly specialised, like operation theaters, it is almost impossible to move it.

Due to these two factors, the NoInitial layout is effectively not expandable, i.e. the capacity of the PET center cannot be increased. The execution of interventions 2 to 4 would not remove the bottleneck of intervention 1 preventing the treatment of more patients.

Expanded Layout - AllInitial A second possibility is to include all future modifications in the current layout, i.e. to define the robust layout ALLInitial with the necessary space for the PET Center already provided (figure 6.10).



R	Reception
WR	Waiting room
AR	Application room
RR	Resting room
PT	Patient toilet
CR	Changing room
PET/CT	PET/CT room
PET/MR	PET/MR room
TR	Technic room
DS	Diagnosis stations
SV	Supervision PET
HL	Hotlaboratory
ST	Staff toilet
SCR	Staff changing room
P	Pipes
S	Storage room

Figure 6.10: Expanded Layout 2 - AllInitial for the new PET center in E1 - all interventions executed - Yellow zones: Expanded space compared to layout 1

All rooms are already modified to accommodate the maximum number of patients, and thus show the state after interventions 1 to 4 were already executed. This leads to an increased demand of space compared to the NoInitial layout of about 134 m^2 for the PET/MR plus adjacent rooms and the area for the resting room, additional 28 m^2 for moving the reception due to the introduction of an additional application room and the expansion of the room for the diagnosis stations. It is assumed that it is possible to plan the PET center at t=0 in the required size, always considering the loss of rent for the used additional area and coordination problems with adjacent clinics. The construction costs are also higher than for the NoInitial layout, because additional load bearing capacity of the floor slab and the installations, such as cooling and electrical installation. The costs of the additional PET/MR are considered in the yearly net benefits B_t as fix costs for replacement every 10 years (compare table 6.5.1.5).

Flexible Layout - FlexInitial As a third possibility, a flexible layout should be considered, which is aligned with the current requirements, but can be modified in the future (unlike layout 1), and is less costly than the robust layout 2.

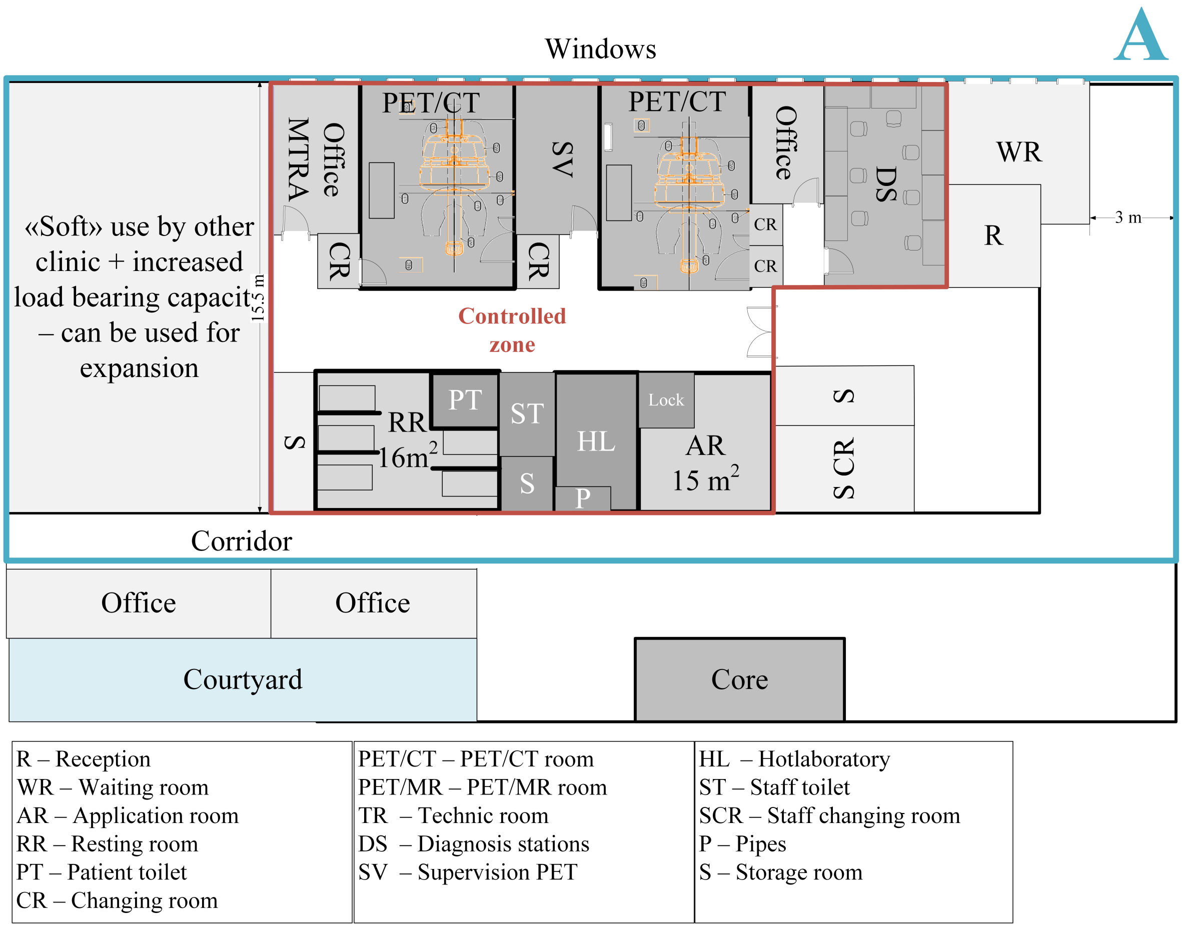


Figure 6.11: Layout 3 - FlexInitial of the new PET center - can be expanded if necessary

The flexible layout 3, compared to the basic layout 1, provides already the additional load bearing capacity of the floor slab for the PET/MR, and the additional area necessary for expansion, is used for "soft" purposes, such as offices or administration, which makes it easy to move should an expansion become necessary. This “soft” use is opposed to the use of an area for “hard” use that is not so easily moved if necessary. Examples for such “hard” use are operating areas or other highly specialised facilities.

Differences in costs and benefits between the three layouts

1. Construction costs at time t = 0 for load bearing capacity etc.

2. Fixed operational costs for “soft” use of additional area

3. Treatment capacity, i.e. number of patients

6.5 Evaluate renewal projects

6.5.1 Step 10 - Estimate additional costs and benefits of each renewal project in $t > 0$

6.5.1.1 Summary real world example

PET center - Basic principles of operation When evaluating the service level of the PET center and making decisions about the execution of interventions, the following principles of the clinic of nuclear medicine and thus the PET center have to be taken into account:

- Principle 1 - Operate the PET center economically
- Principle 2 - Avoid losing patients by making sure that all patients can be treated

Level of service The level of service is evaluated by the sum of the expected incomes and costs over the investigated time period for the treatment of patients, who come to the PET center of the university hospital. This sum of cost and income, discounted back to today, will be referred to as the expected net benefits. Principle 2 is considered by assuming that all patients are treated, even if the regular capacity of the clinic is exceeded. Thus, patients are not sent away, but are treated at considerable additional costs for evasive measure 1 and 2 (section 6.4.1).

Uncertainty The assumption is that this ENB due to the two uncertain parameters

- P_{UP1} - Patient numbers for existing application for localisation of cancer cells and tumors on PET/MR or PET/CT
- P_{UP2} - New application for the pre-screening for Alzheimer's on the PET/MR

6.5.1.2 Level of service

Yearly benefits B_t For all possible scenarios for UP1 and UP2 in combination, the yearly net benefit B_t is determined according to the following equation:

$$B_t = \left(P_{t,UP1} + P_{t,UP2} \cdot f_{\Delta P_{t,UP2}}\right) \cdot (I_{v,t} - O_{v,t}) - O_{f,t} - \Delta B_t \tag{6.6}$$

where

Table 6.13: Parameter for equation 6.6

Name	Description
$P_{t,UP1}$	Patient number for existing application (UP1)
$P_{t,UP2}$	Patient number for new application (UP2)
$f_{\Delta P_{t,UP2}}$	Possible reduction in patient numbers if patients have to be sent to the Wagi-Areal
$I_{v,t}$	Income per patient
$O_{v,t}$	Variable costs per patient
$O_{f,t}$	Fixed costs for the operation of the clinic (independent from actual number of patients)
ΔB_t	Additional costs for treatment of patient over capacity in afternoon shifts

Expected benefits at time t, R_t The expected benefits at time t are calculated as follows:

$$R_{n_{\tau_R}} = \sum_{t=\tau_R+1}^{T} \left(e^{-r(t-\tau_R)} \sum_{n_t=1}^{N_t} \sum_{i_{n_t}=1}^{I_{n_t}} \left(q_{i_{n_t}} \cdot B_{i_{n_t}} \right) \right) \tag{6.7}$$

where

Table 6.14: Parameter for equation 6.7

Name	Description
T	Investigated time period
N_t	Number of nodes with possible values at time t
I_{n_t}	Number of possible paths leading to node n in time t
$q_{i_{n_t}}$	Probability of path i_{n_t} to node n at t
$B_{i_{n_t}}$	Yearly net benefit at node n at t

Additional expected net benefits for intervention at time t, X_t^+ The additional expected net benefits for an intervention are calculated as follows, and correspond to the general equation 4.10 in section 4.4.1:

$$X_{\tilde{n}}^+(\tau_{DI}) = max\left[0; R_{\tilde{n},\tau_{DI}}^+ - C_{\tau_{DI}}\right] \tag{6.8}$$

where

Table 6.15: Parameter for equation 6.8

Name	Description
$R_{n_{\tau_{DI}}}^+$	Additional expected net benefits at node n at time τ_{DI} after execution of intervention
$C_{\tau_{DI}}$	Costs for the execution of an intervention at τ_{DI}

The yearly benefit, B_t, and the expected net benefits, R_{n_t}, are directly linked to the values of UP1 and UP2, i.e. subject to the same uncertainties as parameters UP1 and UP2.

6.5.1.3 Decision making

In general, the following questions have to be asked when choosing between various decision times :

1. Why should an intervention be executed later?
    (a) Save rent for used space.
    (b) Save additional fixed costs.
    (c) Avoid investment if not necessary.
    (d) Through the discount factor, and thus through the risk in the future, money is worth more today than in the future, thus, a later investment in an intervention is advantageous.
2. Why should an intervention be carried out earlier?
    (a) Save additional costs for treatment of patients over capacity.
    (b) Avoid patient loss due to unattractive premises in the external branch of the clinic of nuclear medicine.

Flexible decision making (ROM AO) and inflexible decision making (TM) For this real world example, only the American Option type of the ROM was applied in addition to the TM, because it represented the actual decision making more precisely than the European option type: Decisions about the execution of the interventions were possible in every year over the investigated time period, and the decisions in each t depended on possible future decisions, i.e. the possibility to postpone the execution to a later t existed in reality. The difference between ROM AO and TM lies in the assumptions about the decision making. The ROM AO assumes that the decision maker will change his opinion about decision making if the situation is beneficial, which is the case in reality, whereas the TM assumes that all decisions about the timing and type of the intervention are made at t=0, i.e. are fixed.

- Flexible decision making (ROM AO): Decision about the execution of an intervention is made at any time in the future for every possible outcome for the parameters UP1 and UP2, while the alternative with the highest expected net benefits for the particular scenario at the time is chosen.
- Inflexible decision making (TM): All possible combinations of type and execution time of all interventions are assumed to be fixed over the considered time span, while the combination with the highest expected net benefits is chosen.

6.5.1.4 Evasive measures in detail

As already mentioned, all patients have to be treated, but evasive measures need to be taken whenever the regular treatment capacity is exceeded. The capacity threshold dM0, valid before the execution of any of the 4 interventions, applies in the case of regular operation of the PET center, i.e. the treatment of patients in the regular morning shift (until 2 pm).

- Evasive measure 1 (EM1) - Patients exceeding dM0 are treated in an afternoon shift. These additional shifts require
  - an additional tracer production for 10,000 CHF/shift[4],
  - more staff expenses if more than 5 additional shifts per year are required (because the existing medical team (currently: 1.5 teams) can only cover so many additional shifts) with team costs of approximately 1.4 Mil. CHF in annual salary costs (see calculation in appendix F.2.2)
  - additional costs for treatment per patient in the afternoon shifts, about 100 CHF/Pat[5]
- Evasive measure 2 (EM 2) - Send patients to the Wagi-Areal for screening for Alzheimer's.
  - Cancer patients can be treated in the E1 without problems in extra shifts at the PET center
  - Alzheimer's patients, however, can only be scanned on a PET/MR, i.e. patients who cannot be treated in the PET center in E1, have to be sent to the external branch of the clinic, where there is already a PET/MR not used to full capacity yet. The assumption is that the unused capacity of this external PET/MR is 2,500 patients/year, i.e. sufficient for maximum excess of treatment capacity in E1.
  - The disadvantage of the treatment in the external branch is that the location is unattractive (according to the head of the clinic). This can be modeled by assuming that a percentage of patients who are sent to the external branch will switch to another, more attractive private clinic, which are available in Zurich. This reduces the attractiveness of sending patients to the external branch, compared to treating them in E1 on the premises of the University hospital.

6.5.1.5 Exact calculation of benefits

Yearly Benefit B_t The calculation of the yearly benefit is given in equation 6.9, the addition in equation 6.10 for all patients that exceed the current capacity threshold:

$$B_t = \left(P_{t,UP1} + P_{t,UP2} \cdot f_{\Delta P_{t,UP2}}\right) \cdot (I_{v,t} - O_{v,t}) - O_{f,t} - \Delta B_t \tag{6.9}$$

where

- the loss of benefits by exceeding the treatment capacity of the PET center, ΔB_t, is defined as

$$\Delta B_t = \Delta PN_t \cdot \Delta TC + \Delta S \cdot C_Z + \Delta Team \cdot o_{f,mtra,year} \tag{6.10}$$

- the number of patients above capacity, ΔPN_t, is defined as

$$\Delta PN_t = max\left(0; \left(P_{t,UP1} + P_{t,UP2} \cdot f_{\Delta P_{t,UP2}}\right) - \Delta M_x\right) \tag{6.11}$$

---

[4] 1 shift = morning shift (regular shift) or afternoon shifts (additional shift), with 250 treatment days per year

[5] The afternoon shifts would have to last until 10 pm to justify the additional tracer production

- the number of additional necessary shifts per year, ΔS, is defined as follows

$$\Delta S = \lceil \Delta PN_t / N_d \rceil \tag{6.12}$$

- $\Delta Team$ defines whether an additional team (additional to the existing 1.5 teams) is necessary

$$\Delta Team = \begin{cases} 1 & \text{if } \Delta S > b_S \\ 0 & \text{if } \Delta S < b_S \end{cases}$$

and other parameters are defined as follows:

Table 6.16: Description and calculation of the input parameters for the calculation of additional costs after transgression of capacity threshold

Name	**Description**	**Unit**	**Value**
$P_{t,UP1}$	Number of patients for existing application for cancer localisation in year t	Pat./year	-
$P_{t,UP2}$	Number of patients for pre-screening for Alzheimer's in year t	Pat./year	-
$I_{v,t}$	Income per treated patient	CHF/Pat.	5'000
$O_{v,t}$	The variable operational costs per treated patient	CHF/Pat.	S. section below
$O_{f,t}$	Fixed operational costs of the PET center per year, independent from the actual patient number	CHF/Year	S. section below
ΔS	S. equation 6.12		
C_Z	Fixed costs for one tracer production in the radiopharmacy	CHF/ shift	10'000
$o_{f,mtra,year}$	Fixed costs for medical team per year	CHF/ Team*Year	1.4 Mil.
ΔTC	Additional variable costs for additional afternoon shifts	CHF/ Pat.*shift	100
$f_{\Delta P_{t,UP2}}$	Reduction factor for patient numbers that have to be send to the Wagi-Areal	-	0.7, before 1, before Installation PET/MR
N_d	Number of patients per shift that lead to the need for additional shifts	Pat./shifts	20
ΔM_x	Capacity threshold of PET center corresponding to executed interventions	Pat./ Year	-
b_S	Capacity buffer for shifts that can be covered with the basic 1.5 teams without the need for an additional team	Shifts/ Year	5

Additional expected net benefits with intervention $X_{n_t}^{+}$ The advantage of an intervention is the reduction of additional fixed costs for patients over capacity ΔPN_t, i.e. increasing the capacity threshold in the existing situation, e.g. initially $M0$, by $\triangle M1$ to capacity threshold after carrying out the action, e.g. $M1$ with intervention 1.

Figure 6.12 shows how the optimization process can occur when the number of patients exceeds the capacity thresholds by ΔPN_t. The decision maker can make the following decisions:

- Do nothing
- Execute intervention I1

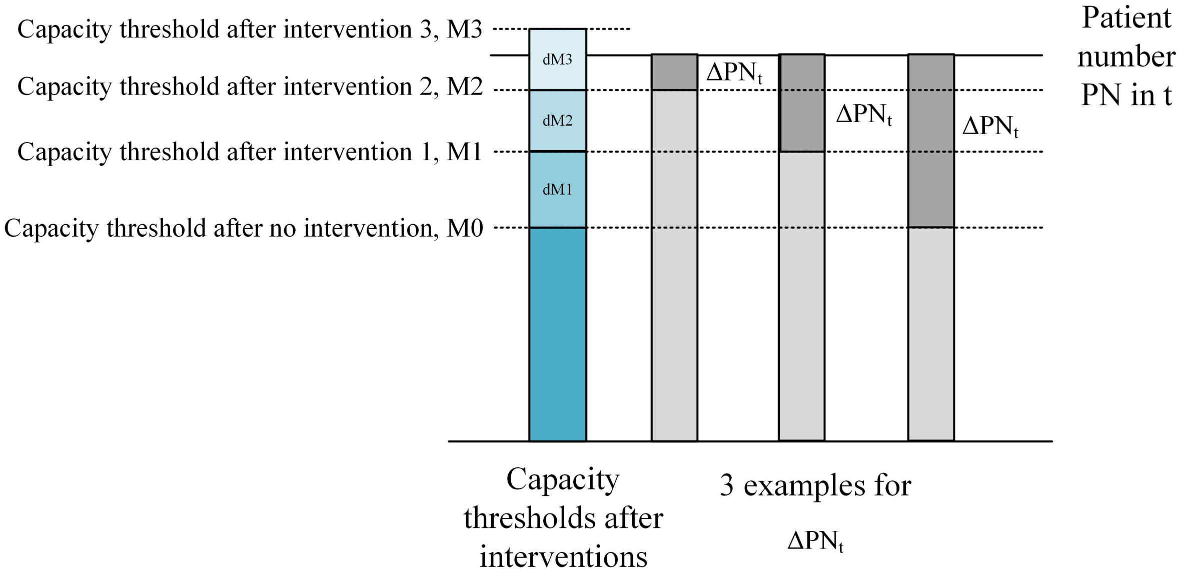


Figure 6.12: Expected net benefits according to capacity thresholds and executed interventions

- Execute interventions I1, I2
- Execute interventions I1, I2 and I3[6]

each with the assumption that the remaining patients who cannot be treated regularly can be treated with evasive measures 1 and/or 2. It is assumed that a decision maker is interested, over the entire investigated time period T, in optimization of the intervention program and the related expected net benefits, i.e. basing his decision not only on the patient numbers in the considered year t, but also on the expected patient numbers in all years until the end of the investigated time period.

The expected benefits after an intervention, $R_{n_\tau,Ix}$, are calculated according to equation 6.4. The additional expected benefits of an intervention, $R^+_{nt,Ix}$, result from the comparison with the expected benefits before and after the intervention, i.e. they are the difference between the expected benefits before and after an intervention.

$$R^+_{nt,Ix} = R_{nt,Ix+1} - R_{nt,Ix} \tag{6.13}$$

The expected net benefits from the execution of an intervention, $X_{t,n,Ix}$,consider the intervention costs, $C_{t,Ix}$,

$$X^+_{nt,Ix} = R^+_{nt,Ix} - C_{t,Ix} \tag{6.14}$$

Variable operational costs O_v per treated patient (used in equation 6.9 for the calculation of the yearly net benefit) The variable costs are the operating costs per patient, and, therefore, always taken into account in connection with the revenue, $I_{t,v}$, per patient.

$$O_v = O_{v,a} + O_{v,m} + O_{v,el} + O_{v,cool} \tag{6.15}$$

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[6] As has been explained before, the interventions are either executed at the same time or sequentially, i.e. I1 at the same time as or before I2, I2 at the same time as or before I3 and so on.

Table 6.17: Calculation of all variable costs (per treated patient)

Name	**Variable operational costs for...**	**Unit**	**Value**
$O_{v,m}$	Other material	CHF/Pat.	1'000
$O_{v,el}$	Electricity	CHF/Pat.	500
$O_{v,cool}$	Cooling	CHF/Pat.	500
$O_{v,a}$	Administration	CHF/Pat.	500

Fixed operational costs Of (used in equation 6.9) The fixed operational costs are defined as follows:

$$O_{f,NoInit} = O_{f,c} + O_{f,a} + O_{f,mtra} + O_{f,rp} + O_{f,el} + O_{f,cool} + O_{f,repl,CT/MR} + O_{f,rent,NoInit} \quad (6.16)$$

and

$$O_{f,FlexInit} = O_{f,c} + O_{f,a} + O_{f,mtra} + O_{f,rp} + O_{f,el} + O_{f,cool} + O_{f,repl,CT} + O_{f,rent,FlexInit} \quad (6.17)$$

where

Table 6.18: Description and calculation of fixed costs

Name	**Description**	**Calculation**	**Value**	**Unit**
$O_{f,c}$	Fixed costs for cleaning	$= +o_{f,c} \cdot m^2 a_{M0}$	400	CHF/year
$O_{f,a}$	Fixed costs for administration of the clinic	$= +O_{f,a}$	150'000	CHF/year
$O_{f,rp}$	Fixed costs for the tracer production in the radiopharmacy	$= +o_{f,rp} \cdot NoS$	2'500'000	CHF/year
$O_{f,mtra}$	Fixed costs of the medical team	$= +o_{f,mtra} \cdot NoTeam$	2'100'000	CHF/year
$O_{f,el}$	Fixed costs for electricity	$= +o_{f,el} \cdot m^2 a_{M0}$	1'600	CHF/year
$O_{f,cool}$	Fixed costs for cooling	$= +o_{f,cool} \cdot m^2 a_{M0}$	6'000	CHF/year
$O_{f,repl,CT}$	Fixed costs for replacement and maintenance existing PET/CTs	$= +NoPET \cdot CPETCTd \cdot (freplMRCT + fmaintMRCT)$	1'000'000	CHF/year
$O_{f,rent,FlexInit}$	Fixed costs for rent of used area, including the expansion area for PET/MR in figure 6.11 (see explanation below)	$= +o_{f,rent,soft,as} \cdot m^2 a_{M0,Flex}$	225'000	CHF/year
$O_{f,rent,NoInit}$	Fixed costs for rent of used area, not including the expansion are for the PET/MR in figure 6.11	$= +o_{f,rent,soft,as} \cdot m^2 a_{M0}$	160'000	CHF/year

with the input defined in table 6.19.

Table 6.19: Parameter for the calculation of the yearly fixed costs

Name	**Description**	**Value**	**Unit**
$o_{f,c}$	Fixed costs for cleaning	1	$CHF/m^2 \cdot year$
$O_{f,a}$	Fixed costs for administration	150'000	$CHF/year$
$CPETCTd$	Retail price for one PET/CTs installed from the beginning	2'500'00	$CHF/year$
$NoPET$	Number of existing PET/CTs in the PET center	2	PET/CT
$f_{replMRCT}$	Yearly ratio of retail price for PET/MR or PET/CT over time span of 10 years, thus considering the replacement every 10 years (s. text below)	0.1	-
$f_{maintMRCT}$	Yearly maintenance costs for PET/MR and PET/CT in percent of retail price	0.1	-
$o_{f,mtra,year}$	Fixed costs for medical team per year	1'400'000	$CHF/Team \cdot year$
$o_{f,mtra,shift}$	Fixed costs for medical team for additional afternoon shift	5'600	$CHF/Team{*}shift$
$o_{f,el}$	Fixed costs for electricity	4	CHF/$m^2 \cdot year$
$o_{f,cool}$	Fixed costs for cooling	15	CHF/$m^2 \cdot year$
$o_{f,heat}$	Fixed costs for heating	15	CHF/$m^2 \cdot year$
$o_{f,rent}$	Fixed costs for rent for “hard” use of any area in the clinic	800	CHF/m^2
$o_{f,rent,soft,as}$	Fixed costs for “soft” use of expansion area for M1	400	CHF/m^2
a_{M0}	Initial area of PET center before any interventions	400	m^2
$a_{M0,flex}$	Area of PET center after execution of all interventions	562	m^2
NoS	Number of regular shifts in the morning per year	250	shifts/year
$NoTeam$	Number of necessary teams for the regular morning shifts	1.5	Teams/year
$NoPET$	Number of existing PET/CTs in the PET center	2	PET/CT

The assumption is that the retail costs for a PET/MR and PET/CT are not payed at once in the year of installation, but are payed off over the operational time period of 10 years, after which it needs to be replaced, thus defining $f_{replMRCT}$. As explained in step 9 in section 6.4.2, the FlexInitial Layout is different to the NoInitial Layout, amongst others, because the expansion area for the additional PET/MR has to be kept available by assigning only “soft” use, i.e. offices for admin or other, to that area that can be relocated easily if needed. Opposed to this “soft”, “hard” use that is not so easily moved if necessary are for example operating areas or other highly specialised facilities. To assign additional costs to the FlexInitial Layout, it was assumed that each clinic has to be pay rent to the University hospital for the used area in the building, and that renting space for “soft” use is less expensive than renting space for “hard” use to account for the special equipment of the area. To keep the expansion area available for expansion, the clinic for nuclear medicine has to pay the difference between the rent for “soft” use and the “hard” use, which would be payed otherwise, to the University hospital (see table 6.19).

Effect of interventions on the capacity thresholds The effect of each intervention on the treatment capacity and on fixed costs of the PET center fare described in table 6.20.

Table 6.20: Description of effects of interventions

Abb.	Description	Current capacity	Increase in patient capacity/ year (PC)	PC	Other impact changes (except additional income I)
I0	No intervention	5'000	+ 0	PC 0	-
I1	Additional PET/MR	7'500	+ 2'500	PC1	$\Delta O_{f,c,M1} + \Delta O_{f,el,M1}$ $+\Delta O_{f,cool,M1} + \Delta O_{f,repl,MR}$ $+ \Delta O_{f,rent,M1}$
I2	Additional application room	8'000	+ 1'500	PC2	$\Delta O_{f,c,M2} + \Delta O_{f,el,M2}$ $+ \Delta O_{f,heat,M2} + \Delta O_{f,rent,M2}$
I3	Additional resting room	8'500	+ 1'500	PC3	$\Delta O_{f,c,M3} + \Delta O_{f,el,M3}$ $+ \Delta O_{f,heat,M3} + \Delta O_{f,rent,M3}$
I4	Additional diagnosis station	9'000	+ 500	PC4	$\Delta O_{f,c,M4} + \Delta O_{f,el,M4}$ $+ \Delta O_{f,cool,M4} + \Delta O_{f,rent,M4}$

Changes in fixed costs for each intervention The fixed operational costs O_f do not change with the number of patients, but after the execution of an intervention, i.e. O_f increases by ΔO_f, if an intervention has been executed by the operational costs for the additional area:

Table 6.21: Calculation of cost changes through the execution of interventions

Int.	Name	Additional fix costs for...	Calculation	Value	Unit
I1	$\Delta O_{f,c,M1}$	Cleaning	$= +o_{f,c} \cdot m^2 a_{M1}$	115	$CHF/year$
I1	$\Delta O_{f,el,M1}$	Electricity	$= +o_{f,el} \cdot m^2 a_{M1}$	465	$CHF/year$
I1	$\Delta O_{f,cool,M1}$	Cooling	$= +o_{f,cool} \cdot m^2 a_{M1}$	1'743	$CHF/year$
I1	$\Delta O_{f,repl,MR}$	Retail (every 10 years) and maintenance of PET/MR	$= C_{PET,MR,d} \cdot (f_{replMRCT} + f_{maintMRCT})$	600'000	$CHF/year$
I1	$\Delta O_{f,rent,M1}$	Rent	$= +o_{f,rent,M1} \cdot m^2 a_{M1}$	46'468	$CHF/year$
I2	$\Delta O_{f,c,M2}$	Cleaning	$= +o_{f,c} \cdot m^2 a_{M2}$	14	$CHF/year$
I2	$\Delta O_{f,el,M2}$	Electricity	$= +o_{f,el} \cdot m^2 a_{M2}$	57	$CHF/year$
I2	$\Delta O_{f,heat,M2}$	Heating	$= +o_{f,heat} \cdot m^2 a_{M2}$	215	$CHF/year$
I2	$\Delta O_{f,rent,M2}$	Rent	$= +o_{f,rent} \cdot m^2 a_{M2}$	5'720	$CHF/year$
I3	$\Delta O_{f,c,M3}$	Cleaning	$= +o_{f,c} \cdot m^2 a_{M3}$	30	$CHF/year$
I3	$\Delta O_{f,el,M3}$	Electricity	$= +o_{f,el} \cdot m^2 a_{M3}$	120	$CHF/year$
I3	$\Delta O_{f,heat,M3}$	Heating	$= +o_{f,heat} \cdot m^2 a_{M3}$	450	$CHF/year$
I3	$\Delta O_{f,rent,M3}$	Rent	$= +o_{f,rent} \cdot m^2 a_{M3}$	12'000	$CHF/year$
I4	$\Delta O_{f,c,M4}$	Cleaning	$= +o_{f,c} \cdot m^2 a_{M4}$	12	$CHF/year$
I4	$\Delta O_{f,el,M4}$	Electricity	$= +o_{f,el} \cdot m^2 a_{M4}$	47	$CHF/year$
I4	$\Delta O_{f,cool,M4}$	Cooling	$= +o_{f,cool} \cdot m^2 a_{M4}$	178	$CHF/year$
I4	$\Delta O_{f,rent,M4}$	Rent	$= +o_{f,rent} \cdot m^2 a_{M4}$	4'736	$CHF/year$

Necessary input parameters for calculations in table 6.21 are shown in tables 6.22 and 6.19.

Table 6.22: Input parameters for table 6.21

Int.	Name	Additional costs for...	Value	Calculation
I1	a_{M1}	Additional area for the PET center after intervention 1	116	$m^2 a_{M1}$
I1	$N_M R$	Number of additional PET/MRs	1	PET/MR
I2	a_{M2}	Additional area for the PET center after intervention 2	14	$m^2 a_{M2}$
I3	a_{M3}	Additional area for the PET center after intervention 3	30	$m^2 a_{M3}$
I4	a_{M4}	Additional area for the PET center after intervention 4	12	$m^2 a_{M4}$

Intervention costs The intervention costs are calculated as follows:

Table 6.23: Description and calculation of intervention costs

Int	Description	Calculation
I1	Additional PET/MR	$C_{PET} = C_{PET,cool} + C_{PET,r} + C_{PET,rad} + C_{PET,el}$
I2	Additional application room	$C_{AR} = C_{AR,r} + C_{AR,el}$
I3	Additional resting room	$C_{RR} = C_{RR,el} + C_{RR,c} + C_{RR,w}$
I4	Additional diagnosis station	$C_{DS} = C_{DS,el} + C_{DS,ds} + C_{DS,r}$

where

Table 6.24: Calculation of intervention costs (used in table 6.23)

Interv.	Name	Description of costs for...	Unit	Value
I1	$C_{PET,MR,d}$	Additional PET/MR	CHF	3'000'000
I1	$C_{PET,cool}$	Increase of cooling and additional rooms	CHF	10'000
I1	$C_{PET,r}$	Additional room	CHF	100'000
I1	$C_{PET,rad}$	Radiation protection in room	CHF	500'000
I1	$C_{PET,el}$	Expansion electrical installations	CHF	10'000
I2	$C_{AR,r}$	Additional space for application room	CHF	500'000
I2	$C_{AR,el}$	Additional electricity for application room	CHF	10'000
I3	$C_{RR,r}$	Additional space for resting room	CHF	500'000
I3	$C_{RR,el}$	Additional electricity for resting room	CHF	10'000
I3	$C_{RR,w}$	Costs per additional separation walls for resting room	CHF/ separation wall	30'000
I3	$addRRw$	Number of additional separation walls for resting rooms	Separation wall	6
I4	$C_{DS,el}$	Additional electricity for diagnosis stations	CHF	10'000
I4	$C_{DS,ds}$	Additional diagnosis station	$CHF/station$	100'000
I4	$C_{DS,r}$	Additional space of one station	$CHF/m^2 \cdot Station$	100'000
I4	$addnDS$	Number of additional diagnosis stations	$Station$	6

6.5.1.6 Initial construction costs for different layouts compared to layout 1

In the calculation of the initial construction costs for the three different layouts, only the differences are considered, with the assumption that all other constructions costs are the same for each layout.

6.5.2 Step 11 - Estimate total additional net benefits of each project at t=0

The evaluation of possible intervention programs for layout 3 was done for this example with the method for the evaluation of intervention programs with consideration of decision flexibility, ROM, and the Traditional Method without the consideration of decision flexibility, TM. For this example, only the ROM AO type of evaluation was used, i.e. under the assumption, that decisions are to be made at multiple specific points in time in the future, or at the last possible time interval and in the intervals before. The reason for this is that this corresponds to the actual decision situation. The ROM EO was not used for this example, because it did not correspond to the decision situation.

For the purpose of comparison, however, the expected net benefits from layout 1 without any interventions and the expected net benefits for layout 2, with all interventions already executed in t=0, were determined.

6.5.2.1 Possible intervention program types

Corresponding to the intervention program types defined in the simple example, three different intervention program types were defined for this real world example, following the actually possible decision situations: The Do nothing type, the single-stage type and the multi-stage type. These types are described in table 6.25.

Table 6.25: Intervention program types

IP type	Name	Short description	Long description	No. of possible IPs
1	Do nothing	Do nothing	No physical interventions are executed over the investigated time period.	1
2	Single-stage	Expand PET center to maximum capacity by PET/MR, application room, resting room and diagnosis stations in year t=0	Only one intervention (additional to the do nothing intervention) is possible, with that intervention being the installation of a new PET/MR with surrounding installations, the addition of a second application room, the expansion of the resting room and the expansion of the room with additional diagnosis stations. This intervention is possible only at t=0.	1
3	Multi-stage	Expand PET center in stages (Purchase PET/MR, expand application room, expand resting room, purchase diagnosis stations)	All IPs that have 4 interventions (additional to the Do nothing intervention), where the first intervention is to purchase a PET/MR, the second is to expand the application room, the third is to expand the resting room and the fourth is to purchase more diagnosis stations (they include the IP with doing nothing at all and the IPs with only executing intervention 1, intervention 1+2, or intervention 1+2+3 and so on). The second intervention is only possible after or at the same time as the first, the third only after or at the same time as the second and so on. All interventions are possible only once over the investigated time period.	148’996

6.5.2.2 Decision making

Once the combined lattice for the number of patients is defined over the investigated time period, the time steps in which decisions are possible, is defined. The time steps for decisions are not necessarily the same as the time steps for the change of the uncertain parameters, but the number of decision time steps must be smaller or the same as the times of change in the combined uncertain parameters. In this example, a decision about the execution of an intervention is possible every year.

Flexible decision making - ROM AO If options are available, the decision can be made at any node of the lattice in the selected t. The decision making at each node of the combined lattice can be described mathematically as follows (the formulation is based on equations 4.10 and 4.11 in section 4.4.1). The maximum expected net benefits, X , from the chosen alternative are defined as follows in a general form:

$$X_{n_t} = max\left(X_{DoNothing,n_t}; X_{I1,n_t}; X_{I2,n_t}; X_{I3,n_t}; X_{I4,n_t}\right) \tag{6.18}$$

Assuming that measures cannot be carried out regardless of one another, but must be executed in stages, i.e. the next intervention can only be executed with or after the execution of the previous intervention, it is necessary to consider the possible optimal decisions in the subsequent time steps, i.e. in $t+1$, when making a decision in t. This leads to the following equations for the four possible interventions, where the option value $X_{n_t,I1}$ represents the final option value at this node since I1 is the first possible intervention:

$$X_{n_t,I4} = max\left(\sum_{i=0}^{I_{n_{t+1}},} \left(p_{n_{t+1},i} \cdot X_{n_{t+1},I4,i}\right); R^{+}_{nt,I4} - C_{t,I4}\right) \tag{6.19}$$

$$X_{n_t,I3} = max\left(\sum_{i=0}^{I_{n_{t+1}},} \left(p_{n_{t+1},i} \cdot X_{n_{t+1},I3,i}\right); R^{+}_{nt,I3} - C_{t,I3} + X_{n_t,I4}\right) \tag{6.20}$$

$$X_{n_t,I2} = max\left(\sum_{i=0}^{I_{n_{t+1}},} \left(p_{n_{t+1},i} \cdot X_{n_{t+1},I2,i}\right); R^{+}_{nt,I2} - C_{t,I2} + X_{n_t,I3}\right) \tag{6.21}$$

$$X_{n_t,I1} = max\left(\sum_{i=0}^{I_{n_{t+1}},} \left(p_{n_{t+1},i} \cdot X_{n_{t+1},I1,i}\right); R^{+}_{nt,I1} - C_{t,I1} + X_{n_t,I2}\right) \tag{6.22}$$

where

Table 6.26: Components for equations 6.19 to 6.22

Name	**Description**
C_{Ix}	Intervention costs for interventions I1 to I4
$X_{n_t,Ix}$	Expected net benefits of optimal decision about execution of interventions I1 to I4
$I_{n_{t+1}},$	No. of nodes "following" node n at time $t+1$
$p_{n_{t+1},i}$	Probability of one node "following" node n at time $t+1$
$X_{n_{t+1},Ix,i}$	Expected net benefits of optimal decision about execution of interventions at nodes following node n in $t+1$ for NOT EXECUTING intervention Ix at node n in t
$R^{+}_{n_t,Ix}$	Additional expected net benefits from the execution of interventions I1 to I4

As an example, equation 6.20 describes the decision that is possible when intervention 3 has not yet been executed, i.e. execute intervention 3 or do nothing. If, on the one hand, the decision is to not execute intervention 3 at t at node n, the expected net benefits of not this non-execution is described by $\sum_{i=0}^{I_{n_{t+1}}} \left(p_{n_{t+1},i} \cdot X_{n_{t+1},I3,i}\right)$, i.e. the result of the optimal decision in all nodes n_{t+1} in $t+1$. On the other hand, the additional expected net benefits from intervention 3, $R^{+}_{nt,I3}$, can be gained by execution of the intervention. This will bring the additional option value for the succeeding intervention 4, which now can or cannot be executed at t or at a later time after the execution of intervention 3. This decision is made according to equation 6.19.

The same approach can be applied for interventions 2 and 1 in formula 6.22 and 6.21. For intervention 4, no additional option value of a subsequent intervention is considered in equation 6.19. Table 6.27 shows the exact steps necessary for the decision at each node n in each t.

Table 6.27: Decision making at each node n in each t with the ROM AO method, from τ to $t = 0$

Step	**Description**
1	Calculate B_t at n before and after each intervention $I1$ to $I4$
2	Calculate $R_{n_t,I1}$ to $R_{n_t,I4}$
3	Calculate $R^+_{n_t,I1}$ to $R^+_{n_t,I4}$
4	Calculate $X_{n_t,I4}$
5	Calculate $X_{n_t,I3}$ under consideration of $X_{n_t,I4}$
6	Calculate $X_{n_t,I2}$ under consideration of $X_{n_t,I3}$
7	Calculate $X_{n_t,I1}$ under consideration of $X_{n_t,I2}$

Inflexible decision making - Traditional method With the TM, it is assumed that the decision about the time of the execution of any intervention is taken in $t = 0$, without the possibility to postpone the decision at a later point in time when the uncertainty of parameters UP1 and UP2 is resolved. The net benefit, B_t, at each node is in the TM calculated in the same way as for the ROM AO. The expected benefits from the execution of an intervention, however, are calculated differently, because of the assumption that the decision of execution is made at t=0 and not at a particular node in the lattice, i.e. when the uncertainty about the actual outcome of UP1 and UP2 is resolved. Thus, with the TM, the decision maker has to consider the probability of all nodes n in each t, $q_{i_{n_t}}$, relative to $t = 0$, which applies to the possible expected benefits, $R_{n_\tau,I}$, from the execution of an intervention for all possible nodes n in time t (compare equations 4.6 ff.).

$$R_{n_{\tau_R}} = \sum_{t=\tau_R+1}^{T} \left(e^{-r(t-\tau_R)} \sum_{n_t=1}^{N_t} \sum_{i_{n_t}=1}^{I_{n_t}} \left(q_{i_{n_t}} \cdot B_{i_{n_t}} \right) \right) \tag{6.23}$$

while the additional expected benefits are

$$R^+_{n_{\tau_R},Ix} = R^+_{n_{\tau_R+1}+1,Ix} - R^+_{n_{\tau_R},Ix} \tag{6.24}$$

The expected net benefits from the execution of an intervention, X^+_{nt}, consider the intervention costs, C_t, according to equation 4.8:

$$X(\tau_{TM}) = R_0 + e^{-r\tau_{TM}} \left(\sum_{n_{\tau_{TM}}=1}^{N_{\tau_{TM}}} R^+_{n_{\tau_{TM}},Ix} - C_{\tau_{TM},Ix} \right) \tag{6.25}$$

The expected net benefits of the individual intervention can initially be calculated independently of each other. Then, all possible combinations K, under the consideration of the sequential execution, of all interventions with the sum of all expected net benefits $X^+_{t=0,I}$, from all interventions, need to be determined. The combination with the maximum sum of expected net benefits is chosen as the optimal intervention program (compare table 6.28).

Table 6.28: Decision making at t=0 with TM

Step	**Description**
1	Calculate B_t at n before and after each intervention
2	Determine probabilities of all nodes in t, $p_{i_{n_t}}$, for each t
3	Calculate $R_{t,I1}$ to $R_{t,I4}$ for each year t considering $p_{i_{n_t}}$
4	Calculate $R^+_{t,I1}$ to $R^+_{t,I4}$ for each year t
5	Calculate $R^+_{t,I1} - C_{t,I1}$ to $R^+_{t,I4} - C_{t,I4}$ for each year t
6	Determine all possible combinations, K, of interventions 1 to 4
7	Determine $\Sigma X^+_K = X^+_{t,I1,K} + X^+_{t,I2,K} + X^+_{t,I3,K} + X^+_{t,I4,K}$
8	Determine combination K with highest ΣX^+_K

6.6 Results and discussion of real world example

In this section, the results with the presented evaluation model with the given input, described in section 6.5, are presented in subsection 6.6.1. In subsection 6.6.2, the input is varied for the sensitivity analysis of the results. Then follow the discussion of the real world example and its results with the overall conclusions.

6.6.1 Results of evaluation for given input

The results are divided in three parts: (1) The expected net benefits for the three possible layouts, with the focus on the flexible layout that allows for a staged execution of the four relevant interventions, their differences and a short summary of the execution years and the corresponding probabilities for execution, (2) the possible execution times of the four interventions with the ROM AO method, i.e. the description of a flexible intervention program, (3) an excerpt from a table depicting the possible execution nodes of intervention 1 with the corresponding conditional probabilities of execution of the subsequent intervention 2.

6.6.1.1 Expected net benefits for different designs, intervention program types and evaluation methods

Table 6.29 shows the expected net benefits, discounted back to today, for the three different layouts (see chapter 6.4), the years of execution and their corresponding probabilities of execution.

Table 6.29: Results table for all layouts

Layout	IP type	Eval. meth.	Inter-vention	τ	Years of ex.	q^{ex} in %	ENB	ΔENB IP1-NoInitial	ΔENB IP2-AllInitial	ΔENB IP3-FlexInitial-TM
NoInitial	IP1	All	No Int.	-	No Exec.	0	139.36	-	-	-
AllInitial	IP2	All	All Int.	-	0	100	163.46	24.1	-	-
FlexInitial	IP3	All	No Int.	-	No Exec.	0	137.85	-1.51	-	-
FlexInitial	IP3	TM	1	τ_{TM}	3	100	166.33	26.97	2.87	-
FlexInitial	IP3	TM	2	τ_{TM}	4	100	-	-	-	-
FlexInitial	IP3	TM	3	τ_{TM}	No Exec.	0	-	-	-	-
FlexInitial	IP3	TM	4	τ_{TM}	No Exec.	0	-	-	-	-
FlexInitial	IP3	AO	1	τ_{AO}	1	99.5	167.18	27.82	3.72	0.85
FlexInitial	IP3	AO	2	τ_{AO}	3	53.9	-	-	-	-
FlexInitial	IP3	AO	3	τ_{AO}	4	15.7	-	-	-	-
FlexInitial	IP3	AO	4	τ_{AO}	6	1.6	-	-	-	-

For layout 1 - NoInitial, the building manager cannot execute any of the four interventions for capacity expansion (corresponding to intervention program IP1), which still yields an expected net benefit at t=0 over the investigated time period of about **139.36** Mil. CHF.

For layout 2 - AllIntial, the building manager executes all four interventions at t=0 (corresponding to intervention program IP2), which yields and expected net benefit of about **163.46** Mil. CHF.

For layout 3 - FlexIntitial the building manager can execute the four interventions for capacity expansion in stages. She can choose between intervention program type IP1 (Do nothing) or intervention program type IP3 (execute four interventions in stages). The building manager can also evaluate the IP3 type of intervention programs either with the Traditional Method or the ROM AO.

If the building manager chooses the IP0 intervention program type for layout 3, the expected net benefits are **137.85** Mil. CHF.

If she chooses the IP3 type and evaluates possible intervention programs with the TM, the optimal IP would recommend to execute intervention 1 in year 3, intervention 2 in year 4 and to not execute interventions 3 and 4 at all. The probabilities of execution of the four interventions are considered as 100%, or 0% in case of non-execution, with the TM evaluation method, i.e. yield a fixed intervention program[7]. This IP yields expected net benefits of **166.33** Mil. CHF.

If the building manager chooses the IP3 type and evaluates possible intervention programs with the ROM AO, there are different recommendations for the execution of the different stages, depending on the future development of the uncertain numbers of patients for the clinic.

- For intervention 1, the first year of recommended execution in year 1,
- For intervention 2, the first year of recommended execution is in year 3,
- For intervention 3, the first year of recommended execution is in year 4, and
- For intervention 4, the recommended year is year 6.

As the execution of any of the four interventions depends on the future values for the patient numbers, the overall probability of execution of intervention for the American type of the Real Options Method, q^{ex}_{AO}, (opposed to no execution) can lie between 0 and 100 %. Intervention 1 will be executed over the investigated time period with a probability of 99.5 %, intervention 2 with a probability of 53.9 %, intervention 3 with a probability of 15.7 % and intervention 4 with a probability of 1.6 %. These probabilities consider all possible execution points over the investigated time period and the probabilities of preceding interventions (e.g. intervention 1 has to be executed before intervention 2); that means they are the joint probabilities explained in section 4.6.4. The expected net benefits yielding from this flexible intervention program is **167.18** Mil. CHF.

There are differences between the expected net benefits from each layout but also between the different evaluation methods. These differences are also summarised in Table 6.29.

Compared to the expected net benefits from choosing layout 1 - NoInit, and executing no intervention, layout 2 - AllInitial, with IP2, yields additional expected net benefits, $\triangle ENBIP1$ *NoInitial*, of 24.1 Mil. CHF. Layout 3 - FlexInitial yields with IP1, i.e. no execution of any intervention, expected net benefits of 1.51 Mil. CHF less than layout 1. However, if the IP3 type is possible, layout 3 yields additional net benefits of 27.0 Mil. CHF with the TM and even additional 27.8 Mil. CHF with the ROM AO. These results apply, with a difference of 1.51 Mil. CHF to the comparison with the IP1 for layout 3.

Compared to the expected net benefits from choosing layout 2 - AllInitial, with IP2, layout 3 - FlexInitial yields with IP3, i.e. the possible execution of any intervention, additional net benefits, $\triangle ENB\ IP2$ *AllInitial*, of 2.87 Mil. CHF with the TM, with the ROM AO even 3.7 Mil. CHF.

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[7] $\tau_{TM}$and τ_{AO} are explained in detail in chapter 5.3.1.

Finally, compared to the expected net benefits from Layout 3 - NoInitial, with IP3 and the TM, the ROM AO yields additional net benefits, $\triangle ENB\, IP3\, FlexInitial - TM$, of 0.85 Mil. CHF.

6.6.1.2 The probability that it will be beneficial to execute an intervention at each time

Tables 6.30 and 6.31 show the likely years of execution for each intervention, τ_{AO}, with their corresponding probabilities, $q^{ex}_{\tau_{AO}}$, when flexible decision making is considered with ROM AO. These execution times correspond to the results for the expected net benefits for layout 3 and an evaluation with the ROM AO in table 6.29 in the previous section.

Table 6.30: Joint probability of execution of all stages in years n - Years 0 to 20

Layout	IP type	Eval. meth.	Interv.	q^{ex}_{AO}	τ_{AO}	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
FlexInit	Multi-stage	AO	1	99.5	$q_{\tau_{AO}}$		37.5		50	0.6	8.3	0.2	2		0.7	0		0	0		0		0		0	
FlexInit	Multi-stage	AO	2	53.9	$q_{\tau_{AO}}$				1.4	6.6	0.3	4.9	0.1	3.9	0	3.4		3		2.8		2.6		2.5		2.4
FlexInit	Multi-stage	AO	3	15.7	$q_{\tau_{AO}}$					0.1	1.4	0	1.2	0	1.1	0	1		0.9		0.8		0.8		0.8	
FlexInit	Multi-stage	AO	4	1.6	$q_{\tau_{AO}}$							0.1		0.1		0.1		0.1		0.1		0.1		0.1		0.1

Table 6.31: Joint probability of execution of all stages in years n - Years 21 to 40

Layout	IP type	Eval. meth.	Interv.	q^{ex}_{AO}	τ_{AO}	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
FlexInit	Multi-stage	AO	1	99.5	$q_{\tau_{AO}}$	0		0		0		0		0		0	0		0		0		0		0
FlexInit	Multi-stage	AO	2	53.9	$q_{\tau_{AO}}$		2.3		2.2		2.2		2.1		2		2		1.8		1.8		1.7		1.7
FlexInit	Multi-stage	AO	3	15.7	$q_{\tau_{AO}}$	0.8		0.8		0.8		0.8		0.8		0.7		0.8		0.8		0.8		0.8	
FlexInit	Multi-stage	AO	4	1.6	$q_{\tau_{AO}}$		0.1		0.1		0.1		0.1		0.1		0.1		0.1		0.1		0.1		0.1

Tables 6.30 and 6.31 and figure 6.13 show that intervention 1 can possibly be executed in years 1, 3, 4, 5, 6, 7 and then almost every second year until year 40. The probabilities of execution however decrease with proceeding time; the probability in year 1 is 37.5%, in year 3 50%, in year 4 0.6%, in year 5 8.3%, and only 0.2, 2 and 0.7% for years 6, 7 and 9. The probabilities of execution after year 9 for stage 1 approach 0.

Intervention 2 can possibly be executed in years 3, 4, 5, 6, 7, 8, 9, 10 and then every second year until year 40. The probabilities of execution however decrease with proceeding time; the probability in year 3 is 1.4%, in year 4 6.6%, in year 5 0.3%, in year 6 4.9%,in year 7 0.1%, in year 8 3.8%, in year 9 almost 0%, in year 10 3.4%. The probabilities of execution after year 12 decrease and approach 1.7%.

Intervention 3 can possibly be executed in years 4, 5, 6, 7, 8, 9, 10, 11 and then every second year until year 39. The probabilities of execution however decrease with proceeding time, starting in years 3, 5, 6, 7, 8, 9, 10 and 11 with probabilities of 0.1%, 1,4%, 0%, 1.1%, 0%, 1%, 0.9% and then, decreasingly, approach 0.8% in year 39.

Intervention 4 can possibly be executed in years 6, 8, 10 and then every second year until year 40. The probabilities of execution are 0.1% for each possible execution year, i.e. very low.

Figure 6.13 shows the probabilities of execution in tables 6.30 and 6.31 in a bar plot, with the intervention probability of intervention 1 on the left in blue and the probability of intervention 4 in orange on the right. This figure shows the flexible intervention program with the probabilities of execution in year t.

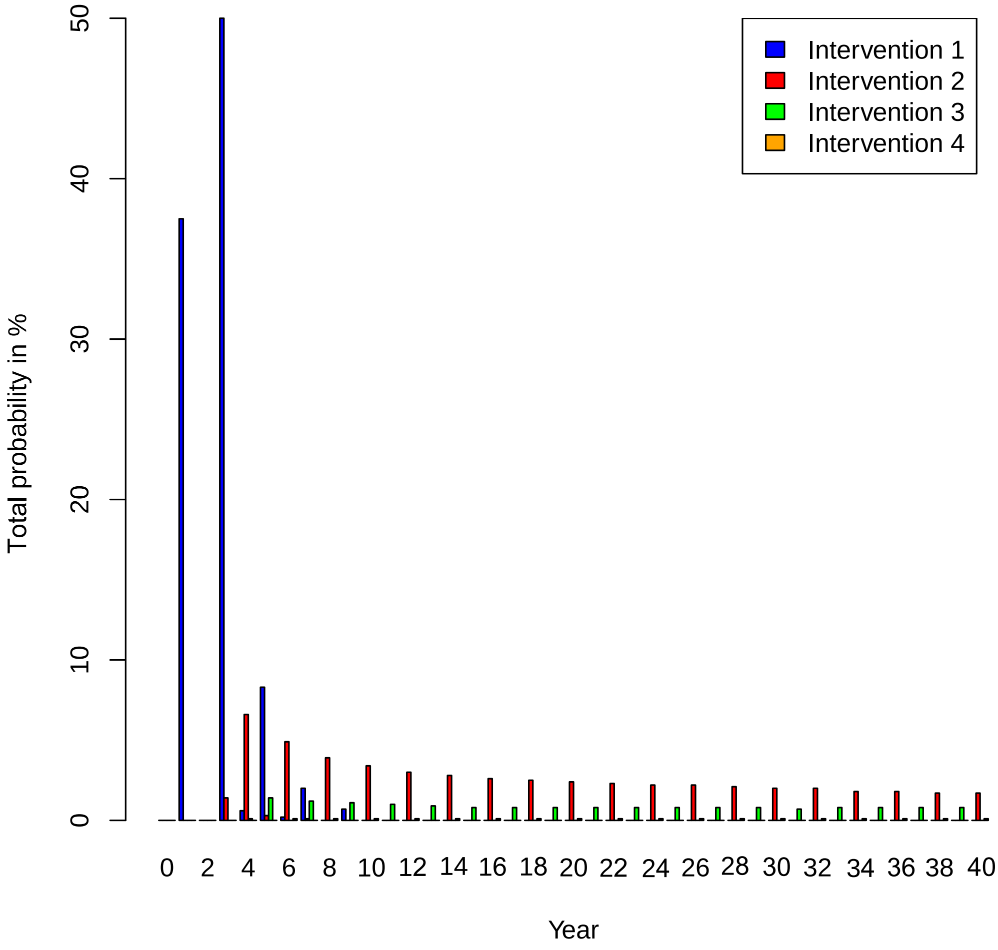

Figure 6.13: Flexible intervention program - Execution times and corresponding total probabilities for interventions 1 - 4

As a support for the decision maker, another output of the ROM AO evaluation method is the prediction of evaluation results at future points in time; it is possible to determine the *conditional probabilities of execution of each intervention following another*, e.g. intervention 2 following intervention 1 (compare section 4.6.4). For example, assuming that intervention 1 is executed at a given time, the time intervals where there is a non-zero probability of executing intervention 2 are given in table 6.32 and table 6.33. These probabilities depend on the time when intervention 1 has been executed and what the actual number of patients to be treated, i.e. the values of the uncertain parameters, is at that time.

If, for example, intervention 1 has been executed in year 1 when there are 5'194 patients per year (5'194 for UP1 and 0 for UP2), the time intervals with non-zero probabilities for replacing the windows are years 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, and then every second year until year 40, with probabilities of 4, 11, 0, 6, 0, 4, 0, 3, 3, 3, then 2% every second year, and 1% in year 40, respectively (table 6.32).

If, for example, intervention 1 has been executed in year 3 when there are 5'482 patients per year (3'482 for UP1 and 2'000 for UP2), the time intervals with non-zero probabilities for replacing the windows are years 8, 10, 12 and then every second year until year 36, with probabilities of 2% in year 8 and 3% in years 10 to 28, and then 2% every second year until year 36, respectively (table 6.33).

Table 6.32: Probability of execution of stage 2 relative to execution of stage 1 - Part 1

Year of ex.	$q^{ex}_{t_A O}(I1)$ in %	UP1	UP2	Year of ex.	$q^{c}(I2 \mid I1)$ in %	UP1	UP2
1	37	5194	0	3	4	6344	2000
1	37	5194	0	4	11	5741	2000
1	37	5194	0	5	0	6344	2000
1	37	5194	0	6	6	5741	2000
1	37	5194	0	7	0	6344	2000
1	37	5194	0	8	4	5741	2000
1	37	5194	0	9	0	6344	2000
1	37	5194	0	10	3	5741	2000
1	37	5194	0	12	3	5741	2000
1	37	5194	0	14	3	5741	2000
1	37	5194	0	16	2	5741	2000
1	37	5194	0	18	2	5741	2000
1	37	5194	0	20	2	5741	2000
1	37	5194	0	22	2	5741	2000
1	37	5194	0	24	2	5741	2000
1	37	5194	0	26	2	5741	2000
1	37	5194	0	28	2	5741	2000
1	37	5194	0	30	2	5741	2000
1	37	5194	0	32	2	5741	2000
1	37	5194	0	34	2	5741	2000
1	37	5194	0	36	2	5741	2000
1	37	5194	0	38	2	5741	2000
1	37	5194	0	40	1	5741	2000

6.6.1.3 Discussion of the results

The results in section 6.6.1.1 show that in this example the execution of the suggested four interventions is beneficial; even if there is the possibility to only execute all intervention at t=0 (for layout 2 - AllInit and IP2), additional net benefits of more than 27 Mil. CHF can be expected compared to IP1 intervention program type of doing nothing. This corresponds to an increase of the expected net benefits of more than 20 %.

The IP3 intervention program types for layout 3 allow for more decision flexibility by providing the possibility of a sequential, staged execution of the four interventions. Even if the assumption is that the building manager can only choose a fixed intervention program and evaluate it with the TM, the additional expected net benefits compared to IP2 for the layout 2 - AllInit of 2.9 Mil. CHF amount to an increase of 1.7 % of the expected net benefits. When offered this staged execution with the TM evaluation, however, the building manager would not execute intervention 3 and 4, an advantage compared to IP2, as the benefits of these interventions are not high enough to justify their intervention costs.

The increase in decision flexibility with the evaluation of flexible intervention programs of the IP3 type with the ROM AO leads to an improvement in the expected net benefits of 0.85 Mil. CHF, which amounts to 0.5% of improvement compared to a inflexible intervention program. With the flexible intervention program, however, there is the possibility of execution of interventions 3 and 4, with total probabilities of 15.7 and 1.6% respectively. The difference in the expected net benefits results from the fact that with the ROM AO, the execution of interventions is considered only if the values of UP1 and UP2 are beneficial. Both TM and ROM AO already consider that the four interventions can be executed in stages, which in itself is already a kind of flexibility, which can be evaluated without the consideration of flexibility in decision making, i.e. with the TM.

Table 6.33: Probability of execution of stage 2 relative to execution of stage 1 - Part 2

Year of ex.	$q^{ex}_{t_A O}(I1)$ in %	UP1	UP2	Year of ex.	$q^{c}(I2\|I1)$ in %	UP1	UP2
3	11	3482	2000	8	2	5741	2000
3	11	3482	2000	10	3	5741	2000
3	11	3482	2000	12	3	5741	2000
3	11	3482	2000	14	3	5741	2000
3	11	3482	2000	16	3	5741	2000
3	11	3482	2000	18	3	5741	2000
3	11	3482	2000	20	3	5741	2000
3	11	3482	2000	22	3	5741	2000
3	11	3482	2000	24	3	5741	2000
3	11	3482	2000	26	3	5741	2000
3	11	3482	2000	28	3	5741	2000
3	11	3482	2000	30	2	5741	2000
3	11	3482	2000	32	2	5741	2000
3	11	3482	2000	34	2	5741	2000
3	11	3482	2000	36	2	5741	2000

The probabilities of execution of intervention 3 and 4 are low, and thus reflect the general recommendation from the results of the TM, i.e. to probably not execute interventions 3 and 4 at all. There are, however, some scenarios with very high values for UP1 and a value of 2000 for UP2 when the execution of interventions 3 and 4 might be beneficial, a situation that the TM cannot consider, as with the TM, only average outcomes of the uncertain parameters are considered for the decision making. The conditional probabilities from table 6.32 and table 6.33 provide the decision maker with a support tool to reconsider the question about the execution at a later point in time, when the actual number of patients is known and an execution of these two interventions might be more favourable.

The results show the expected net benefits of 3 different types of intervention programs: The Do nothing intervention program (IP1) without any execution, applicable on layout 1 and 3, the single-stage intervention program (IP2), applicable to layout 2, and the multi-stage intervention program (IP3), applicable on layout 3 and evaluated with the Traditional Method and the Real Options Method of the ROM AO type. The results show that an execution of any intervention (i.e. IP2 and IP3) lead to ENBs of more than 20% higher than for the IP1 type with no execution of interventions. The ENBs for the IP3 type for layout 3, i.e. the multi-stage execution of the interventions, are higher than the ENBs from the IP2 type for layout 2 with a single-stage execution of all interventions in year t=0, by 1,7% for the optimal IP determined with the TM, and 2.3% for the preferred IP determined with the ROM AO. The ENBs of the IP3 type intervention program determined with the ROM AO are by 0.5% higher than the ENBs of the optimal IP determined with the TM.

The comparison of the optimal IPs shows that the IP determined with the TM recommends to execute intervention 1 in year 3, intervention 2 in year 4 and intervention 3 and 4 not at all. The IP determined with the ROM AO, however, recommends an earlier possible execution of intervention 1 in year 1, but only if conditions are favourable, i.e. patient numbers are high enough, and to wait otherwise. The overall probability of executing intervention 1 over the investigated time period is almost 100%, because the overall probability of UP2 to rise to 2000 patients per year is high in the first 8 years of the investigated time period, which in turn is the main driver for the execution of the intervention. The earliest possible year of execution for intervention 2 is in year 3, with an overall probability of execution of 53.9%. The ROM AO recommends, other than the IP determined with the TM, to execute interventions 3 and 4 if the conditions are favourable, earliest in years 4 and 6, and with overall probabilities of 15.7 and 1.6% respectively.

6.6.2 Sensitivity analysis

The example has multiple input parameters, with values often based on assumptions. These assumptions can be confirmed and in some cases improved with additional effort. A sensitivity analysis can help reducing this additional effort by showing which assumptions have a significant impact on the results and the validity of the general conclusions of the real world example. It is especially interesting to see if a variation of the input parameters leads to significant changes in

1. the value of a flexible evaluation, i.e. with the ROM AO, in comparison to the evaluation with the TM ($\triangle ENB - IP3 - FlexInitialTM$ in table 6.29), as the difference in the expected net benefits is small with the given input (0.5%),
2. the value of a staged execution of the interventions in comparison to a single-stage execution ($\triangle ENB - IP2 - AllInitial$ in table 6.29), as the difference in the expected net benefits is small with the given input (1.7%), and
3. the probability of execution of intervention 4 (table 6.29), as this probability is small (2% in total).

Table 6.34 shows the input parameters based on assumptions together with their possible ranges, according to literature sources or expert opinion. After all these input parameters were varied, not all variations had significant influence on the results of the evaluation mentioned above.

Table 6.34: Variation of Input parameters in sensitivity analysis

No.	**Parameter**	**Symb.**	**Initial value/ Calculation**	**Range**	**Unit**	**Discussed in section...**
1	Costs for additional PET/MR	$CPETMRd$	3	2.5 to 7	$Mil.CHF$	6.6.2
2	No. of additional patients UP2	$addUP2$	2000	1’000 to 5’000	$Patient/year$	6.6.2
3	Initial probability of introduction of Alzheimer screening	$pUP2$	0.8	0.2 to 0.8	-	6.6.2
4	Discount rate	r	0.06	0 to 0.16	-	6.6.2
5	Increase in variable costs for treatment above capacity on PET/CT	$delta_{TC}$	100	100 to 200	$CHF/patient$	F.3
6	Difference in capacity thresholds	dMx	5000, 6500, 7000, 7500, 8000	Increase difference by 100 to 300	$Patients/year$	F.3
7	Reduction in ratio of lost patients when send to external PET-center	$fdeltaUP2$	0.7	0.5 to 0.9	-	F.3
8	Variable yearly income (with operational costs staying the same)	Iv	2500	2’000 to 5’000 in 500 steps	$CHF/year * patient$	F.3
9	Fixed costs per Team per year	$ofmtrayear$	1.4	0.7 to 1.5	$Mil.CHF/year* team$	F.3
10	Difference in rent for highly specialised and normal area use	$ofrentDiff$	400	200 to 600	$CHF/year * m^2$	F.3

A selection of relevant changes in the results with the corresponding changes in input parameters will be presented, more precisely parameters 1, 2, 3 and 4. All other variation of parameters did not result in significant changes of the results, i.e. either in no change or changes below 1% of the results with the initial input parameters (see appendix F.3).

6.6.2.1 Costs of a new PET/MR - CPETMRd

The purchase costs for a new PET/MR were varied between a value of 2.5 Mil. and 7 Mil. CHF, as this is the current price range for PET/MRs.

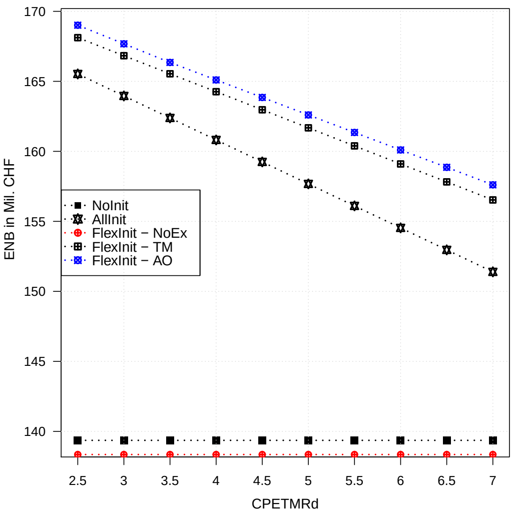

Figure 6.14: SA: Cost PET/MR - All ENBs

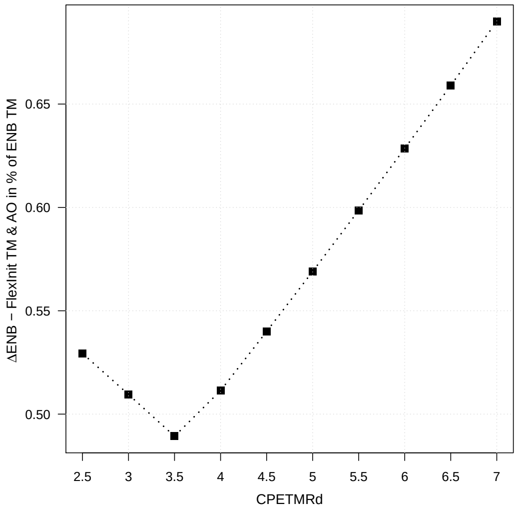

Figure 6.15: SA: Cost PET/MR - ΔENB TM - ROM AO

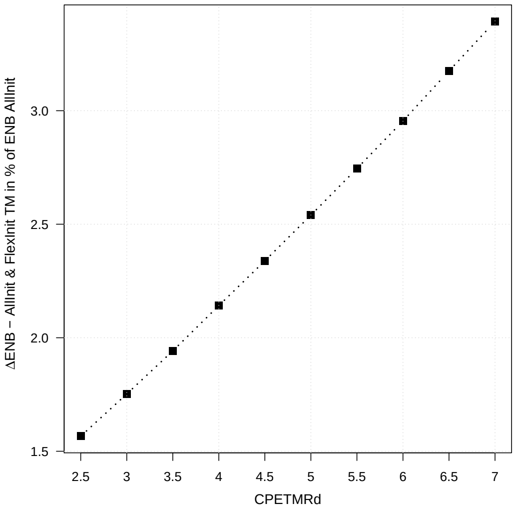

Figure 6.16: SA: Cost PET/MR - ΔENB FlexInit - AllInit

Figure 6.14 shows the change in expected net benefits for all IP types and all layouts. The ENBs for the IP1 type (Do nothing) do not change, because they do not consider any intervention costs and, thus, not the costs for a new PET/MR. The ENBs of the IP2 and IP3 type for the layouts 2 and 3 decrease with increasing purchase costs of the PET/MR, because the intervention costs for intervention 1 increase, an intervention which has a probability of execution of almost 100%.

Table 6.35: Sensitivity Analysis - Change in CPETMRd

CPETMRd in Mil. CHF	**2.50**	**3.00**	**3.50**	**4.00**	**4.50**	**5.00**	**6.00**	**7.00**
NoInitial - ENB in Mil. CHF	139.36	139.36	139.36	139.36	139.36	139.36	139.36	139.36
AllInitial - ENB in Mil. CHF	165.53	163.96	162.39	160.82	159.25	157.68	154.53	151.39
FlexInitial - Do nothing - ENB in Mil. CHF	138.35	138.35	138.35	138.35	138.35	138.35	138.35	138.35
FlexInitial - TM - ENB in Mil. CHF	168.12	166.83	165.54	164.26	162.97	161.68	159.10	156.53
τ_{TM} interv. 1 in years	3	3	3	3	3	3	3	3
τ_{TM} interv. 2 in years	4	4	4	4	4	4	4	4
τ_{TM} interv. 3 in years	No Ex.	No Ex.	No Ex.	No Ex.	No Ex.	No Ex.	No Ex.	No Ex.
τ_{TM} interv. 4 in years	No Ex.	No Ex.	No Ex.	No Ex.	No Ex.	No Ex.	No Ex.	No Ex.
FlexInitial - ROM AO - ENB in Mil. CHF	169.01	167.68	166.35	165.10	163.85	162.60	160.10	157.61
τ_{AO} interv. 1 in years	2	2	2	3	3	3	3	3
$q^{ex}_{\tau_{AO}}$in year t=1	0.37	0.37	0.37	0.44	0.44	0.44	0.44	0.44
q^{ex}_{AO}	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99

Figure 6.15 shows the change in difference between the expected net benefits from the TM and the ROM AO for layout 3, $\triangle FlexInit - TM - AO$: The difference decreases minimally first and then increases again This first decrease can be explained by the fact that in the ENBs it is considered that, up to purchase costs of 3.5 Mil. CHF, the TM recommends to execute intervention 1, i.e. install a PET/MR, in year 3, but the ROM AO to execute already in year 2 (see table 6.35). Thus, the purchase costs for the PET/MR are discounted more and have a lower probability of execution with the TM than with the ROM AO. From purchase costs of 4 Mil. CHF, the ROM AO also recommends to wait with the execution to year 3, so that this difference to the TM disappears. This decrease in difference, however, is minimal (0.04%) and can most likely be attributed to deviations due to the discrete properties of the multinomial lattice and are of little significance. The increase of the difference for purchase costs of 4 Mil. CHF and more on the other hand, can be expected to increase for increasing purchase costs, and thus intervention costs, because the ROM AO allows for the postponement of the execution until the values of the uncertain key parameters make the execution beneficial.

Figure 6.16 shows that the difference between the IP2 type of intervention program for layout 2 and the IP3 type of intervention program with the TM,$\triangle AllInit - FlexInit$: increases with increasing purchase price because the intervention costs can be moved to the future with the FlexInitial Layout, i.e. are discounted more, i.e. the possibility to execute later is beneficial for the ENB. More importantly, the intervention is only executed if beneficial, thus avoiding unnecessary costs.

The sensitivity analysis of the retail price for the PET/MR shows that the general results of the evaluation hold, i.e. that the ENB for a IP from the ROM AO is higher than the ENB for a IP from the TM or even the IP2 type of layout 2 with an execution of all interventions in year 0. However, there is no significant increase of $\triangle FlexInit - TM - AO$ or $\triangle AllInit - FlexInit$ with 0.06 and 1% of increase respectively for any change in the retail price for the PET/MR.

6.6.2.2 Number of additional patients for new application - addUP2

The number of additional patients after the acceptance of the Alzheimer's vaccination by the Swiss health care system is a strong assumption and the model is simplified. This additional number, $addUP2$, has been varied from -50 to +250%, i.e. from 1'000 to 5'000 additional patients.

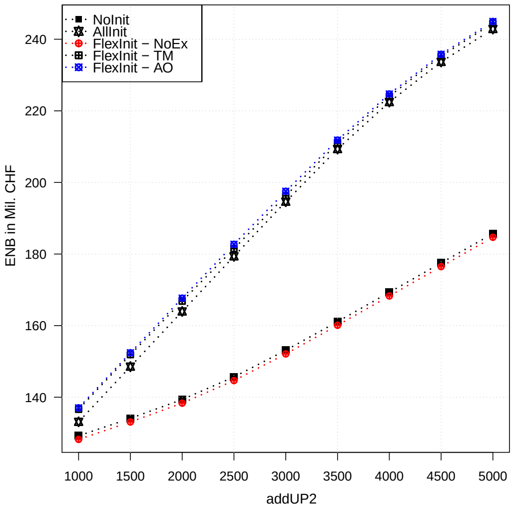

Figure 6.17: SA: No. additional patients addUP2 - All ENBs

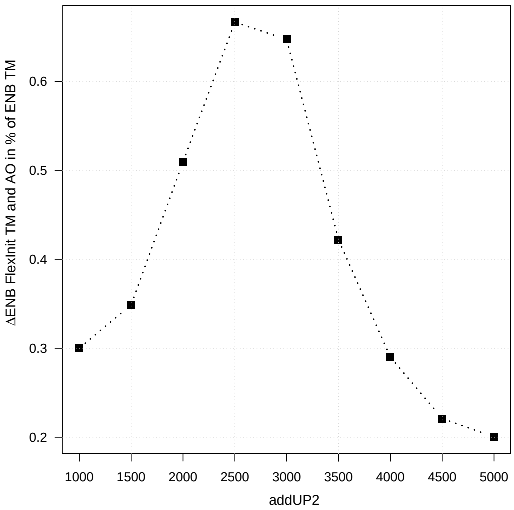

Figure 6.18: SA: No. additional patients addUP2 - ΔENB ROM AO - TM

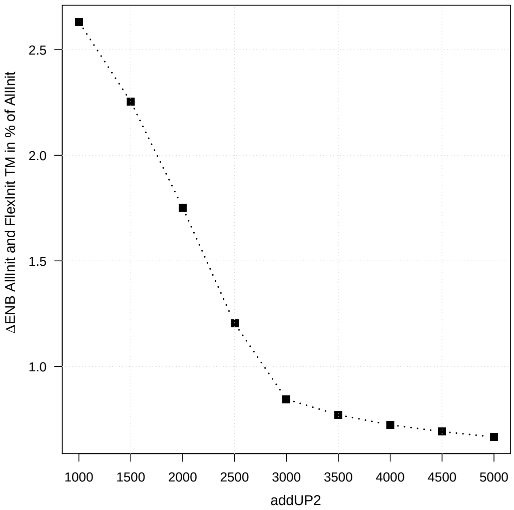

Figure 6.19: SA: No. additional patients addUP2 - ΔENB FlexInit TM - AllInit TM

Figure 6.17 shows that all ENBs increase with increasing *addUP2*, because there is an increasing number of patients to be treated, i.e.there are more benefits from the treatments. The ENBs with the IP2 and IP3 types increase faster, because they can take advantage of the possibilities to save costs through interventions. An increase of $addUP2$ leads to higher benefits through the execution of the interventions.

Figure 6.18 shows also that $\triangle FlexInit - TM - AO$ increases with increasing $addUP2$, but then shows a decline again to approach zero. The increase of $\triangle FlexInit - TM - AO$ up to a value of $addUP2$ of 2’500 shows that the ROM AO allows for consideration of decision flexibility, which in turn allows for executing interventions if they are beneficial, but not when they are not. The advantage of flexible decision making increases with the possible benefits from the execution of the interventions.

The reason for the decrease in $\triangle FlexInit - TM - AO$ for addUP2 above 2’500 is the same as for the decrease of the difference $\triangle AllInit - FlexInit$, in figure 6.19. Figure 6.19 shows that the difference between the single-stage and the multistage IP types, $\triangle AllInit - FlexInit$, decreases with the number of additional patients, because the IPs adopted with IP3 approach the IP2 type of AllInitial, i.e. executing all interventions earlier, this time approaching t=0.

Thus, the advantage of the flexibility in decision making, by postponing the decision about the execution to a later time, is decreasing.

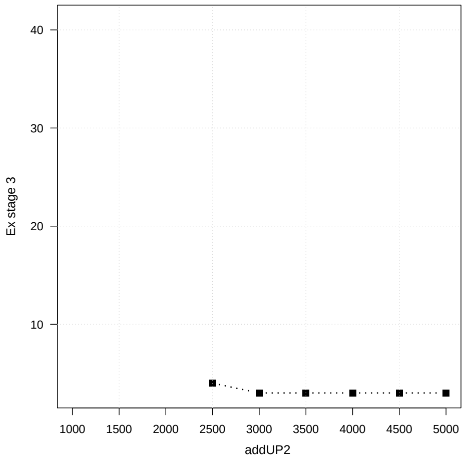

Figure 6.20: SA: No. additional patients addUP2 - τ_{TM} stage 3

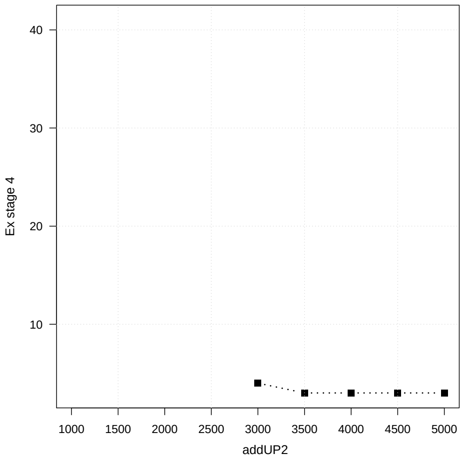

Figure 6.21: SA: No. additional patients addUP2 - τ_{TM} stage 4

Figure 6.20 and figure 6.21 show that interventions 3 and 4, which are not executed with the initial input values could be executed with increasing additional patient numbers for UP2, because more patients over capacity increase the probability of these interventions to be beneficial.

Table 6.36: Sensitivity Analysis - Change in addUP2

addUP2 in patients/year	1000	1500	2000	2500	3000	3500	4000	4500	5000
NoInitial - ENB in Mil. CHF	129.23	134.09	139.36	145.66	153.10	161.11	169.29	177.50	185.70
AllInitial - ENB in Mil. CHF	133.13	148.54	163.96	179.36	194.63	209.33	222.45	233.67	242.86
FlexInitial - Do nothing - ENB in Mil. CHF	128.21	133.08	138.35	144.65	152.09	160.10	168.28	176.49	184.68
FlexInitial - TM - ENB in Mil. CHF	136.63	151.89	166.83	181.52	196.27	210.94	224.06	235.29	244.48
τ_{TM} interv. 1 in years	3	3	3	3	3	3	3	3	3
τ_{TM} interv. 2 in years	-	-	4	3	3	3	3	3	3
τ_{TM} interv. 3 in years	-	-	-	4	3	3	3	3	3
τ_{TM} interv. 4 in years	-	-	-	-	4	3	3	3	3
FlexInitial - ROM AO - ENB in Mil. CHF	137.04	152.42	167.68	182.73	197.54	211.83	224.71	235.81	244.97
τ_{AO} interv. 1 in years	2	2	2	2	2	2	2	2	2
$q^{ex}_{\tau_{AO}}$ in year t=1	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
q^{ex}_{AO}	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99

6.6.2.3 Probability of introduction of new application - pUP2

The probability of the vaccination against Alzheimer's to be approved by the Swiss health care system, and thus the probability of a significant increase in the demand for the pre-screening in the PET center from 0 patients to 2'000 patients has a significant impact on the decision to execute interventions to expand the capacity of the PET center, i.e. an intervention is very likely if the pre-screening is introduced. Also, the probabilistic model describing this introduction has been simplified significantly in this example. Thus, it is necessary to investigate the influence of the chosen input parameters such as the probability of introduction. The probabilities of introduction (in the example 0.8 in year 2 and decreasing by 0.1 in years 4, 6 and 8) have been varied between 0.2 in the first year and the current value 0.8, always with decreasing probabilities in years 2, 4, 8 to 0.

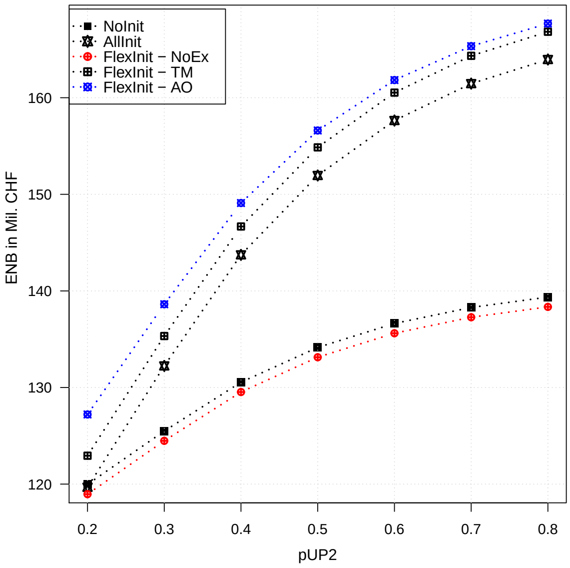

Figure 6.22: SA: Probability pUP2 - All ENBs

Figure 6.22 shows that all ENBs increase with increasing probability p_{UP2}, because the probability of more patients to be treated increases, i.e. the probability of more benefits increases. The ENBs with the IP2 and IP3 types (the execution of interventions) increase faster because they can take advantage of the possibilities to save costs while treating the patients. It shows how important the jump in patient numbers from UP2 is because if the probability is very low, the ENBs of IPs of all types converge.

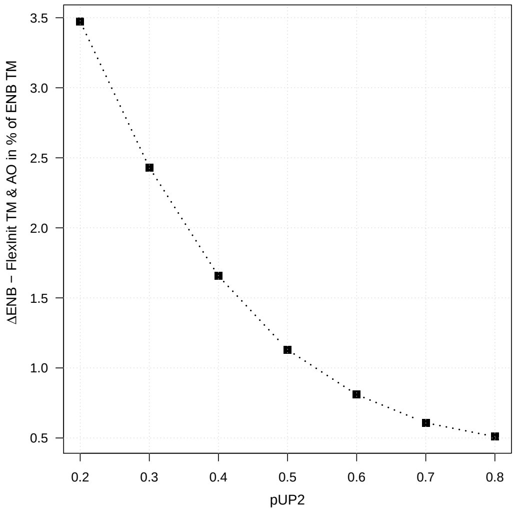

Figure 6.23: SA: Probability pUP2 - ΔENB ROM AO - TM

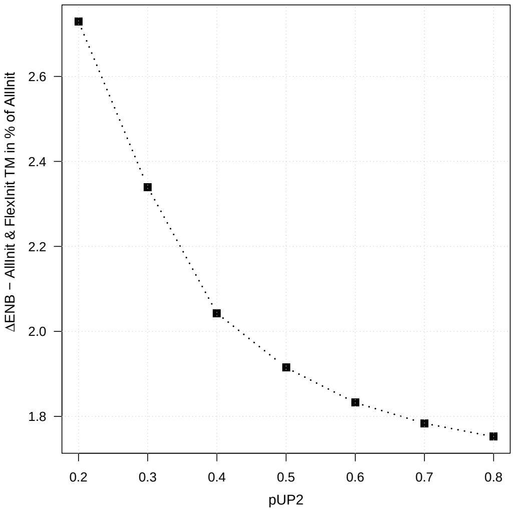

Figure 6.24: SA: Probability pUP2 - ΔENB FlexInit TM - AllInit TM

Figure 6.6.2.3 shows the difference in expected ENBs of the intervention programs from the ROM AO and the TM, $\triangle FlexInit - TM - AO$, and shows that the ENB with consideration of flexible management decreases from 3% to 0.5 % with increasing probability of UP2 jumping, because the jump of 2'000 is most relevant for the execution of the interventions, because it pushes the patient number over the required threshold for the execution to become beneficial, whereas UP1 leads only to a passing of the execution threshold with lower probability, i.e. a small tail of the probability distribution above the threshold. Such a small tail is better exploited with flexible decision making than with the assumption of fixed IPs. That means that in this example, the necessity for an intervention is too certain for flexibility to have value. Similar reasoning applies to $\triangle AllInit - FlexInit$ in figure 6.24. The higher the probability of execution is (in years 2 to 8), the more the preferred IPs of the IP3 type (both TM and ROM AO) will suggest an early execution of all interventions, i.e. those preferred IPs will be similar to the IP2 type with an execution at t=0, i.e. yielding similar ENBs and thus reducing the difference.

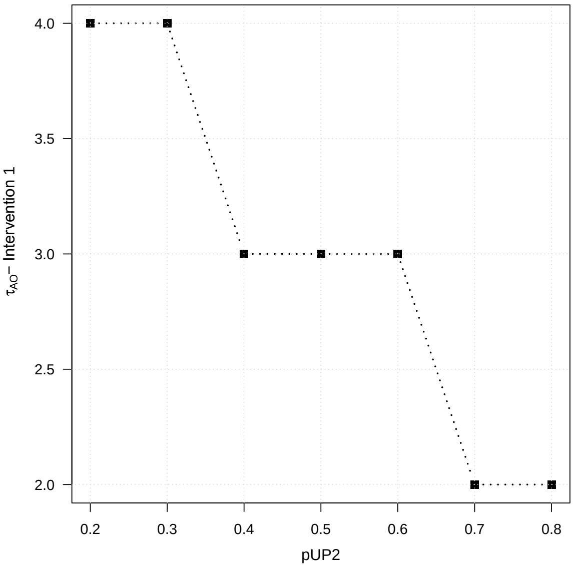

Figure 6.25: SA: Probability pUP2 - τ_{AO}

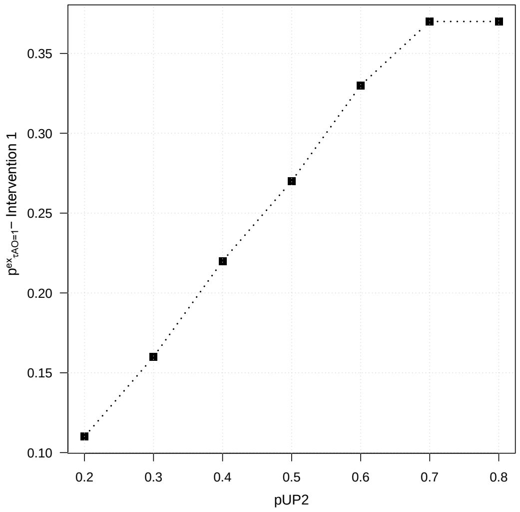

Figure 6.26: SA: Probability pUP2 - $q^{ex}_{\tau_{AO}}$

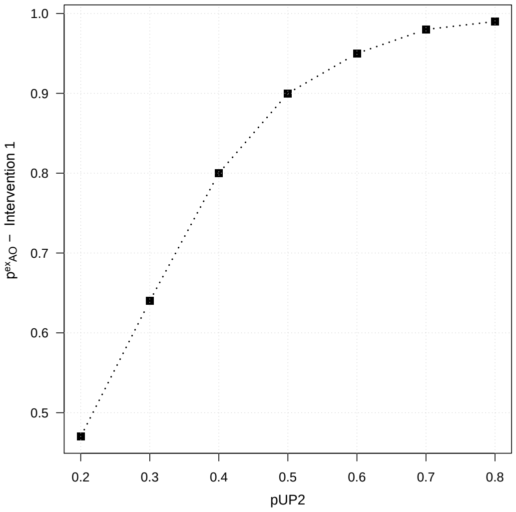

Figure 6.27: SA: Probability pUP2 - q^{ex}_{AO}

Figure 6.25 shows that τ_{AO} decreases with increasing pUP2, i.e. moves towards t=0, as a transgression of the execution threshold in patient numbers becomes more likely with increasing pUP2 earlier in the investigated time period. For the same reason, figure 6.26 shows that the $q^{ex}_{\tau_{AO}}$ and, in figure 6.27, the overall probability of execution, q^{ex}_{AO}, increase.

6.6.2.4 Discount factor - r

The discount factor r is always a significant input factor with a huge impact on the result, and also one subject to uncertainty. Thus, its variation has to be considered in this sensitivity analysis.

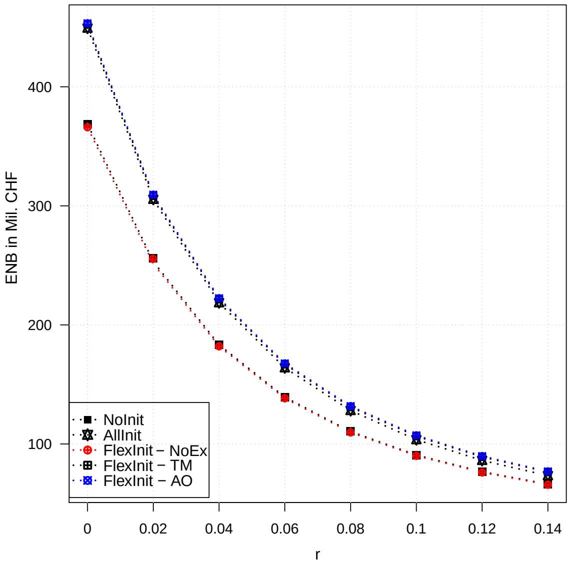

Figure 6.28: SA: Discount factor r - All ENBs

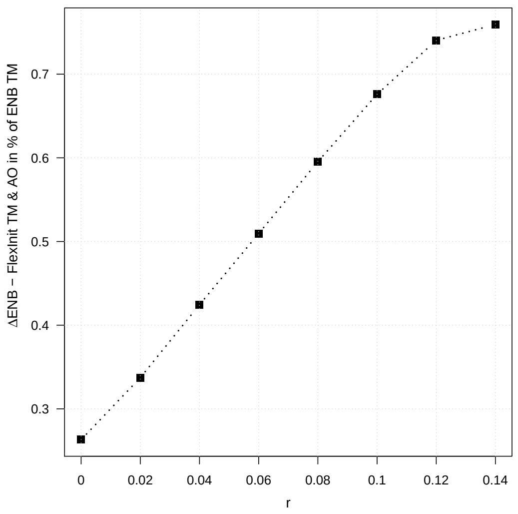

Figure 6.29: SA: Discount factor r - ΔENB ROM AO - TM

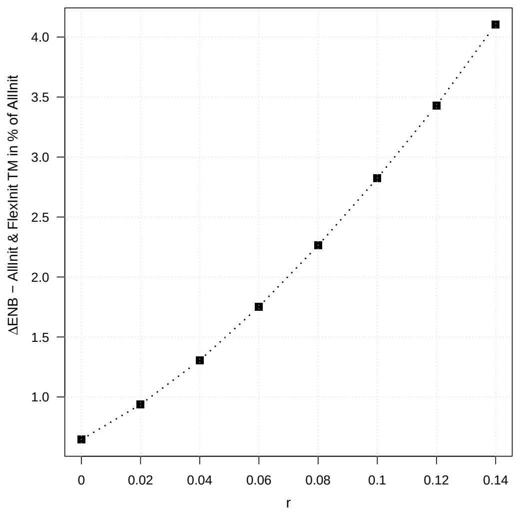

Figure 6.30: SA: Discount factor r - ΔENB FlexInit TM - AllInit TM

Figure 6.28 shows that all ENBs decrease with increasing r, because benefits in the future are discounted more strongly. As the benefits of an IP occur mostly in the future, their decrease influences the total ENB in this case strongly. The same reasoning applies to figure 6.29 which shows $\triangle AllInit - FlexInit$, where the expected net benefits from the execution of the interventions take effect in the future and are thus discounted while the costs for these interventions have to be paid today. Figure 6.29 shows that the difference in expected ENBs of the intervention programs from the ROM AO and the TM, $\triangle FlexInit - TM - AO$, increases with increasing r, because with a higher r, a later execution of interventions becomes beneficial only in the case when an execution is absolutely beneficial, which is considered with ROM AO, but not with the TM.

6.6.2.5 Discussion of sensitivity analysis

The sensitivity analysis showed that the ENB for a IP from the ROM AO remain higher than the ENB for a IP from the TM or even the IP2 type of layout 2 with an execution of all interventions in year 0 for a variation of the assumed input parameters in realistic ranges:

- The expected net benefits for an evaluation with consideration of flexible decision making, i.e. with the ROM AO, are higher or at least the same as the expected net benefits with the TM ($\triangle FlexInit - TM - AO$ in table 6.29). $\triangle FlexInit - TM - AO$ increases with increasing intervention costs for the purchase of the PET/MR, an increasing value of the discount factor r and the decreasing probability of UP2 to increase by 2'000 patients per year. However, the difference does not exceed 3 % of the overall expected net benefits from the clinic's operation.

- The ENBs of a staged execution of the interventions with layout 3 and the TM are generally higher in comparison to a single-stage execution with layout 2 ($\triangle AllInit - FlexInit - TM$ in table 6.29). The small difference in the results of the real world example (1.5%) increases with the increasing costs for the PET/MR, the discount rate and the decreasing probability of UP2 to increase by 2000 patients per year. However, the difference does not exceed 4 %.

- The execution of stages 3 and 4 for a IP determined with the TM (table 6.29) becomes possible when the number of additional patients from UP2 increases.

6.6.3 Summary

The methodology and method presented in chapters 3 and 4 were applied to a real world example of the premises of the clinic of nuclear medicine (CNM) of the university hospital, more specifically the PET center, which is a part of the clinic. With the help of the 11 steps of the methodology presented in chapter 3 it was investigated which uncertain changes in parameters significantly influence the service level of the PET center over an investigated time period of 40 years; the level of service was defined as the economic operation of the PET center with the expected net benefits from the operation over the investigated time period, while ensuring that all patients could always be treated. Thus, the analysis focused on uncertain parameters that would lead to changes in costs and benefits from the clinic operation and possible interventions for the improvement of the service level. Possible changes in the construction of the premises supporting interventions during the investigated time period were also considered.

The clinic of nuclear medicine, and in particular the PET center, offers, next to therapies, primarily imaging techniques using radioactive substances and radiating devices. These applications on patients result in direct income per patient, requiring frequently special devices, equipment and highly specialised and protected rooms, always under the consideration of radiation protection of all involved persons, i.e. staff, patients, visitors and others. This requires expensive and complex modification interventions in case of operational changes. Many key parameters, which might lead to changes in operation and thus changes in operating costs and income, are part of complex external processes such as, among others, medical research and development of disease treatments or the number of patients to be treated, and which are therefore hard to predict.

The assumption is that the clinic of nuclear medicine will move in the near future to new premises in the first stage E1 of the newly planned building complex of the university hospital, which can be planned today. Three possible layouts for the new premises of the PET center as part of the clinic of nuclear medicine were developed: Layout 1 fits current needs but cannot be modified, layout 2 includes all possible future modifications from the beginning, and layout 3 fits current needs but is flexible enough to be modified if needed in the future.

Many key parameters have an impact on the level of service of the PET center. Two key parameters were selected as the most relevant for the service level and their development over the investigated time period has been modelled in discrete, probabilistic models. All other key parameters and all factors were integrated in a dynamic model with adequate deterministic models.

The two main uncertain key parameters were

1. the number of patients for existing application for cancer localisation with PET/CT or PET/MR (**UP 1**)
2. the number of patients for new application for pre-screening for Alzheimer's with PET/MR (**UP 2**)

Both key parameters have an impact on the number of patients who are treated in the PET center, following the same patient path. UP1 was modelled with a discretised mean reverting process, fluctuating around an average of 4'700 patients. UP2 was modelled with a jump process, reflecting a sharp increase of number of patients for the Alzheimer's pre-screening in case of a research success of the vaccination against Alzheimer's. These two models for the uncertain development of the key parameters were integrated into the dynamic model.

The dynamic model is modelled in a multinomial discrete lattice, representing possible combinations of UP1 and UP2. In this multinomial lattice, the decisions about possible execution of interventions at certain times were integrated. This allowed the decision flexibility of the decision makers to be simulated in the model and possible selections to be identified and evaluated in intervention programs with the optimal execution times of each intervention. Both uncertain parameters lead to an alteration of the number of patients to be treated in the PET center on the PET/CT and PET/MR following the same path otherwise. Bottlenecks in this patient path are caused by lack of capacity (1) on the PET scanners, (2) the application rooms for the radioactive tracer substances, (3) resting rooms after the application, (4) and the diagnosis stations for the physicians to use the scan. Possible interventions lead to the extension of those premises. The various interventions can be executed only simultaneously or consecutively, e.g. intervention 2 can be executed only after or simultaneously to intervention 1. The decision about if an intervention should be executed and when was flexible, i.e. it was considered that the decision maker could change the decision depending on the actual outcome of the two uncertain parameters at certain times in the investigated time period. The decisions were made according to the two main objectives of the clinic : (1) Treatment of all patients, (2) economical operation of the clinic. To assess the efficiency of the clinic, the following costs and benefits were taken into account: (a) Income from patient care, (b) variable costs for the treatment of patients, (c) fixed costs for treatments, (d) additional costs for treating patients outside of regular capacity of PET center by introducing afternoon shifts, and (e) intervention costs. Maintenance costs were not included.

The results show the expected net benefits of 3 different types of intervention programs: The Do nothing intervention program (IP1) without any execution, applicable on layout 1 and 3, the single-stage intervention program (IP2), applicable to layout 2, and the multi-stage intervention program (IP3), applicable on layout 3 and evaluated with the Traditional Method and the Real Options Method. The results show that an execution of any intervention (i.e. IP2 and IP3) lead to ENBs of more than 20% higher than for the IP1 type with no execution of interventions. The ENBs for the IP3 type for layout 3, i.e. the multi-stage execution of the interventions, are higher than the ENBs from the IP2 type for layout 2 with a single-stage execution of all interventions in year t=0, by 1,8% for the optimal IP determined with the TM, and 2.2% for the preferred IP determined with the ROM AO. The ENBs of the IP3 type intervention program determined with the ROM AO are by 0.5% higher than the ENBs of the optimal IP determined with the TM.

The comparison of the optimal IPs shows that the IP determined with the TM recommends to execute intervention 1 in year 3, intervention 2 in year 4 and intervention 3 and 4 not at all. The IP determined with the ROM AO however, recommends an earlier possible execution of intervention 1 in year 1, but only if conditions are favourable, i.e. patient numbers are high enough, and to wait otherwise. The overall probability of executing intervention 1 over the investigated time period is almost 100%. The earliest possible year of execution for intervention 2 is in year 3, with an overall probability of execution of 53.9%. The ROM AO recommends, other than the IP determined with the TM, to execute interventions 3 and 4 if the conditions are favourable, earliest in years 3 and 4 and with overall probabilities of 15.7 and 1.6%.

6.6.4 Discussion of results and the application of evaluation method

The goal of this chapter was to show that the methodology for the identification and evaluation of intervention programs with consideration of flexible decision making and design in chapter 3 and the evaluation method from chapter 4 are applicable to an example in the real world of the use of a building, or parts of it, as close as possible to an example in the real world. More specifically, the application of both method and methodology was to show that (1) the ROM produces useful results, i.e. that the consideration of decision flexibility generates (a) other intervention programs and (b) higher expected net benefits than with the evaluation with a Traditional Method, i.e. without the consideration of decision flexibility, and (2) there are problems in the real world with (a) uncertain changes of the service level in the future (for example, operating costs and expenses), (b) the possibility to model the uncertain changes probabilistically in a discrete multinomial lattice, (c) the possibility to counteract these changes with expensive modification interventions that need to be avoided under certain circumstances, (d) the possibility to be flexible in the decision making about the time of these interventions, (e) the possibility to increase the flexibility of the current design of the premises through additional investments today with regard to the modifications in the future.These goals have been achieved in steps 1 to 10 of the methodology in chapter 3 and generally, with the use of the proposed method for the evaluation of intervention programs with consideration of decision making, in step 11. The application of the methodology and the method also helps to ensure that appropriate consideration is given to the uncertain level of service required from the building, how the building might be changed to deal with these different possible levels of service, and how an initial design (or layout in this case) can be adapted to provide the flexibility to modify the building in the future according to these changes in level of service.

6.6.4.1 Methodology for the identification and evaluation of intervention projects with consideration of decision and building flexibility

With the exception of step 11, i.e. the application of the Real Options Method for the evaluation of intervention programs with consideration of decision flexibility, stakeholder knowledge was essential in all steps of the methodology for the obtainment of the necessary data. For the application of the methodology and the method, the following main information groups were essential: (1) Information about the function of the clinic building and the resulting process flow, (2) the current and future demands on the buildings resulting from these processes, (3) external influence factors on the demands on these processes and the building, (4) the technical and structural attributes of the existing building, (5) possible interventions on the existing building, and (6) costs and benefits from the operation of the clinic and (7) costs for the construction of and the interventions on the building. In this case, the most important stakeholders delivering the input data were the head of the clinic, the head of the technical-medical staff of nuclear medicine, and the senior construction project manager responsible for the observed building of the construction department of the university hospital[8]. To obtain all necessary information, several clinic visits during operation, several interviews with the head of the clinic and the head of the technical-medical staff, and multiple presentation and meetings with the construction project manager were conducted.

Step 1 - The assessment of the level of service provided by and expected from the building: This step was the most time consuming, as it required the analysis of the processes in the existing NUK building by discussing the operation and the resulting demands of the clinic of nuclear medicine with the stakeholders. The treatments with the highest impact on the yearly net benefits had to be identified. There were many influence factors that had to be analysed for current and future impact on the service levels of the building. To identify the possible need of modifications of the clinic's building, and their type, a deep analysis of the existing building was required.

Step 2 - Identify key parameters: This step required a thorough understanding of the processes in the clinic of nuclear medicine, especially the different treatments the clinic offered, the necessary patient paths and the special requirements on the structure due to radioactive substances and radiating devices in these patient paths. The PET center was chosen as an example because it has the major impact on the economical success, i.e. the level of service, of the clinic; 90% of all patients treated in the clinic are treated in the PET center. The economical success was chosen as the main level of service while others were ignored, e.g. the research activities and the goal of the clinic to be cutting edge in the area of nuclear medicine. The two main key parameters were identified directly based on the opinion of the head of the clinic.

Step 3 - Analyse past evolution of values of possible key parameters: In this case, the analysis of past evolutions of possible key parameters was not directly possible or not helpful, i.e. the evolution of the patient numbers for the existing treatment, UP1, no significant quantity of data was available, since the existing treatment had only been introduced 10 years ago,

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[8] The former two were able to deliver information groups (1) to (3) and part of (6), while the latter could deliver groups (4) to (7).

increasing steadily up to reaching a plateau. To establish a connection between other external parameters, e.g. cancer rates or growth of population, were possible but would have required extensive additional effort, while not contributing to the goal of this example. For the patient numbers of UP2, no historical data was available as the application did not exist yet.

Step 4 - Analyse changes in trends: Possible trend breakers for UP1 were the replacement of the existing application with a new application for the same purpose. It could have been possible that this new application would have been conducted by another clinic, i.e. could be lost for the CNM. This trend breaker could only have occurred earliest in 20 years and was ignored for reasons of simplicity. UP2 had the nature of a trend-breaker itself, and it was also assumed, for reason of simplification, that upon introduction of the application, it would remain active in the clinic over the investigated time period. Both these simplifications could be investigated further.

Step 5 - Develop models to predict likelihood of future scenarios: The probabilistic models for the two uncertain parameters were chosen according to information from the clinic stakeholders and assumption, as they could hardly be based on historical data. UP1 was modelled as a mean reverting process around the current patient number. The jump process for UP2 is the result of a strong simplification and could have been modelled more detailed, e.g. also as a mean reverting process, after the jump of introduction. However, the more detailed model would have increased the complexity of the discrete, multinomial model immensely. By using the simpler jump model, the general applicability of the complete methodology could be tested while leaving room for further investigation in the future. Modelling UP2 as a mean reverting process would lead to higher uncertainty in the patient numbers for the PET center, thus possibly increasing the additional expected net benefits of the IP determined with the ROM AO compared to the one determined with the TM, i.e. increasing the benefit for considering the decision flexibility.

Step 6 - Establish static model: The static model was established to determine the expected net benefits from the operation of the PET center. It was assumed that the decision was made according to the goal of economical optimisation of the ENBs from the operation of the PET center, ignoring other parameters as the research activities and the operation of other parts of the clinic in order to create a concise example for illustration.

Step 7 - Establish dynamic model: For the application of the ROM AO evaluation method, it was clear that both uncertain key parameters would have to be modelled in discrete binomial lattices to allow for the evaluation of flexible decision making for different outcomes of the two key parameters at a future time. Lattices, i.e. trees with reconnecting paths, were used instead of trees with independent paths to minimize complexity and be able to use existing evaluation concepts from the Real Option Analysis. Both the mean reverting process for UP1 and the jump process for UP2 could be modelled as binomial lattices, which were combined to model the complete uncertainty in patient numbers for the PET center. The input parameters for both lattices were chosen according to simplified assumptions about their future development, which is discussed in more detail in the appendix E.1, and could be developed further with the help of the clinic stakeholders for increased accuracy.

Step 8 - Identify possible ways in t > 0 to change the building use or operation so that new LOS could be provided: Possible changes in the operation of the building was identified as the treatment of an increased number of patients when necessary. To accommodate these changes, four bottlenecks were identified in the patient paths, i.e. stations in the patient paths with capacity thresholds below some possible values of the patient numbers over the investigated time period. Four modification interventions, which have to be executed consecutively, were determined to increase the capacity of these four bottlenecks and thus of the treatment capacity of the PET center. The thresholds for the last three of the four stations with bounded capacity were assumptions and could be refined with further consultation with the clinic personnel. Their effect on the overall results, however, were tested in the sensitivity analysis (see appendix F.3) and proved to be insignificant.

Step 9 - Identify possible renewal projects at t = 0: To determine possible renewal projects at t=0, a basic layout, layout 1, was defined in the new building E1 for the demands of the current patient numbers for UP1, based on the current layout of the PET center in the basement of the NUK building. This layout on the ground floor of E1 was developed under collaboration with a member of the clinic board and a member of the construction department of the university hospital. As the planning of building E1 was still in a very early stage, the layout of the complete floor is an assumption for this example, similar to the layout of the PET center. These assumptions, however, were made with all information available and could describe a realistic layout for the PET center in the new building E1. The assumption was that layout 1, the basic layout, could not be modified for the expansion of the capacity of the building, i.e. was non-flexible but also the cheapest possibility. Layout 2 was planned to be robust, i.e. accommodating all modification interventions 1 to 4 and thus offering the highest level of expansion from t=0. Both these layouts were necessary as a basis for comparison for layout 3 for the new PET center, which, like layout 1, provided the premises for the current patient numbers, but provided the possibility to expand in the future. This possibility led to a difference in costs between layout 3 and layout 1, this difference being the price for the flexibility to execute the interventions. This difference in costs, i.e. the costs for flexibility in layout 3, was assumed to consist of costs for strengthening the floor of the level of E1 with the PET center to provide structural stability for an expansion, and the loss of free use for the possible expansion area on this floor by accounting for a use in this area by another user that can move easily if expansion becomes necessary. There are possibly other differences in costs that need to be considered, and the estimation of losses for keeping the expansion area flexible and thus available is certainly simplified. The definitions of the situation in this step and the associated input, however, were estimated totally independent from the actual plans for E1 and the PET center, as the planning for this part of the overall refurbishment of the university hospital campus had not started by the time this example was set up.

Step 10 - Estimate additional costs and benefits of each renewal project in t > 0: The estimation of costs and benefits needed as input for the evaluation system were determined mostly based on information by the department of construction of the USZ and the clinic of nuclear medicine. The costs for increasing the load bearing capacity of E1 and the losses for keeping the expansion area flexible and thus available, are based on estimation. The difference, however, does not have an effect on the results, as the difference between the ENB without intervention for layout 1 and the ENBs for all other layouts with intervention, i.e. layout 2 and 3, is so significant, being about 30 Mil. CHF, that not even the highest estimates for the costs for the additional load bearing capacity would change the recommendation to execute interventions over the investigated time period (from both TM and ROM). Other inputs with uncertainties in the assumptions, i.e. in the quality of the assumptions, were varied within the possible ranges in the sensitivity analysis to test their effects on the general conclusions.

6.6.4.2 Step 11 - Estimate total additional net benefits of each project at t = 0 with and without consideration of decision flexibility

This step corresponds to the method for determination and evaluation of intervention programs with consideration of decision flexibility and is discussed in the next section. Here, the multi-stage execution of the four interventions was investigated with the TM and the ROM AO, i.e. with or without consideration of decision flexibility, for the building layout 3 with design flexibility. Additionally, the expected net benefits were calculated for building layout 1 without the execution of any intervention over the investigated time period, and building layout 2 with the execution of all four interventions in year t=0. Several points can be discussed according to the results. Both evaluation methods, TM and ROM AO, estimated that IPs including interventions (IP2 and IP3) are better than doing nothing over T, i.e. the OIP with interventions have higher expected net benefits of about 30 Mil. CHF than the doing nothing IP1.

ROM AO results in higher estimates of expected net benefits and different IPs than the TM The results from the comparison of the use ROM AO and the TM on layout 3 show that for this real world problem, the determination and evaluation of IPs with the consideration of decision flexibility with the ROM AO results in higher expected net benefits and other intervention programs than without the consideration of flexibility in decision making, with the TM. The IPs determined with the ROM AO for layout 3 and the type 3 intervention programs (multi-stage execution) yield higher expected net benefits at $t = 0$ than the one determined with TM, due to the fact that the ROM AO considers flexibility in decision making about the executing of interventions in the future. As the use of the ROM AO in most cases is a better reflection of reality, because a building manager normally has substantial flexibility, then the use of the TM will result in not only different IPs but less expected net benefit.

As the expected net benefits from the ROM AO and the TM methods are different, so are the IPs, i.e. if a building manager uses different methods to estimate net benefits, she will arrive at different recommended IPs. Although the recommended intervention programs by ROM and TM for intervention 1 and 2 are quite similar, the ROM AO recommends for certain outcomes of parameters UP1 and UP2 to wait with the execution of these interventions to a later time over the investigated time period. While the TM recommends to not execute interventions 3 and 4 at all, the ROM AO considers the possibility of their execution for certain outcomes of parameters UP1 and UP2.

The differences in ENBs and intervention programs from the ROM AO and the TM are small The benefit of the consideration of flexibility in decision making, i.e. the differences between the ENBs from the ROM AO and the TM, is with 0.5% of the overall expected net benefits from the operation of the clinic small for this real world example in layout 3. The reason for this is that the uncertainty about the actual patient numbers is not high enough for the advantages of the consideration of decision flexibility to take effect. First, the mean reverting process adopted for UP1 does not allow for a variation of patient numbers high enough to make flexibility in decision making, based only on UP1, significantly beneficial, but also because the execution of all interventions is mainly driven by parameter UP2. Secondly, the chosen jump-process for UP2 does not provide a high uncertainty about the introduction of the Alzheimer's vaccination and thus a jump of patient numbers for the new application. The probability of introduction in year 2 of 80% is very high, and the probability of non-introduction with the next possible jumps in years 4, 6 and 8 is only 5%. Thus, even with the combination of two uncertainties, the uncertainty about the patient numbers over the investigated time period is low, reducing the benefit of the consideration of flexibility in decision making. The difference between the expected net benefits of ROM AO and TM increases if the probability of introduction of the new treatment, i.e. the probability of UP2 to changes, decreases (as it is shown in the sensitivity analysis of pUP2 in section 6.6.2.3). With this decrease, the overall uncertainty of the uncertain parameter increases. Another reason for the small difference in ENBs and intervention programs can be that both TM and ROM AO already consider that the 4 interventions can be executed in stages, i.e. are IP3 types - multi-stage, which in itself is already a kind of flexibility, which can be evaluated without the consideration of flexibility in decision making, as in the TM.

The differences in ENBs and intervention programs for layout 2 and IP2 to layout 3 and IP3 are small The difference of expected net benefits from the evaluation of IP 3 type of intervention programs of layout 3 and the IP2 type of intervention program - single-stage is small, only slightly over 2.5%. The reason for this is again that UP2 is the relevant parameter for an execution of the interventions, and, increasing with a high probability in the first 10 years of the investigated time period, thus leading to IP3 type intervention programs to recommend an execution of all four interventions in the first 4 years for TM and ROM AO (here with the highest probability of execution). Thus, the type 2 intervention program and the type 3 intervention programs are very similar and deliver similar expected net benefits.

Also, the possible benefits from the execution of the interventions 1 and 2 are probably very high compared to the costs for all possible values of the uncertain parameters and the resulting expected net benefits, making the execution of these interventions beneficial, i.e. paying the intervention costs even for the average of the outcomes of the expected net benefits, thus giving flexibility in decision making no particular advantage. The expected net benefits of interventions 3 and 4 on the other hand seem to be too low for the mean values of the possible ranges of the uncertain key parameters, compared to their costs, that their execution becomes only beneficial for certain outcomes of the key parameters, a fact that can be only considered with the ROM AO. The sensitivity analysis shows that the execution of stages 3 and 4 for a IP determined with the TM (table 6.36) becomes possible when the number of additional patients from UP2 increases, i.e. the possible benefits from the execution of these interventions increases.

ROM AO gives recommendations for the decision making at t>0 The ROM AO offers additionally a tool to make decisions about the execution of any intervention for the optimisation of the IP at a later point in time, if the decision maker adopts decision flexibility over the investigated time period. The execution probabilities in figure 6.13 give an indication in which years the execution is possible and table 6.30 and table 6.31 show at what times and outcomes an execution should be reconsidered, and give at the same time an updated prediction about decision making until the end of the investigated time period, i.e. the results in tables 6.32 and 6.33 for a shorter time span and updated starting values for UP1 and UP2, which have been revealed by then.

Additional effort for ROM AO versus additional expected net benefits The application of the methodology and the ROM AO on this real world example has shown that the ROM AO requires input that is generated by the application of the methodology in steps 1 to 10. This input is in majority the same as for the TM, with the exception of additional effort, compared to the TM, that is required for (1) the definition of possible decision flexibility, i.e. the definition of time and possible values of the uncertain key parameters, and (2) the modelling of the consequences of the flexible decision making, e.g. the expected net benefits at time and node of decision. If applicable, the determination of multiple building designs with different levels of design flexibility can be another additional factor. In step 11, the calculation of the execution probabilities can be additional effort to the TM, although this can be addressed through proper implementation of the method in a software solution.

After the ROM AO has been applied, the results have to be implemented, and, if decision flexibility is beneficial, the selected intervention programs have to be reconsidered at the appropriate times recommended by the intervention programs. For this particular example, the additional expected net benefits of the ROM AO are based on the assumption that the decision maker will reconsider her decision at the recommended times over the investigated time period whenever the probability of execution is non-zero. This reconsideration is quite frequent for the four interventions, in almost every time interval over the investigated time period the execution of one intervention is possible (compare tables 6.30 and 6.31). This requires additional management effort for the reconsideration and generates an additional problem, especially when considering the low probabilities of execution of interventions 3 and 4 in the later half of the investigated time period: Planning security is low, so that integration with related interventions, e.g. in adjacent building parts, and the allocation of budget, e.g. for 5 years, becomes difficult. Thus, there is a trade-off between the advantage of the ROM AO, i.e. the difference of the expected net benefits, and the additional effort for the modelling and the disadvantages of the planning security.

Layout with the highest expected net benefits at t=0 The expected net benefits at t=0 for the three layouts 1 to 3 with different levels of design flexibility show that the highest net benefits can be expected with layout 3, the layout with the highest design flexibility, but not the most robust one. With layout 1, where no interventions are possible, the lowest expected net benefits are generated, as the execution of the interventions is beneficial by a high difference. Layout 2, where all interventions are included in the initial design at t=0, generates lower expected net benefits than the flexible layout 3, where interventions are only executed if the values of the uncertain key parameters make an execution beneficial. Conclusions for application of evaluation model on real world example

The goal of the chapter was achieved, which was to show that the methodology for the identification and evaluation of intervention programs with consideration of flexible decision making and design and the evaluation method are applicable to an example in the real world of the use of a building, or parts of it, as close as possible to an example in the real world. The example showed that (1) the ROM produces useful results, i.e. that the consideration of decision flexibility generates (a) other intervention programs and (b) higher expected net benefits than with the evaluation with a Traditional Method, i.e. without the consideration of decision flexibility, and (2) there are problems in the real world with (a) uncertain changes of the service level in the future, (b) the possibility to model the uncertain changes probabilistically in a discrete multinomial lattice, (c) the possibility to counteract these changes with expensive modification interventions that need to be avoided under certain circumstances, (d) the possibility to be flexible in the decision making about the time of these interventions, (e) the possibility to increase the flexibility of the current design of the premises through additional investments today with regard to the modifications in the future.

6.6.5 Conclusions on the real world example

6.6.5.1 Methodology for the identification and evaluation of intervention projects with consideration of decision and building flexibility

The application of the methodology for the identification and evaluation of intervention projects with consideration of decision and building flexibility showed that this process relies strongly on stakeholder knowledge about the processes and parameters that might affect the required levels of service in the future, how the use and operation of the building can be modified, how the building can be modified to counteract those changes, and how the building itself might change over the investigated time period. Thus, steps 1 and 2, identification of the service level and the relevant key parameters, are the most time consuming part. Good stakeholder communication and management is absolutely necessary to make sure that stakeholder knowledge is obtained as efficiently and completely as possible.

However, this methodology shares a number of steps with the infrastructure management process shown in figure D.3 in appendix D. Most of these steps are necessary to generate the input for the Traditional Method as well as the Real Options Method. Additional steps (to the traditional infrastructure management process) necessary to produce the input for the method for the evaluation of intervention programs with consideration of decision flexibility are steps 8 and 9 with the identification of intervention projects with consideration of design and decision flexibility, and of course the use of the method with consideration of decision flexibility itself in step 11.

The determination of the ranges of the values of the key parameters and their probabilities of occurrence is not always straightforward, e.g. because external influence factors, such as success of research and development, are hard to predict, as could be seen in this example for the clinic of nuclear medicine. It was shown, however, that it is essential for the choice and the evaluation of intervention programs with consideration of decision flexibility and the determination of flexible designs.

The results of the evaluation, therefore, had to be treated carefully, as they are based on simplifications and assumptions, and had to be verified by a sensitivity analysis. The application of the methodology in this example showed that substantial simplifications were required to make the analysis tractable and to conduct in a sensible time frame. Although these simplifications are unavoidable, they need to be made with care so as not to exclude important key parameters and their projects, which again requires frequent consultations with the building stakeholders. Nonetheless, if those assumptions and simplifications are made carefully and checked under consideration of inaccuracy in the assumptions, the general recommendations have a high probability of being correct.

6.6.5.2 Method for determination and evaluation of intervention programs with consideration of decision flexibility

The application of the American option type of the method for the evaluation of intervention programs with consideration of decision flexibility, ROM AO, in comparison with the evaluation with the Traditional Method, TM, for this example showed that the ROM AO results in higher expected net benefits and different intervention programs than the TM. The results show that the ROM AO is a better reflection of reality than the TM, because the decision flexibility of the building manager over the investigated time period is considered. The sensitivity analysis suggests, similar to the results from the simple example in chapter 5, that the expected net benefits for the intervention programs of the ROM AO are always higher or at least the same as for the intervention programs of the TM.

The intervention programs determined with the ROM AO give precise indications at what times over the investigated time period and for which values of the uncertain key parameters the decision about the execution of the interventions should be reconsidered. The intervention program indicates the probabilities of these possible executions over the investigated time period. Thus, the use of the ROM AO may even lead to the creation of more decision flexibility and, therefore, further increased benefits, because it gives the building manager an indication when and for which scenarios of the uncertain key parameters a reconsideration is in order. The expected net benefits at t=0 for the three layouts 1 to 3 with different levels of design flexibility show that the highest net benefits can be expected the layout with the highest design flexibility, layout 3.

The application of the method on this example showed that the ROM AO required more effort than the TM before and during the evaluation for

- the definition of the flexible decision making, i.e. the definition of possible times and values of the two uncertain key parameters, and their combination in binomial lattices, where a reconsideration of the decision is possible over the investigated time period,
- the definition of the consequences of the decision making at these decision and values over the investigated time period, e.g. the expected net benefits at the time and value of decision before and after the decision to execute an intervention, and
- the calculation of the probabilities of execution for each possible time and value where a decision of execution is beneficial, for this example with consideration of the conditional probabilities of the staged execution of the four interventions.

After the evaluation of the intervention programs with the ROM AO, the results generated with the ROM AO require active reconsideration of the IPs during the investigated time period at the times where the probability of execution is non-zero, i.e. the reconsideration of the decision is possible, and thus more management effort. If the intervention programs from the ROM AO resemble those from this example, i.e. with multiple possible intervention times and values with low probabilities of execution (compare tables 6.30 and 6.31), certain problems can arise for

- the planning of other interventions, which are interacting with the interventions in the IPs with consideration of decision flexibility, as the times of execution are distributed over investigated time period and have a low probability of execution, and

- the allocation of budget for interventions over the investigated time period, which is less clear for ROM AO, as the times of execution are distributed over investigated time period.

The use of the ROM and the TM on this example showed that the consideration of decision flexibility with the ROM does not necessarily result in significantly higher expected net benefits and significantly different IPs in comparison with the TM. Thus, in this case, the decision maker can make a choice of which intervention program to follow, either with or without consideration of decision flexibility. This depends on the decision maker's need to make predictions about the times of execution of the intervention, e.g. for the integration with other interventions on the building or more precise budget allocation.

In summary, the ROM AO requires additional effort for the evaluation and the implementation of the results in the context of the management of other interventions, compared to the TM, and does not necessarily generate significantly higher expected net benefits and different intervention programs that. The results and the sensitivity analysis from this example indicate that, similar to the results of the simple example, it is beneficial to use the ROM AO instead of the TM when

- the uncertainty of the key parameters and, as a result, the uncertainty of the expected net benefits is high, i.e. (1) the values deviate far from the mean, which was not fully the case for the uncertain key parameter 1, and (2) the probability of occurrence is not concentrating on one scenario, which was not fully the case in this real world example for the uncertain key parameter 2, and, at the same time,
- the intervention costs are high compared to the expected net benefits from the execution of the interventions, always taking into consideration that if the costs are so high that the Traditional Method without consideration of decision flexibility would recommend to do nothing, technically, all methods would recommend the same thing at t = 0, i.e. to do nothing. The IPs for interventions 3 and 4 from both ROM AO and TM suggest that the intervention costs are quite high compared to the possible benefits, as the ROM AO recommends an execution only for very high values of the key parameters with low probability of occurrence, and the TM recommends no execution. Here, the intervention programs from the ROM AO exploit even the smallest chance of additional benefits.

Chapter 7

Summary, discussion, conclusion and outlook

7.1 Summary

One task of building managers is to ensure that their buildings function as required over a defined period of time. This is a challenging task, particularly because the ability of buildings to meet demands changes over time due to two reasons: (1) The change of the ability of the building to meet fixed demands, which normally decreases as elements and connections between elements deteriorate, and (2) the change of demands for the building, for example new laws concerning the energy consumption of buildings, which causes the building to become gradually obsolete.

Building managers want to determine what they should do with their buildings now to maximize their net-benefit in the long term. This requires determining the intervention to be executed today and estimating the ones that might be executed in the future, i.e. determining the optimal intervention programs. To determine when to intervene on buildings and what intervention is to be done, building managers are increasingly supporting their decision making process through the use of computerized intervention management systems. The most advanced of these systems support the decision making process through the modelling of deterioration and the determination of the optimal intervention program to restore the building to a condition in which it can continue to, or can again, provide the present required level of service. Changes in demand, however, have been considered less widely than deterioration in most of these systems.

Although the assumption of non-changing demands is convenient from a mathematical modelling point of view, it is rarely true in the real world. The change of demands is an important factor in the life cycle of a building and should be considered in its life cycle planning, especially in infrastructure management.

Uncertain changes in demand make it undesirable to attempt to evaluate intervention programs now and then determine exactly which one to follow over the remaining planning horizon. Instead, uncertain changes in demand make it desirable to find flexible solutions that consider the possibility that the decision about the actual intervention program to follow can be postponed to a later moment, i.e. whether or not an intervention is to be executed now or not. Taking into consideration this flexibility of management to decide which intervention program to follow, and thereby allowing more information to be considered at a later date, is believed to be a cornerstone of any method to be used to determine optimal intervention programs in management systems where there is uncertainty with respect to future demand.

To make a decision about whether to introduce decision flexibility in intervention planning, e.g. by altering the design to allow for future modifications, it is necessary to evaluate this decision flexibility and show that it is beneficial. Consideration of decision flexibility in the construction of intervention programs has value relative to intervention programs without consideration of flexibility, because it enables the building manager to adapt the system to new information and thus avoid losses or even seize opportunities.

The methods for putting a value to this flexibility that were investigated are (I) the Real Options Analysis and (II) Decision Tree Analysis. The focus of research done about the Real Option Analysis has been on the flexibility of the infrastructure or buildings themselves, which has to be distinguished from the decision flexibility in the determination of intervention programs.

In chapter 2, the state of research and the state of practice, is presented in the area of the construction of intervention programs and the evaluation of decision and building flexibility in building management and design, and the research gap is identified. Methods are presented that are used for the construction of intervention programs on buildings and other infrastructure, methods considering the deterioration and the change of demand and boundary conditions. Also, methods for the evaluation of decision and building flexibility in building management and design are presented.

Chapter 3 describes the methodology for the identification and evaluation of intervention projects with consideration of decision and building flexibility. The presented methodology can be divided in three main parts: (1) Identify and model the system key parameters, (2) identify possible intervention and design projects, and (3) evaluate the possible intervention and design projects.

Chapter 4 describes the method for the evaluation of intervention programs with consideration of decision flexibility. The implementation of the method is demonstrated in chapter 5 on a simple example of a fictive office building, and the possible results, with a sensitivity analysis of the input parameters, were presented and discussed.

Chapter 6 shows that the methodology for the identification and evaluation of intervention projects and method for the determination and evaluation of intervention programs with consideration of decision flexibility can be applied to a real world example, the clinic of nuclear medicine of a Swiss university hospital. The methodology and the method were applied by analysing the situation, building adequate models of the uncertain key parameters, establishing the static and dynamic evaluation models, identifying possible intervention projects, evaluating these intervention projects with the method for the evaluation of intervention programs with consideration of decision flexibility. The results of the real world example were presented and investigated further in a thorough sensitivity analysis.

The background for this thesis is presented in appendix D, i.e. the basics for building and infrastructure management and the construction of intervention programs, the terms risk and uncertainty and the positioning of the content of this work with regard to these terms, the definition of flexibility in the context of building management, and the evaluation of flexibility with real option analysis and decision tree analysis.

7.2 Discussion

The findings in this thesis will be discussed in this section. First, the application of the methodology for the identification and evaluation of intervention projects are discussed with regard to how it is an improvement compared to existing methods, what the limitations and weaknesses are and in which cases it is applicable. Second, the application of method for the evaluation of intervention programs with consideration of decision flexibility are discussed with regard to how it is an improvement compared to existing methods, what the limitations and weaknesses are and in which cases it is applicable. Third, the integration of the methodology and method presented in this thesis in existing building management methodologies and infrastructure management systems are discussed. Finally, implications for the use of the methodology and the method on building portfolios and infrastructure networks are discussed.

7.2.1 Methodology for the identification and evaluation of intervention projects

The use of the proposed methodology for the identification and evaluation of intervention projects on the real world example of the clinic of the university hospital showed that it is applicable to the real world and produces useful results. Its use helps to ensure that appropriate consideration is given to the uncertainty in service level required from the building resulting from changes in demand and how intervention programs and the building design can be changed to ensure that the building provides an adequate service level under uncertainty. The methodology resulted in the construction of a flexible intervention program and a building design with increased flexibility, resulting in higher expected benefits from the operation of the building than from inflexible intervention programs and a less flexible building design. Even though the examples in this thesis consider the monetary costs and benefits in the evaluation, also non-monetary components could be considered in this method, e.g. the environmental or social impacts of a decision. This depends on the preference and perspective of the decision maker. The use of the methodology on a real example in collaboration with building stakeholders showed that following the methodology has benefits without the construction of flexible intervention programs. The systematic analysis of the situation and the development of scenarios gave the building stakeholders the opportunity to rethink the general building management approach and the building design qualitatively and to improve them accordingly.

The use of the methodology on the real world example showed, however, that

- the application of the methodology relies strongly on stakeholder knowledge about the processes and parameters that might affect the required service in the present and in the future, about how the use and operation of the building can be modified, and about how the building can be modified to adapt the building to the new service level,
- the first two steps, identification of the service level and the relevant key parameters, are the most time consuming part, which requires good stakeholder communication and management, which is necessary to make sure that stakeholder knowledge is obtained as efficiently and completely as possible,
- the determination of the ranges of the key parameters and their probabilities of occurrence, i.e. the uncertainty about the future state of nature, is not always straightforward, e.g. because historical data is not available, external influence factors, such as success of research and development, are hard to predict, and the consequences on the service level of the clinic's operation are not clear. The reliable modelling of the future state of nature and its consequences on the service level are essential for the choice and the evaluation of intervention programs and the determination of the appropriate flexible designs, and
- substantial simplifications were required to make the analysis tractable and to conduct the analysis in a reasonable time frame. Although these simplifications are unavoidable, they need to be made with care so as not to exclude important key parameters and their consequences. The simplifications require frequent consultations with the building stakeholders. Nonetheless, if those simplifications are made carefully and checked, taking into consideration the inaccuracy in the assumptions made for the simplifications, the general recommendations from the results of the methodology, e.g. intervention programs or changes in the building design, are likely correct.

The application of this methodology requires a high effort from all stakeholders for being successful. However, this methodology shares a number of steps with the infrastructure management process in in figure D.3 in appendix D. It is assumed that existing methodologies for building or infrastructure management and also computerised infrastructure management systems follow this management process. Additional steps (to the traditional infrastructure management process) necessary to produce the input for the method for the evaluation of intervention programs with consideration of decision flexibility are steps 8 and 9 with the identification of intervention projects with consideration of design and decision flexibility, and of course the use of the method with consideration of decision flexibility itself in step 11. The highest chances for useful results from the methodology can be expected when buildings are modified or newly built at the time of analysis, as the building flexibility can be increased, leading to higher decision flexibility. It is also beneficial, if the building is managed by members in an organisational structure of sufficient size, e.g. the construction department of a hospital with a building portfolio. In that case, there is the possibility of an infrastructure management systems or a systematic infrastructure management process already being implemented. This supports the application of the methodology for the identification and evaluation of intervention projects, as the steps of the general infrastructure management process (in figure D.3 in chapter D) support the methodology and the resources (e.g. personnel and data) for the application of the methodology are already available.

7.2.2 Method for the evaluation of intervention programs with consideration of decision flexibility

The use of the method for the evaluation of intervention programs with consideration of decision flexibility on the simple example and the real world example showed that the method can be applied to real world situations and can deliver meaningful results, i.e. intervention programs with consideration of flexibility, which are different to, and lead to higher expected net benefits, from the building operation than intervention programs constructed with a traditional method. The results from the application of the method on the simple and the real world example suggest that the expected net benefits for the intervention programs of the ROM AO are always higher or at least the same as for the intervention programs of the TM.

The difference in intervention programs refers to the recommended time of execution of the suggested interventions. The difference between the intervention programs occurs because the method for the determination and evaluation of intervention programs with consideration of decision flexibility takes into consideration the fact that a building manager will evaluate in the future whether or not it is beneficial to execute an intervention and will make a decision to intervene only if it is beneficial. Thus, the results from the Real Options Methods are a better reflection of reality than the ones from the TM.

The intervention programs determined with the Real Options Method, especially the American option type, give precise indications at what times over the investigated time period the decision about the execution of the interventions and for which values of the uncertain key parameters should be reconsidered. The intervention program indicate the probabilities of these possible executions over the investigated time period. Thus, its use may even lead to the creation of more decision flexibility and, therefore, further increased benefits, because it gives the building manager an indication when and for which scenarios of the uncertain key parameters a reconsideration is in order.

The method with consideration of decision flexibility will show that there are possible times in the future where it might be beneficial to execute an intervention. The results from the method with consideration of decision flexibility can support the decision maker in the mobilisation of additional initial investment costs for a more flexible design, i.e. initial capital expenditure, the CAPEX. With the differences in expected net benefits over the investigated time periods of a more flexible design and intervention project, higher initial costs can be justified in front of investors. The Real Options Method also enables the evaluation of different building design with different levels of building flexibility, according to the expected net benefits at t=0, as it has been done before..

The application of the method on this example showed that the Real Options Method required more effort than the Traditional Method before and during the evaluation for

- the definition of the flexible decision making, i.e. the definition of possible times and values of the two uncertain key parameters, and their combination in binomial lattices, where a reconsideration of the decision is possible over the investigated time period,
- the definition of the consequences of the decision making at these decision and values

over the investigated time period, e.g. the expected net benefits at the time and value of decision before and after the decision to execute an intervention, and

- the calculation of the probabilities of execution for each possible time and value where a decision of execution is beneficial, for this example with consideration of the conditional probabilities of the staged execution of the four interventions.

After the evaluation of the intervention programs with the Real Options Method, the results require active reconsideration of the intervention programs during the investigated time period at the times where the probability of execution is non-zero, i.e. the reconsideration of the decision is possible, and thus more management effort. Certain problems can arise from the intervention programs with consideration of decision flexibility, especially from the American option type of the method, for

- the planning of other interventions, which are interacting with the interventions in the intervention programs with consideration of decision flexibility, as the times of execution can be distributed over investigated time period and can have a low probability of execution at each of these times,
- the allocation of budget for interventions over the investigated time period, which is less clear for American option type of the method, as the times of execution are distributed over investigated time period.

In some cases, additional effort might be necessary for the physical change of the building to facilitate interventions with consideration of decision flexibility in the future, which might not be possible otherwise.

The results from the application of the method on the simple and the real world example show that, even though the expected net benefits from the evaluation with the method with consideration of decision flexibility are higher than the ones from the TM, the difference can be small. In such a situation, the decision maker can make a choice of which intervention program to follow, either with or without consideration of decision flexibility. This depends on her need to make predictions about the times of execution of the intervention, e.g. for the integration with other interventions on the building or more precise budget allocation.

In summary, the Real Options Method with consideration of decision flexibility requires additional effort for the evaluation and the implementation of the results in the context of the management of other interventions, compared to the Traditional Method, and does not necessarily generate significantly higher expected net benefits and different intervention programs that. The results and the sensitivity analysis from both examples indicate that it is beneficial to use the Real Options Method instead of the Traditional Method under the following conditions at the same time:

- The uncertainty of the key parameters and, as a result, the uncertainty of the expected net benefits is high, i.e. (1) the values deviate far from the mean, and (2) the probability of occurrence is not concentrating on one scenario. This is due to the fact that the higher the assumed volatility of the uncertain key parameters, the bigger the expected range of values for the uncertain key parameter, with higher and lower benefits in case of intervention. In the determination of the expected net benefits with the Traditional Method, the high and low benefits cancel each other out whereas with the Real Options Method types, there are increasingly better opportunities to exploit positive risk.
- The intervention costs are high compared to the expected net benefits from the execution of the interventions, always taking into consideration that if the costs are so high that the Traditional Method without consideration of decision flexibility would recommend to do nothing, technically, all methods would recommend the same thing at t = 0, i.e. to do nothing. If the costs are low compared to the benefits, however, both the Real Options Method and the Traditional Method would recommend to execute the intervention as

soon as possible, because there is little disadvantage from the execution, but a lot to gain through it.

General prerequisites for the application of the ROM are that

- decision flexibility is a possibility, i.e. decisions are possible not only at t=0 and the management of decisions at t>0 is an option, and
- the integration with interventions outside the intervention programs determined with the ROM is possible.

The American Option type of the Real Options Method requires more effort during the evaluation and for the implementation, while the intervention programs determined with the ROM AO yield higher expected net benefits than the ones determined with the European Option type of the Real Options Method, because the European option type of the Real Options Method considers a higher degree of decision flexibility. The American Option type of the method should be used if there is more than two possible decision times, i.e. as soon as there are two time intervals of which one is $t > 0$, and it is possible to make the decision at either of these. It applies to single properties, on which interventions can be planned independently. The European Option type of the Real Options Method should be used if there is only one decision interval (either $t = 0$ or $t > 0$), e.g. through time constraints; such constraints can occur through contractual arrangements or through the interaction with interventions in connected buildings or building elements, if, for example a group of buildings is refurbished successively where one of the buildings must always serve as a spare area to accommodate the people or equipment displaced from the building being renovated.

Modelling the stochastic processes as discrete lattices is advantageous with regard to the transparency of the process and ease of decision making at each node, especially when applying the American Option type of the Real Options Method. The consideration of more than one uncertain key parameter, however, next to the requirement of deeper knowledge concerning the calculation of the joint probabilities, increases the amount of nodes in the multinomial lattice exponentially, which can possibly lead to running times for the evaluation method which are not feasible anymore. Other solutions, like the use of analytic solutions like the Black-Scholes method or Monte Carlo simulation, might be more suitable for the application of the evaluation method with consideration of decision flexibility if multiple key parameters need to be considered. This is a topic that could be investigated in future research.

Even though the focus of this work lies on the evaluation of the decision flexibility with regard to intervention programs, the design flexibility of the considered building is often evaluated as well. This design flexibility of a building can contribute significantly to avoiding obsolescence of the building or its parts over the investigated time period. The methodology supports the identification of appropriate changes in the design to improve the design flexibility, and the Real Options Method supports the choice of the best design, or prioritisation of design changes, to avoid obsolescence. Specific obsolescence criteria can be considered in the decision making in the Real Options Method, e.g. by defining thresholds for the yearly energy consumption or the yearly operational costs, that are subject to uncertainty and must not be exceeded, which can be ensured by executing interventions. In the representation of the method, the decisions were made by choosing the maximum expected net benefits that could be expected after each decision. If other criteria than the monetary costs and benefits were to be considered, e.g. environmental or social impacts, the decision making at each node or in each time step could include multi-criteria decision making, depending on the preferences and perspective of the decision maker.

7.2.3 Integration in existing methodologies and infrastructure management systems

The consideration of decision flexibility in the construction of intervention programs is not applicable for all building components. Maintenance and modification interventions and the decisions about optimal intervention programs depend on many parameters, which are subject to no or little uncertainty over the investigated time period. The failure intervals of the components of heating and ventilation systems are for example well known, and maintenance is executed in regular intervals on these components. The application of the presented method with consideration of decision flexibility is only beneficial if the uncertainties in key parameters is high enough, as could be seen in the discussion of the previous section. It can be assumed that many of the intervention programs constructed for a complete building are determined without the consideration of decision flexibility, resulting in inflexible intervention programs. Thus, the methodology and method with consideration of decision flexibility investigated in this thesis have to be applied in the context of the management of related building components without consideration of flexibility.

The infrastructure management process in figure D.3 in appendix D shares a number of steps with the methodology for the identification and evaluation of intervention projects. The method for the evaluation of intervention programs with consideration of decision flexibility is used in the same step of the infrastructure management process as other traditional methods for the determination of inflexible intervention programs. It is assumed that existing methodologies for building or infrastructure management and also computerised infrastructure management systems follow this management process.

In the following section, it is discussed which additions are necessary to the steps in the infrastructure management process to integrate the methodology and method presented in this thesis.

1. Establish service level goals and constraints:
    - Provide data base with changes in demand and constraints, influence factors, effects and consequences on the service level (compare collection in appendix E).
    - Provide data base with possible relevant service level definitions with regard to changes in demand (see appendix D.1.3 for examples).
    - Provide methods for the identification of risk or the consequences for the service levels by applying methods suggested in appendix D.2.2.
2. Establish organisation structure, processes, models, strategies:
    - Provide probabilistic modelling (possibly already provided) with focus on discrete models and possible combinations of key parameters.
    - Provide data base for connections between influence factors, changes in demand and the consequences for service levels.
3. Construct maintenance and modification programs:
    - Provide module for the method for the evaluation of intervention programs with consideration of decision flexibility for different cases.
    - Provide a module for the integration of flexible and inflexible intervention programs.
4. Monitoring and updating of information:
    - Provide module for the monitoring of changes in the relevant key parameters and updating of the flexible intervention program.
    - Provide organisational structure to allocate resources for monitoring and updating.

A step needs to be added to support steps 8 and 9 of the methodology for the identification and evaluation of intervention projects, with the following steps:

- Provide data base with example changes in use and operation.
- Provide data base with definition of decision flexibility.

- Provide data base with possible changes in the building flexibility (compare table D.4 in appendix D).
- Provide module for rough sensitivity analysis to identify feasible projects in step 9 of methodology.

The application of the presented methodology and method could be facilitated by adapting existing standards for building management, by, for example,

- defining changes in demand, influence factors and consequences for the service levels,
- defining relevant changes in service levels due to changes in demand and constraints,
- defining the necessary additions to the infrastructure management process elaborated above,
- defining the necessary organisational structures to implemented the methodology and method.

7.2.4 Building portfolios

In this thesis, the use of the presented methodology and method was investigated for buildings and single components. When considering buildings as part of building portfolios, it might be useful to consider the same changes in demand for a complete portfolio of buildings as the changes of demand might apply to other buildings in the portfolio. As modifications are often significant interventions, they can have an impact on other buildings in portfolio, and it might be beneficial to bundle modification interventions for multiple buildings.

7.2.5 Other infrastructure objects and networks

Even though the methodology and method presented in this thesis was determined for and applied to buildings and building components, they can be used for the identification and evaluation of identification and evaluation of intervention projects for other infrastructure objects and network, e.g. bridges, road networks or industrial plants. The relevant changes in demand and the required service levels would have to be adapted to fit the considered infrastructure. It would have to be investigated, if the uncertainty in the key parameters and the consequences for the service level are high enough to justify a use of the methodology and method.

7.3 Conclusions

The main objective of this research is to investigate how to consider the decision flexibility of the decision maker in the determination and evaluation of intervention programs with consideration of the uncertainty in future demand and to define a method that can support a decision maker in the determination and evaluation of such intervention programs. This objective was reached in this thesis, as is elaborated in the following text according to the main necessary points stated in the introduction, together with the main conclusions.

7.3.1 Relevant classes of uncertain changes in demand

Relevant classes of uncertain changes in demand, together with their influence factors and their effects, i.e. obsolescence types, and the consequences for the service level of a building were identified and grouped. This was done without a deeper definition of the connections between the changes in demand, influence factors and consequences. There is a great body of parameters with a potential impact on building engagement. Several sources suggest that the changes in demand have an impact on the execution of intervention programs, often a higher impact than deterioration of building components.

7.3.2 Methodology for the identification and evaluation of intervention projects with consideration of decision and building flexibility

A methodology for the identification and evaluation of intervention projects with consideration of decision and building flexibility was determined and used on the real world example of a clinic of nuclear medicine of Swiss university hospital. It was shown that the methodology was applicable as defined and resulted in the determination and evaluation of an intervention program with consideration of decision flexibility.

7.3.3 Real Option Analysis and Decision Tree Analysis used in a Real Options Method to evaluate optimal intervention programs with consideration of decision flexibility

Real Option Analysis and Decision Tree Analysis were investigated and found useful for the evaluation of intervention programs with consideration of decision flexibility. This method was applied on a simple example of a fictive office building and a real world example of the clinic of nuclear medicine of a major Swiss hospital as part of the methodology for the identification and evaluation of intervention projects. In both cases, the application of the method produced, in comparison to the results of a traditional method for the evaluation of intervention programs without consideration of decision flexibility, different intervention programs and higher expected net benefits over the investigated time period.

7.3.4 Ramifications of the results of the application of the methodology and method

The application of the presented methodology and method and their results lead to the following conclusions:

- Methodology for the identification and evaluation of intervention projects:
    - The methodology can be applied to a real world situation and can deliver meaningful results, but relies strongly on stakeholder knowledge and requires good and extensive stakeholder communication throughout the complete process.
    - Considerable simplifications must be made throughout the process, to keep the complexity at a manageable level. This regards especially
        - the selection of relevant key parameters
        - the models for the uncertain key parameters
    - However, this methodology shares a number of steps with the infrastructure management process in figure D.3 in appendix D. Most of these steps are necessary to generate the input for the Traditional Method as well as the Real Options Method. Additional steps (to the traditional infrastructure management process) necessary to produce the input for the method for the evaluation of intervention programs with consideration of decision flexibility are steps 8 and 9 with the identification of intervention projects with consideration of design and decision flexibility, and of course the use of the method with consideration of decision flexibility itself in step 11.
- Method for the evaluation of intervention programs with consideration of decision flexibility
    - The use of the method allows appropriate consideration of decision flexibility and, therefore, will lead to an increased benefit for building managers.
    - The expected net benefits and optimal intervention program determined with the method with consideration of decision flexibility are closer to reality, and thus enable more realistic budget planning.

  - The method requires higher effort during the evaluation for
    - the definition of the flexible decision making, i.e. the definition of possible times and values of the two uncertain key parameters,
    - the definition of the consequences of the decision making at these decision and values over the investigated time period,
    - the calculation of the probabilities of execution for each possible time and value where a decision of execution is beneficial.
  - The method requires higher effort after the evaluation for
    - the planning of other interventions, which are interacting with the interventions in the intervention programs with consideration of decision flexibility,
    - in certain cases the allocation of budget for interventions over the investigated time period.
  - The method with consideration of decision flexibility does not lead to better intervention programs for all components of a building, and thus should be applied if, at the same time,
    - the uncertainty of the key parameters and, as a result, the uncertainty of the expected net benefits is high, and
    - the intervention costs are high compared to the expected net benefits from the execution of the interventions.

  General prerequisites for the application of the ROM are that

    - decision flexibility is a possibility, i.e. decisions are possible not only at t=0 and the management of decisions at t>0 is an option, and
    - the integration with interventions outside the intervention programs determined with the ROM is possible.

- Even though the expected net benefits from the intervention program determined with the method with consideration of decision flexibility were higher than the ones from the intervention program without consideration of flexibility for both the simple and the real world example, the difference was below 1%, i.e. easily within the error margin of the input parameters. This small difference is mainly due to the reduced impact that the uncertainty considered in the examples have on the expected net benefits of the intervention program, but it is a result that is only possible to obtain through an adequate evaluation method as presented in this thesis. In such a situation, the decision maker can make a choice of which intervention program to follow, either with or without consideration of decision flexibility. This depends on her need to make predictions about the times of execution of the intervention, e.g. for the integration with other interventions on the building or more precise budget allocation. Such a small difference does not necessarily justify the additional effort of the application of the method, and also the complete methodology for identification and evaluation of intervention projects, with consideration of decision flexibility compared to a traditional method without consideration of decision flexibility. Thus, during early steps of the methodology, ideally a test should be made whether the considered case will have a significant impact. For example, a sensitivity analysis of the expected net benefits from the dynamic model in step 7 of the methodology could give an indication here.

7.4 Outlook

Based on the discussion and conclusions of the contents of this thesis, some suggestions for future research and practice can be made.

7.4.1 Identification of relevant cases for intervention programs with consideration of decision flexibility

The method for the evaluation of intervention programs was used on the example of the clinic of nuclear medicine of a Swiss university hospital. For the identification of this example, the 11 steps of the methodology presented in chapter 3 were applied. For future research, the following recommendations are made:

- In step 2 of this methodology, the uncertain key parameters were identified with the help of the clinic stakeholders. Future research could support this step by the definition of classes of changes in demand and boundary conditions that are relevant for the functioning of a building over the investigated time period. This definition should include the connection of main influence factors leading to theses changes and the definition of the effects on the functionality of the building, and, in that context, the definition of obsolescence types (compare table D.2 in appendix D).

- In the steps 3 to 5 of this methodology, appropriate stochastic models were built to represent the uncertain change of the two key parameters over the investigated time period. These models were based on assumptions. In a next step, based also on the classification of influence factors, changes in demand and effects in appendix E, suitable methods for the modelling of changes in demands based on the changes of connected influence factors should be identified and tested for application.

- In steps 6 and 7, the static and dynamic evaluation framework was defined to be used in the later evaluation. In this case, the calculation of benefits was solely described using monetary values (income and costs). Changes in demand, however, mainly concern the functionality of a building for the user and thus many aspects that are difficult to capture using monetary values, e.g. the comfort of patients, the efficiency of processes in the clinic. etc. Thus, the definition of benefit functions of non-monetary values would improve the results when they can be integrated with the benefits measured in monetary costs and benefits, but increase the complexity and decrease the understandability.

- In step 8 and 9, the possible renewal projects, i.e. the combination of decision flexibility for possible modification interventions over the investigated time period and increasing of design flexibility of the building facilitating these interventions, are identified. The collection and classifications of such interventions counteracting changes of demand and boundary conditions, and possible improvements in the flexible design of a building could support the decision maker in these steps.

7.4.2 Identification of eligible cases with significant advantages from the use of the method with consideration of decision flexibility compared to the Traditional Method without consideration of decision flexibility

The results of the simple and the real world example showed that the evaluation with the method with consideration of decision flexibility led to higher expected net benefits at t=0 and different intervention programs than with the Traditional Method without consideration of decision flexibility. The improvement, however, in the expected net benefits was below 1%, i.e. easily within the error margin of the input parameters. Such a difference does not justify the additional effort of the application of the method with consideration of decision flexibility compared to a traditional method without consideration of decision flexibility.

Further research should investigate the identification of cases where the difference between the results from the method with and the method without consideration of decision flexibility is significant enough to justify the additional effort. The test of eligible cases should take place already in early stages of the methodology for the identification and evaluation of intervention projects with consideration of decision flexibility, e.g. by the execution of a sensitivity analysis after step 7 of the methodology.

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Appendix A

Terminology

Term	**Explanation**	**Source**
Availability	The amount of time that infrastructure provides a specific level of service over a specified period of time taking into consideration the length of time that the infrastructure is not providing the specific service level due to the execution of interventions.	(Adey, 2015)
Benefits	Positive effect incurred by stakeholders. They are expressed in quantifiable units, e.g. monetary units.	(Adey, 2015)
Building	A structure with a roof and walls, to be used as a space for people to work, live and conduct other activities. Examples are houses, school, and hospitals. Buildings are one type of infrastructure.	-
Building flexibility	The ability of a [building] to be adapted to new demands	(de Neufville and Scholtes, 2011)
Building management	All processes and activities that are used to ensure that a building provides an adequate service level over a specified time period.	(Adey, 2015)
Building Manager	A person that is responsible for the integration of all processes and activities that are included in building management for an organisation.	(Adey, 2015)
Condition	Physical state a building or another infrastructure, their objects or a network is in.	(Adey, 2015)
Condition state	Describes the condition of a network, an object or component, e.g. functionality, load, physical condition, etc.	(Adey, 2015)
Constraint	Things that can prevent optimal service levels being provided. For example, available financial resources are a constraint.	(Adey, 2015)
Construction of intervention program	Process of determination and evaluation of the intervention programs to be used. Part of infrastructure management process.	-
Decision flexibility	The ability of a decision maker to postpone a decision to a later point in time when more information about the actual state of nature is available. In intervention management, this decision flexibility refers to postponing the decision about time and type of the intervention to be executed. This is also the flexibility of managerial decisions that relate to the whole system without necessarily altering the system itself.	(de Neufville and Scholtes, 2011)
Design flexibility	–> Building flexibility	-
Deterioration	Deterioration is the process of a building or its components going from one service level to a lower one due to environmental influences like moisture, loading etc. The building starts deteriorating from the initial service level.	(Adey, 2015)

Term	Explanation	Source
Flexible intervention program	Intervention program with consideration of decision flexibility	-
Inflexible intervention program	Intervention program without the consideration of decision flexibility opposed to –> Flexible intervention program	-
Infrastructure	Infrastructure consists of the fixed physical items used to ensure the functioning of a society, e.g. the bridges in a road network, the track in a rail network, the pipes in a water supply network or sewer network, the transformers in an energy distribution network, and the masts in telecommunication networks. Buildings are one type of infrastructure.	(Adey, 2015)
Infrastructure management	All processes and activities that are used to ensure that infrastructure provides an adequate level of service over a specified time period. –> Building management	(Adey, 2015)
Intervention	Any action or group of actions that is conducted to restore a building or one of its components to or keep it at a condition in which it can continue to, or can again, provide the present required level of service. This involves concrete interventions, e.g. paint a wall, replace a component of the air conditioning system or replace the built in components of a bathroom. Interventions are necessary to conduct maintenance or change on a building.	(Adey, 2015)
Intervention management system (IMS)	IMS are complete maintenance management systems that take into account all necessary components to produce an applicable strategy and programs for practice. IMS can, but do not have to, refer to software that supports intervention management.	(Adey, 2015)
Intervention program (IP)	A list of interventions to execute over a defined period of time, determined under consideration of the actual state of nature and the constraints over the investigated time period.	(Adey, 2015)
Intervention type	Includes all intervention categories of maintenance and modification	-
Intervention strategy	A list of interventions that should be executed on infrastructure depending on the state of the infrastructure.	(Adey, 2015)
Intervention and design project (IDP)	Combination of intervention programs with flexible decision making and and increase in building flexibility by design	-
Latent process	A latent process is one that happens in a way that there is not enough time to execute an intervention so as to ensure that the infrastructure continues to provide the required service level. opposed to –> manifest	(Adey, 2015)
Maintainability	A measure of the costs associated with the execution of interventions or the time required to execute interventions over a specified period of time.	(Adey, 2015)
Maintenance	Maintenance includes all interventions that is conducted to restore a building or one of its components to or keep it at a condition in which it can continue to, or can again, provide the initial level of service or any service level below it.	(Adey, 2015)
Maintenance area	The area in which maintenance interventions should or are to be executed.	(Adey, 2015)
Maintenance intervention	An intervention that changes the infrastructure but does not change the intended functionality of the infrastructure.	(Adey, 2015)

Term	**Explanation**	**Source**
Maintenance intervention program	A list of maintenance interventions to execute over a defined period of time. They are derived from the maintenance intervention strategies and the actual state of the infrastructure, and are developed taking into consideration service level goals and constraints.	(Adey, 2015)
Maintenance intervention strategy	A maintenance intervention strategy is a list of maintenance interventions that should be executed on infrastructure depending on the state of the infrastructure. The interventions are normally defined here at a more general level than in the maintenance intervention program.	(Adey, 2015)
Maintenance object	An object on which a maintenance intervention is planned or should be planned	(Adey, 2015)
Maintenance project	A project that includes objects that are to have maintenance interventions that are to be planned together. They do not have to be physically near to each other.	(Adey, 2015)
Manifest process	A manifest process is one that happens in a way that there is enough time to execute an intervention so as to ensure that the infrastructure continues to provide the required service level. opposed to –> latent process	(Adey, 2015)
Method	A procedure or process for attaining an object or a way, technique, or process of or for doing something	www.merriam-webster.com
Modification intervention	[Combination] of all technical, administrative and managerial actions intended to change one or more functions of an item.	(DIN, 2010)
Monitoring	All activities used to assess the state of infrastructure.	(Adey, 2015)
Network	All objects in a network with consideration of their relationship to each other.	(Adey, 2015)
Object	Objects and their relationships to each other make up the network. An object can be subdivided into components	(Adey, 2015)
Obsolescence	Obsolescence is the process of an item becoming obsolete. Obsolete is used in the sense of not fulfilling changed demands anymore. Obsolescence is the loss of ability of an item to perform satisfactorily due to changes in service requirements	(ISO 15686 1, p.1)
Organization	An organization is a body (i.e. a company, an institute or likewise) that is using a building and requires processes of building management to support its core business.	-
Predict	To predict is to state, on the basis of knowledge or reasoning, that an event will happen in the future	-
Process	A process is a chain of events that lead that requires actions from a stakeholder or other input and leads to a certain result. The result is not necessarily the desired outcome of the process.	(Adey, 2015)
Risk	Technical risk R is "the sum over the possible consequences multiplied by the corresponding probabilitiy of occurrence".	(Faber and Stewart, 2003)
Risk management	Process to mangage risk of any project according to ISO 31000 (compare section D.2). This process includes the steps (1) Establishing the context, (2) Risk assessment, (3) Risk treatment, (4) Monitoring and review, (5) Communication and consultation.	(International Organization for Standardization, 2009a)
Risk treatment	Risk treatment is an action, taken to reduce risk. Risk treatement is one step of risk managment. In the context of intervention management, actions for risk treatment are modification interventions or changes in building design.	-
Robustness	Design of a system in a way that all possible ranges or conservative estimates of all future considered parameters and requirements can be accommodated	-

Term	**Explanation**	**Source**
Scenario	A scenario is a chain of events or “a product that describes some possible future state and/or that tells the story about how such a state might come about”. In this thesis, the term scenario does not include decisions about interventions.	(Bishop et al., 2007, p.3)
Stakeholder	Person or a group of persons that is directly or indirectly affected by a project or a process.	(Adey, 2015)
Service Level	The service level of a building defines which needs the building and its components are required to fulfil at a certain point of time. The service level states in which condition the building should be according to the needs. These needs, and therefore the service level, can change over time. The building is not necessarily reaching the required service level.	-
Service level (actual)	The service level of a building or its component at a certain point in time.	-
Service level (changed)	The service level that takes into account raised needs for the building due to new laws for example but still refers to the same functionality as the initial service level.	-
Service level (inadequate)	The actual service level that does not meet the required service level.	-
Service level (minimum)	The service level, under which the actual service is not allowed to fall.	-
Service level (raised)	The service level that takes into account raised needs for the building due to new laws for example but still refers to the same functionality as the initial service level.	-
Service level (required)	The service level that a building or its component should meet if functioning completely as required.	-
Service level goals	A goal that describes how stakeholders should be affected.	(Adey, 2015)
Service level indicators	Measures used to evaluate the provided service level. They may be qualitative or quantitative. It should be clear how service level indicators are related to service levels.	(Adey, 2015)
State	A description of the physical state of the infrastructure. It includes the physical condition of the infrastructure, as well as, how the infrastructure is loaded.	(Adey, 2015)
State of nature	Describes the current situation at any time t, including required service level, actual service level, boundary conditions, etc.	-
Uncertainty	Uncertain development of key parameter, i.e. different outcomes are possible with a certain probability	-

Appendix B

Abbreviations

AO (ROM)	American option type (Real Option Method)
CNM	Clinic of nuclear medicine
CO	Change of operation
CT	Computertomograph
DA	Decision analysis
DTA	Decision tree analysis
EM	Evasive measure
ENB	Expected net benefits
EO (ROM)	European option type (Real Option Method)
FDG	A modified and radioactive labeled sugar
FTE	Full-time employee
GBM	Geometric Brownian Motion
IDP	Intervention and design project
IMS	Intervention managment system
IP	Intervention program
LCC	Life cycle costs
LOS	Level of service
MIP	Methodology for the identification and evaluation of intervention projects with consideration of decision and design flexibility
NUK	Building for nuclear medicine
OIP	Optimal intervention program
PET/CT	Combination of Positrone Emission Tomographie and CT
PET/MR	Combination of PET and Magnetic Resonance imaging
ROA	Real Option Analysis
ROM	Real Option Method
SPECT	Single-photon emission computed tomography
SPECT/CT	Combination of SPECT and CT
TM	Traditional Method
UP	Uncertain parameter
USZ	University hospital Zurich

Appendix C

Notation

General notation	
a^*	Optimal decision
$B_{i_{n_t}}$	Yearly net benefit at node n at t
C	Purchase cost for stock
$C_{\tau_{TM}}$	Intervention costs at time τ_{TM}
d	Discrete amount that the key parameter can decrease in each unit of time in the binomial lattice.
dt	An increment in time
dz	An increment of the standard Wiener process in dt that deviates around a mean of 0
D	Decision
E	Event E
F	Event F
G	Amount that is borrowed to create hedging portfolio in CCA
H	Value of the option to invest in a new plant (Explanation CCA)
$i_{n_t^\star,n_t}$	Path leading from node $n_t^\star$ to node n_t
I_{n_t}	Number of possible paths leading to node n in time t
ir	(Risk-free) interest rate
$I_{v,t}$	Variable yearly income (with operational costs staying the same)
Ix	Intervention
k	Mean-reverting factor
K	Possible combinations of interventions for evaluation with traditional method
λ	Mean arrival rate of an event
n_t	Node and position of node in lattice in t, counting starting at n=0 at the top node of lattice in t, for any node in t
$\bar{n}_t$	Node and position of node in lattice in t, if execution is beneficial, i.e. this does not necesserily include all nodes $\bar{n}$ in t (ROM)
$n_t^\star$	Node and position of node at the beginning of a path i in lattice in t, counting starting at n=0 at the top node of lattice in t
$N_{\tau_{TM}}$	Number of nodes with possible values at time τ_{TM}
N_t	Number of nodes with possible values at time t
p	Probability of the key parameter increases in one time unit.
$q_{i_{n_t}}$	Probability of path i_{n_t} to node n at t
$q_{i_{n_t^\star,n_t}}$	Probability of one particular path $i_{n_t^\star,n_t'}$, following a node $n_t^\star$ and leading to node n_t
q_{n_t}	Probability of node n_t
$q_{n_t^\star,n_t}$	Sum of probabilities of all paths $i_{n_t^\star,n_t}$, following a node $n_t^\star$ and leading to node n_t, i.e. the relative probability of node n_t to $n_t^\star$
$q_{n_t}^a$	Adjusted probability of node nt, excluding paths with earlier execution nodes
$q^c(I2\|I1)$	Conditional probability of intervention I2 on the execution of preceeding interventions I1

$q^{ex}_{\tau_{AO}}$	Total probability of execution of intervention in τ_{AO} for the American type of the Real Option Method. Sum of $q^{a}_{n_t}$ in τ_{AO}.
q^{ex}_{AO}	Overall probability of execution of intervention for the American type of the Real Option Method. Sum of all $q^{ex}_{\tau_{AO}}$.
$q^{ex}_{\tau_{EO}}$	Total probability of execution for τ_{EO} relative to t=0, i.e. sum of node probabilities of all execution nodes in τ_{EO}
q^{j}	Joint probabilities of execution of each subsequent intervention
$q^{j,ex}(I1, I2)$	Joint probability of execution of intervention I2 and the preceeding intervention I1
$q^{r}_{n^{\star}_t, n_t}$	Relative probability of an execution node to any of the execution nodes of preceeding interventions, $n^{\star}_t$
r	Discount rate (equals either the risk-free interest rate ir or the sum of the interest rate ir and the risk premium rp, depending on the case (see section D.4.3 for explanation))
R_0	The reference expected net benefits for the entire period $[0, T]$, i.e. for the case that no intervention is executed over the complete investigated time period.
$R^{+}_{n_t}$	Additional expected benefits from executing an intervention only at node n in time t, i.e. this includes all nodes in t (Traditional method).
$R^{+}_{\bar{n}_t}$	Additional expected benefits from executing an intervention only at the node $\bar{n}$, if execution is beneficial, i.e. this does not necesserily include all nodes n in t (RO method).
rp	Risk premium, added to interest rate to determine discount rate
S	Key parameter in general, can also be a stock price
σ	Variance of uncertain key parameter
t	Any time in $[0, T]$
T	Investigated time period (varied in sensitivity analysis of real world example).
τ	Particular time in $[0, T]$
τ_{AO}	The earliest time where the probability of execution is non-zero (for ROM AO)
τ_{DI}	End of decision time interval
τ_{EO}	The best time to decide about the execution (for ROM EO)
τ_{R}	Time for the calculation of $R_{n_{\tau_R}}$
τ_{TM}	Optimal planned time of execution with decision at time t=0
u	Discrete amount that the key parameter can increase in each unit of time in the binomial lattice.
UP	Specific uncertain key parameter, which can be modelled as S
R_0	Expected net benefits without any intervention at t=0
$R^{+}_{n_{\tau_{TM}}}$	Additional expected net benefits at node n at time τ_{TM} after execution of an intervention
R_0	Expected net benefits without any intervention at t=0
$N_{\tau_{TM}}$	Number of nodes with possible values at time τ_{TM}
$R^{+}_{n_{\tau_{TM}}}$	Additional expected net benefits at node n at time τ_{TM} after execution of an intervention
$X(\tau)$	Cumulative expected net present benefits for all yearly benefits with optimal decision about the execution of one or multiple interventions in .
$X^{+}_{\bar{n},down}$	Additional expected net benefits from executing an intervention in the time interval following t at the node with the decreasing value of S, and thus $R(down)$
$X^{+}_{\bar{n},up}$	Additional expected net benefits from executing an intervention in the time interval following t at the node with the increasing value of S, and thus $R(up)$

Real world example

$addnDS$	Number of additional diagnosis stations
$addRRw$	Number of additional separation walls for resting rooms
$addUP2$	No. of additional patients UP2 (varied in sensitivity analysis of real world example)
a_{M0}	Initial area of PET center before any interventions
$a_{M0,flex}$	Area of PET center after execution of all interventions

a_{M1}	Additional area for the PET center after intervention 1
a_{M2}	Additional area for the PET center after intervention 2
a_{M3}	Additional area for the PET center after intervention 3
a_{M4}	Additional area for the PET center after intervention 4
b_S	Capacity buffer for shifts that can be covered with the basic 1.5 teams without the need for an additional team
ΔB_t	Additional costs for treatment of patient over capacity in afternoon shifts
$C_{AR,el}$	Costs for additional electricity for application room
$C_{AR,r}$	Costs for additional space for application room
$C_{DS,ds}$	Costs for additional diagnosis station
$C_{DS,el}$	Costs for additional electricity for diagnosis stations
$C_{DS,r}$	Costs for additional space of one station
C_{Ix}	Intervention costs for interventions I1 to I4
$CPETCTd$	Retail price for one PET/CTs installed from the beginning
$C_{PET,el}$	Costs for expansion electrical installations
$CPETMRd/$ $C_{PET,MR,d}$	Costs for additional PET/MR (varied in sensitivity analysis of real world example)
$C_{PET,r}$	Costs for additional room
$C_{PET,rad}$	Costs for radiation protection in room
$C_{RR,el}$	Costs for costs for additional electricity for resting room
$C_{RR,r}$	Costs for additional space for resting room
$C_{RR,w}$	Costs per additional separation walls for resting room
$C_{\tau_{DI}}$	Costs for the execution of an intervention at τ_{DI}
C_Z	Fixed costs for one tracer production in the radiopharmacy
$delta_{TC}$	Increase in variable costs for treatment above capacity on PET/CT (varied in sensitivity analysis of real world example)
dMx	Difference in capacity thresholds (varied in sensitivity analysis of real world example)
$fdeltaUP2$	Reduction in patient no. when send to Wagi (varied in sensitivity analysis of real world example)
$f_{maintMRCT}$	Yearly maintenance costs for PET/MR and PET/CT in percent of retail price
$f_{\Delta P_{t,UP2}}$	Possible reduction in patient numbers if patients have to be sent to the Wagi-Areal
$f_{\Delta P_{t,UP2}}$	Reduction factor for patient numbers that have to be send to the Wagi-Areal
$f_{replMRCT}$	Yearly ratio of retail price for PET/MR or PET/CT over time span of 10 years, thus considering the replacement every 10 years (s. text below)
$I_{n_{t+1}},$	No. of nodes "following" node n at time $t+1$
$I_{v,t}$	Variable income per treated patient
Ix	Intervention
ΔM_x	Capacity threshold of PET center corresponding to executed interventions
N_d	Number of patients per shift that lead to the need for additional shifts
$N_M R$	Number of additional PET/MRs
$NoPET$	Number of existing PET/CTs in the PET center
NoS	Number of regular shifts in the morning per year
$NoTeam$	Number of necessary teams for the regular morning shifts
$ofmtrayear$	Fixed costs per team per year (varied in sensitivity analysis of real world example)
$ofrentDiff$	Difference in rent for highly specialised and normal area use (varied in sensitivity analysis of real world example)
$O_{f,t}$	Fixed operational costs (independent from actual number of patients)
$O_{v,a}$	Variable costs for administration
$O_{v,cool}$	Variable costs for cooling
$O_{v,el}$	Variable costs for electricity
$O_{v,m}$	Variable costs for other material
$O_{v,t}$	Variable operational costs per patient
$O_{f,a}$	Fixed costs for administration of the clinic

$o_{f,c}$	Fixed costs for cleaning
$O_{f,cool}$	Fixed costs for cooling
$O_{f,el}$	Fixed costs for electricity
$o_{f,heat}$	Fixed costs for heating
$o_{f,mtra,shift}$	Fixed costs for medical team for additional afternoon shift
$O_{f,mtra}$	Fixed costs of the medical team
$o_{f,rent}$	Fixed costs for rent for “hard” use of any area in the clinic
$O_{f,rent,FlexInit}$	Fixed costs for rent of used area, including the expansion area for PET/MR
$O_{f,rent,NoInit}$	Fixed costs for rent of used area, not including the expansion are for the PET/MR
$o_{f,rent,soft,as}$	Fixed costs for “soft” use of expansion area for M1
$O_{f,repl,CT}$	Fixed costs for replacement and maintenance existing PET/CTs
$O_{f,rp}$	Fixed costs for the tracer production in the radiopharmacy
$\Delta O_{f,c,M1}$	Additional fix costs for cleaning
$\Delta O_{f,c,M2}$	Additional fix costs for cleaning
$\Delta O_{f,c,M3}$	Additional fix costs for cleaning
$\Delta O_{f,c,M4}$	Additional fix costs for cleaning
$\Delta O_{f,cool,M1}$	Additional fix costs for cooling
$\Delta O_{f,cool,M4}$	Additional fix costs for cooling
$\Delta O_{f,el,M1}$	Additional fix costs for electricity
$\Delta O_{f,el,M2}$	Additional fix costs for electricity
$\Delta O_{f,el,M3}$	Additional fix costs for electricity
$\Delta O_{f,el,M4}$	Additional fix costs for electricity
$\Delta O_{f,heat,M2}$	Additional fix costs for heating
$\Delta O_{f,heat,M3}$	Additional fix costs for heating
$\Delta O_{f,rent,M1}$	Additional fix costs for rent
$\Delta O_{f,rent,M2}$	Additional fix costs for rent
$\Delta O_{f,rent,M3}$	Additional fix costs for rent
$\Delta O_{f,rent,M4}$	Additional fix costs for rent
$\Delta O_{f,repl,MR}$	Additional fix costs for retail (every 10 years) and maintenance of PET/MR
$\overline{P}_{log}$	Natural log of the mean of the patient numbers
$p_{n_{t+1},i}$	Probability of one node "following" node n at time $t+1$
P_t	Number of treated patients
$P_{log,t}$	Natural log of the current value of the patient numbers at an upward node in t
$P^{+}_{log,t,UP1}$	Natural log of up movement of patient number
$P^{-}_{log,t,UP1}$	Natural log of down movement of patient number
$P_{t,UP1}$	Number of patients for existing application for cancer localisation in year t
$p_{t,UP1}$	Probability of up movement of UP1
$p_{t,UP2}$	Probability of introduction of application in the years t=2, 4, 6 and 8 (with the probability decreasing by 0.1 in each time step)
$P^{+}_{t,UP2}$	Additional number of patients after introduction of application
$P^{-}_{t,UP2}$	Additional number of patients before introduction of application
$P_{t,UP2}$	Number of patients for pre-screening for Alzheimer’s in year t
$pUP2$	Initial probability of introduction of Alzheimer screening (varied in sensitivity analysis of real world example)
$R^{+}_{n_t,Ix}$	Additional expected net benefits from the execution of interventions I1 to I4
$R^{+}_{n_{\tau_{DI}}}$	Additional expected net benefits at node n at time τ_{DI} after execution of intervention
ΔTC	Additional variable costs for additional afternoon shifts
$X_{n_t,Ix}$	Expected net benefits of optimal decision about execution of interventions I1 to I4
$X_{n_{t+1},Ix,i}$	Expected net benefits of optimal decision about execution of interventions at nodes following node n in $t+1$ for NOT EXECUTING intervention Ix at node n in t

Appendix D

Background

In this appendix, the basic definitions in building management and especially the determination of intervention programs for buildings are stated to put the content of this thesis in the right context. First, the basics of building management of buildings will be defined, especially the terms intervention strategy and intervention program. Second, the terms risk and uncertainty will be specified, and the content of this work will be positioned with regard to these terms. The definition of flexibility in the context of intervention programs will be elaborated, and its relevance will be explained. Finally, general attributes of methods and models that can be used in the evaluation of flexible intervention programs will be presented.

D.1 Basic definitions

D.1.1 Buildings

A building is herein defined as a structure with a roof and walls, to be used as a space for people to work, live and conduct other activities. Examples are houses, schools, and hospitals. Buildings are one type of infrastructure objects, other objects being bridges, roads, water networks etc.. Infrastructure consists of the fixed physical items used to ensure the functioning of a society, e.g. the bridges in a road network, the track in a rail network, the pipes in a water supply network or sewer network, the transformers in an energy distribution network, and the masts in telecommunication networks[1] (Adey, 2015).

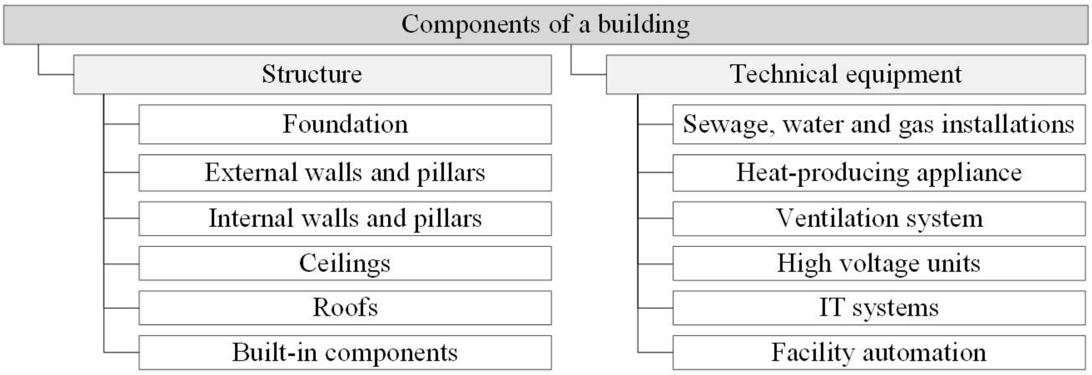

Figure D.1: Components of a building (selection based on (DIN, 2006))

Figure D.1 shows the main components of a building, even though this selection is not necessarily complete and not all buildings have all shown components. Generally, a building consists of the structure and the technical equipment. The combined function of all components

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[1] Herein, the hierarchy between network, object and component is defined as follows: A network consists of multiple connected objects, an objects consists of multiple components.

of a building is necessary for this building to function as required; all of these components are subject to deterioration processes and changes in demand.

D.1.2 Building management

The general parts of the life cycle of a building and other infrastructure, as they are understood in this text, are shown in figure D.2. After its construction, a building or infrastructure is used, operated, modified and maintained, as long as it is needed. When it is not needed anymore, it is demolished. The maintenance and modification of buildings and other infrastructure are two important parts in the life-cycle in its life cycle.

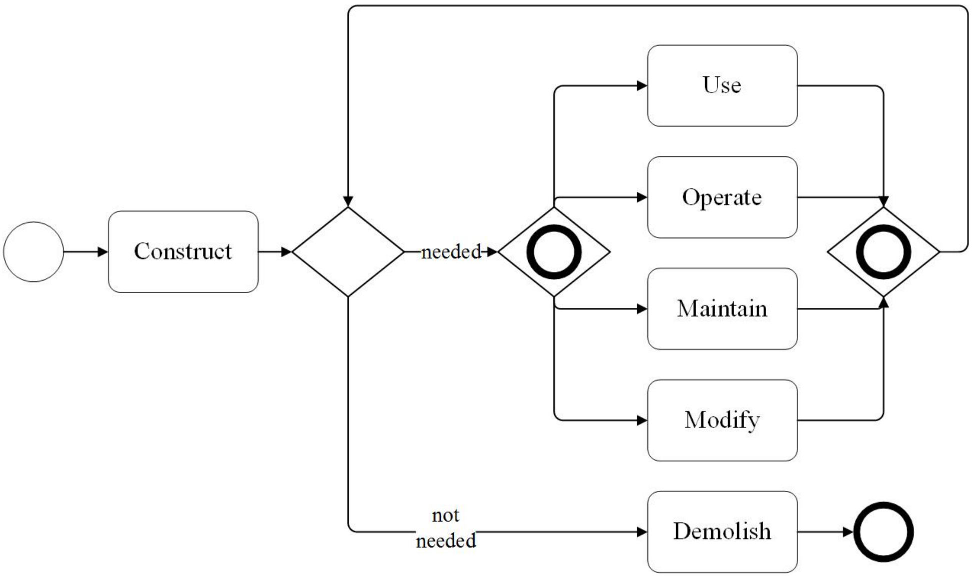

Figure D.2: The life cycle of buildings and other infrastructure (Adey, 2015)

The management process shown in figure D.3 describes the basic steps that a building or infrastructure manager should follow to ensure that the appropriate maintenance and modification interventions are constructed, planned and executed over a defined period of time, to ensure that a building or other infrastructure object functions as required. This process will be referred to as building management process, while it is understood that it can be applied to any other type of infrastructure, i.e. is in fact an infrastructure management process.

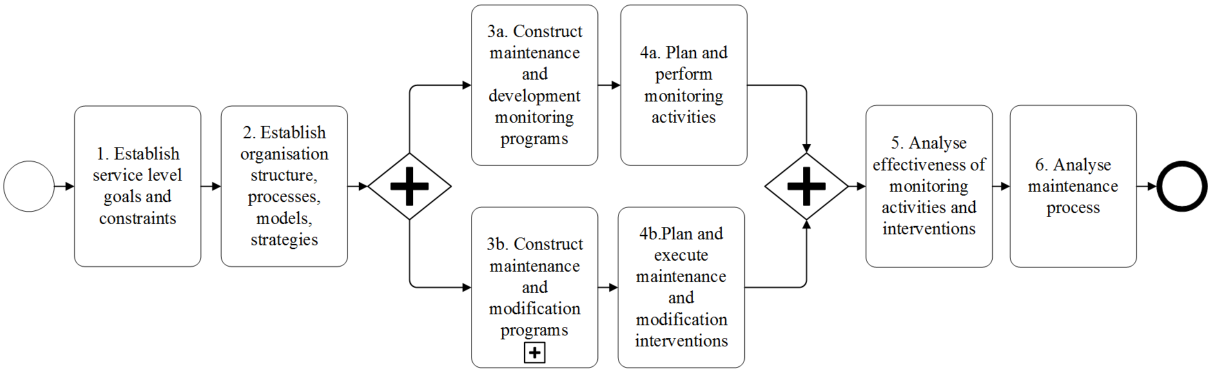

Figure D.3: Building management process (Adey, 2015)

In the construction of intervention programs, all relevant stakeholders of a building need to be considered. A overview of the main building stakeholders is provided in table D.1.2.

Table D.1: Stakeholders in building management (based on (Adey, 2015))

Stakeholders	Definition	Examples
Owner	Persons who are responsible for decisions with respect to physically modifying the building	A federal canton (e.g. Zurich), a bank, a private investor.
Users	Persons who are using the building	A person living and working in the building, any person entering the building.
Directly affected public	Persons who are in the vicinity of the building but are not using it	Persons living in a house next to the building, who are affected by noises from interventions on the building.
Indirectly affected public	Persons who are not in the vicinity of the building but are affected by its use	Persons in a house far away from the building that do not hear the intervention noises, but are affected by the resource consumption of the building, e.g. the electricity that has to be produced elsewhere.

D.1.3 Establish service level

Before a building manager can undertake the necessary steps of constructing, planning and executing intervention programs, the required service level goals and constraints (Step 1 in figure D.3) have to be defined thoroughly. Only if the goals and the constraints are known, the building management can lead to the required functioning of the building. Service levels support the definition of these goals and constraints. The service level of a building defines which needs the building and its components are required to fulfill at a certain point of time.

Service level indicators support the building manager and the stakeholders in the definition of goals and constraints. In intervention planning, goals for optimization with regard to service level indicators can be defined in different categories. Hudson et al. (1997) suggest the economic effectiveness, the technical effectiveness, aesthetic effectiveness, public, user or owner satisfaction and/or the environmental impact. For infrastructure, four common service level indicators are reliability, availability, maintainability and safety.

Apart from these indicators, it is often the goal in decision making to minimize the life-cycle costs (LCC) or maximize the expected net benefit (ENB) from operation of the building. Depending on the system, the costs can include owner costs, user costs and public costs as e.g. Mirzaei and Adey (2015); Adey et al. (2012) define it. A vast number of literature has been focused on types of life cycle cost analysis such as benefit-cost or discounted cash flow analysis (Frangopol et al., 2008; Woodward, 1997). In principle, the benefit-cost ratio or the discounted cash flow of a project or an intervention program results in a value that is then compared against that of other projects or intervention programs. The one yielding the lowest costs, bringing the highest benefits, or having the highest benefit-cost ratio are considered as optimal. This comparison is also possible for the service levels mentioned above, e.g. reliability and availability.

D.1.4 Processes leading to inadequate service level - deterioration and changes in demand

One task of the building manager is to ensure that the building and its components function as required. If the actual service level of the building does not meet the required service levels of the building, the building manager has to intervene to bring the building to the required service level. Such interventions become necessary due to two reasons:

- Deterioration processes that cause a change of the ability of the building and its components to meet the required service level.

- Change of demands on the building that cause a change of the required service level on the building

Figure D.4 shows the general course of the service level of a building over time. For a building, one would rather speak about a group of critical service levels, as a building is composed of many components that need to act together to enable the building to fulfil its function. Expressed in a simplified way, a building starts its lifetime after completion of the construction, when its actual service level complies with the required initial service level. From then on, the difference between the actual service level of the building and the required service level normally increases over time.

Deterioration processes lead to a decrease of the service level of the building and its components from the initial service level. Examples for deterioration processes are chemical deterioration of stone by acid rain, electrolytic corrosion of metal by rust or biological corrosion of wood by bacteria.

The change of demands on the building normally leads to a raised required service level, either with the initial functionality of the building and its components, for example the demand of lower energy consumption for heating, or even a changed required service level with a new functionality, for example the change of an office building into a residential building.

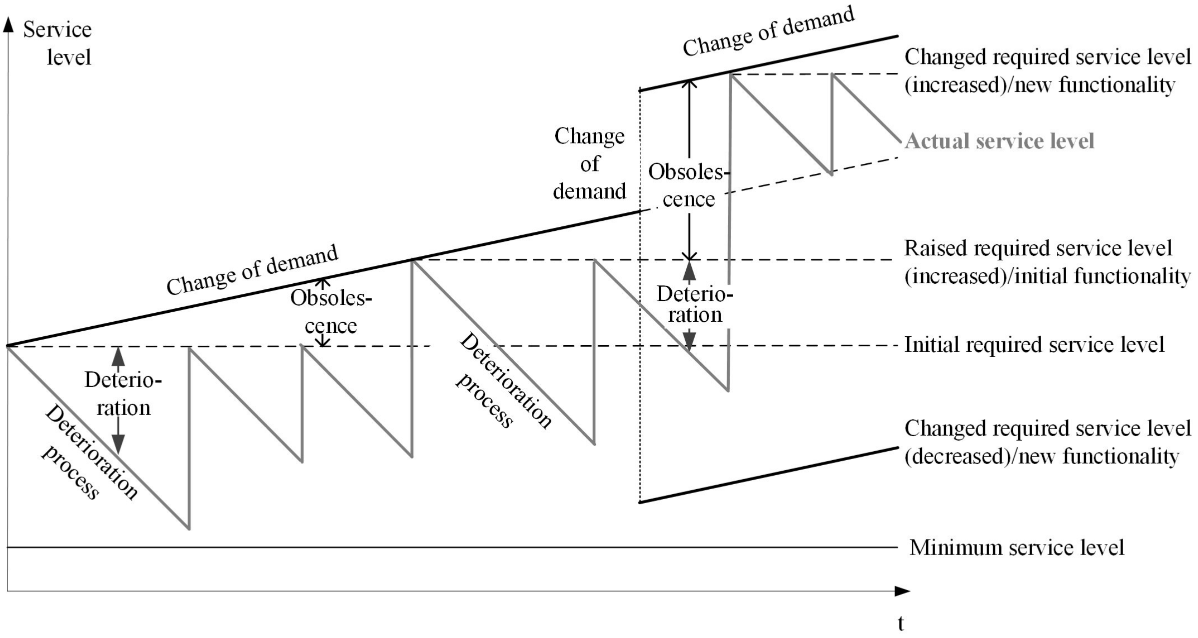

Figure D.4: Deterioration and change of demand and the effect on service level over time (based on (Douglas, 2006; Jones and Sharp, 2007; EN, 2006))

Both deterioration processes and changes in demand lead to an inadequate service level, through the effects of deterioration and obsolescence respectively, i.e. the inadequate service level can result from the effects of deterioration processes and changes of demand on the system, in this case the building. Both deterioration and changes in demand are subject to influence factors, tangible and abstract. A distinction between the processes leading to an inadequate service level, their effects on a building and its components, and influence factors on these processes, is necessary (1) to describe the actual condition of the building and its components, and thus its inadequate service level, clearly stating if it is caused by either deterioration processes or changes of demand, and (2) to analyse and understand the causal relations better and build reliable models of influence factors, processes and effects. The connection of influence factors, processes and effects leading to inadequate service level are illustrated in figure D.5.

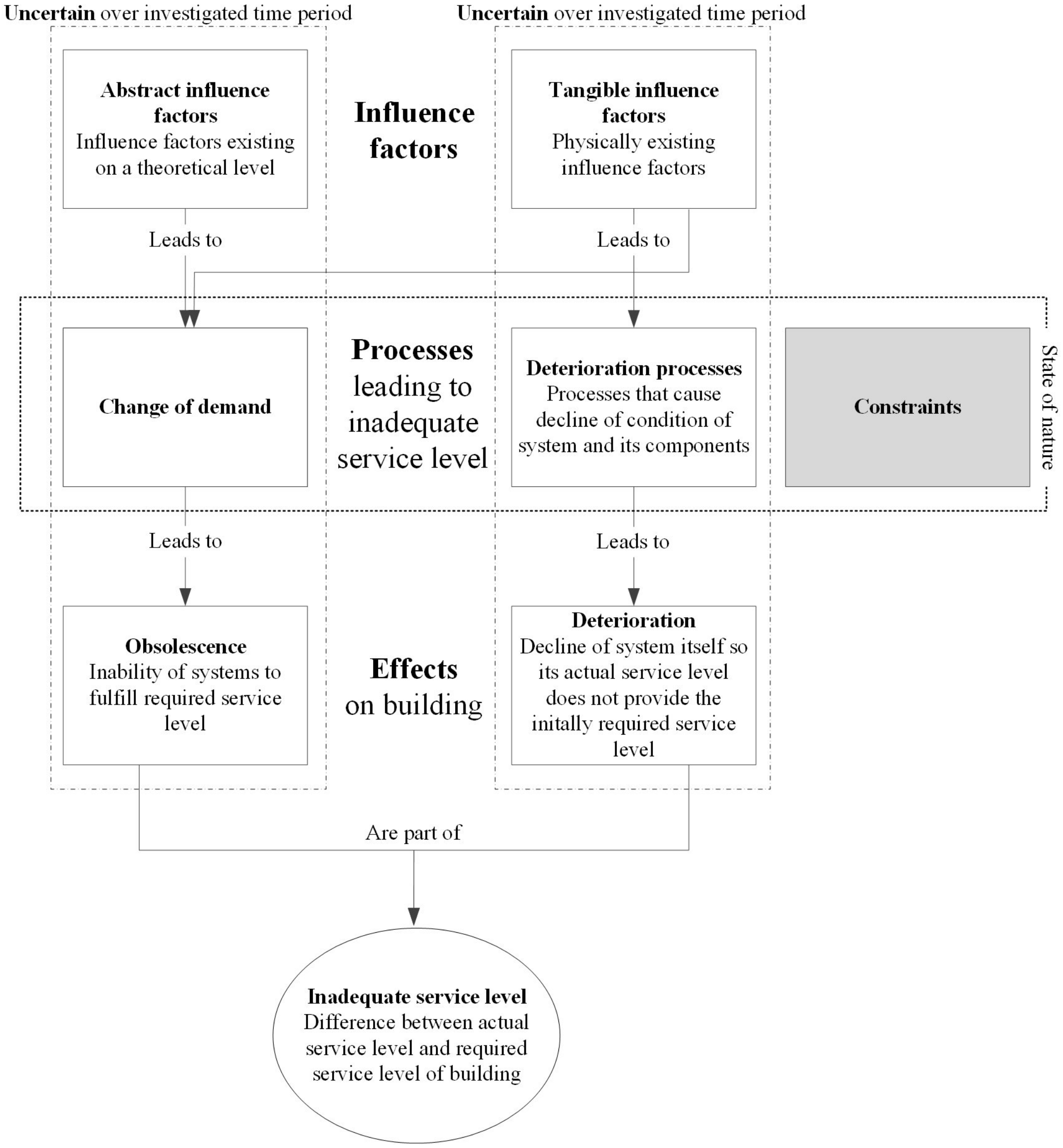

Figure D.5: Processes leading to inadequate service level, influence factors and effects

The effect of deterioration processes is deterioration of the building, i.e. a building is deteriorated if it loses the ability to meet the required service level due to physical decline of its components. To describe the effect of changes of demand, the term of obsolescence is widely suggested in the context of building management. In the international standard ISO 15686 obsolescence is defined as the "loss of ability of an item to perform satisfactorily due to changes in [the required service level]" (International Organization for Standardization, 2008, p.9). The influence factors can be divided into tangible influence factors, i.e. factors that physically exist, like temperature, loading, or chemical attack, and abstract influence factors, i.e. factors that exist on a theoretical level, like demographic change, personal preferences, or price changes. While deterioration processes are only subject to tangible influence factors, changes of demand are affected by both abstract and tangible influence factors. A collection of examples for influence factors on changes in demand are given in appendix E.

D.1.4.1 Deterioration processes, influence factors and effects

Deterioration encompasses a wide field of physical decline of a building and its components due to physical processes. The manifestations of deterioration, i.e. the causes and effects, depend on the material of the component. The main material groups that are affected by deterioration processes are metal, reinforced concrete, masonry, timber, synthetic materials and composites. The components of a building do often not only constitute of one material, but are more often constructed of many different materials. Deterioration of building components does not necessarily occur in the material of a component itself but more often in the joints between the elements of different material of the components. Deterioration processes can be subdivided in manifest and latent processes. There are manifest processes like corrosion of metal components, cracking of pavement or spalling of brickwork, that occur gradually and thus can be observed and counteracted on. On the other hand, there are latent processes, that consist of damage through unexpected events like exceptional loading by floods, landslides or heavy vehicles, and that occur suddenly so that detection might be too late (Fernando et al., 2015). One can see that especially latent processes are subject to uncertainties, similar to changes of demand. Deterioration processes, their effects and the corresponding influence factors have been vastly analysed, described, modelled and used in infrastructure management. The interested reader can find more detailed elaborations of the analysis and description of deterioration of buildings and their components, in e.g. (Chew, 2010; e.V. , BAKA; Moncmanová, 2007; Alexander and Thomas, 2015; Baum and McElhinney, 2000).

D.1.4.2 Changes of demand, influence factors and effects

Changes of demand play an important role in the lifetime of a building. Their effect can be the obsolescence of a building, i.e. the inability of the building to satisfy these changing demands and thus the required service level of the building. The effect of demand changes on the service level of a building is significant. Aikivuori (1994), for example, suggest that obsolescence is responsible for about 25 % of all refurbishments in buildings and for about 50 % of demolitions of buildings and infrastructure. Pinder and Wilkinson (2001) state that obsolescence is important concerning office properties, because many of these buildings were modified due to obsolescence, long before the end of their intended life time. Butt et al. (2010) predict that climate change and its impacts will lead to obsolescence in built environment constructed today.

A selection of changes in demand and their effects, i.e. obsolescence types, are shown in appendix E in tables E.1 to E.7. Changes in demand and obsolescence types are grouped in this thesis into the categories function, environment, economy, health and comfort/social, technology, legal, aesthetic, and location[2]. These categories correspond to the different types of obsolescence, i.e. the effect of changes in demand, which are based on categories used in (Douglas, 2006; Sarja et al., 2006; Reed and Warren-Myers, 2010). Changes of demand occur due to abstract and tangible influence factors, which are very general and can lead to multiple changes in demand. Two influence factors can also influence each other. The influence factors are grouped in the categories of demographic, lifestyle changes, environmental, innovation, political and economic influence factors. Table E.8 to E.9 in appendix E show a selection of influence factors with examples.

Which influence factors, changes in demand and effects are relevant to model the change in the required service levels, and how they are connected, depends on the specific case that is considered. Table D.2 shows simple examples for influence factors leading to changes of demand, the resulting obsolescence types and examples for changes in the required service levels (depending on the goals of the decision maker) together with illustrative examples. Changes in demand in this context include all key parameters that lead to the choice of different optimal intervention programs, i.e. all factors that (1) lead to a change of boundary conditions of the optimisation or (2) different goals of optimization or (3) introduce new candidate solutions.

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[2] These demand categories correspond to a large ratio with the criteria for sustainable buildings, e.g. the criteria presented in the Swiss standard for sustainable construction, SIA 112/1. This places this work in the context of the sustainability of the existing building stock.

Table D.2: Examples for changes of demand, influence factors and effects

Influence factor	**Change of demand**	**Effect (Obsolescence)**	**Change in required service level**
Category: *Demographics* Increasing demand for comfort in residential building	Demand for more spacious rooms in apartments	Category: *Social obsolescence* Rooms sizes are not sufficient anymore	Higher user satisfaction: Increase room sizes
Category: *Lifestyle changes* New working habits in offices	Demand for open office space	Category: *Functional obsolescence* Room layout is not suitable for open office space	Higher user satisfaction: Increase size of open office space
Category: *Environmental* Resource depletion	Demand for lower energy use	Category: *Environmental obsolescence* Energy efficiency is too low	Lower environmental impact: Decrease of maximum heat transmission coefficient in national standards
Category: *Innovation* Development of new building components	Demand for lower maintenance effort	Category: *Economical obsolescence* Maintenance effort is too high	Lower life-cycle costs: Decrease of yearly maintenance costs and time

D.1.5 Intervention categories

The aim of the building manager is to counteract the effects of deterioration processes and changes of demands. There are many possible interventions, ranging from painting a wall to replacing or tearing down the complete building. The concrete actions necessary for an intervention are well-established in literature and practice (e.g. in (Chew, 2010; Moncmanová, 2007)).

On a higher level, the definitions of the Swiss standard SIA 469 "Preservation of buildings"(Swiss Association of Engineers and Architects, 1997) for intervention categories are used: Maintenance interventions restore the building and its components to a condition where it fulfils the initial required service level. Maintenance interventions counteract the effect of deterioration processes, i.e. deterioration. Modification interventions on the other hand refer to interventions that bring the building and its components to a new required service level. Modification interventions are necessary to counteract the effect of changes in demand, i.e. obsolescence, but often counteract the effect of deterioration at the same time. Figure D.6 shows the main intervention categories maintenance and modification as to their effect to the actual service level of the building to establish a terminology that is used throughout this dissertation.

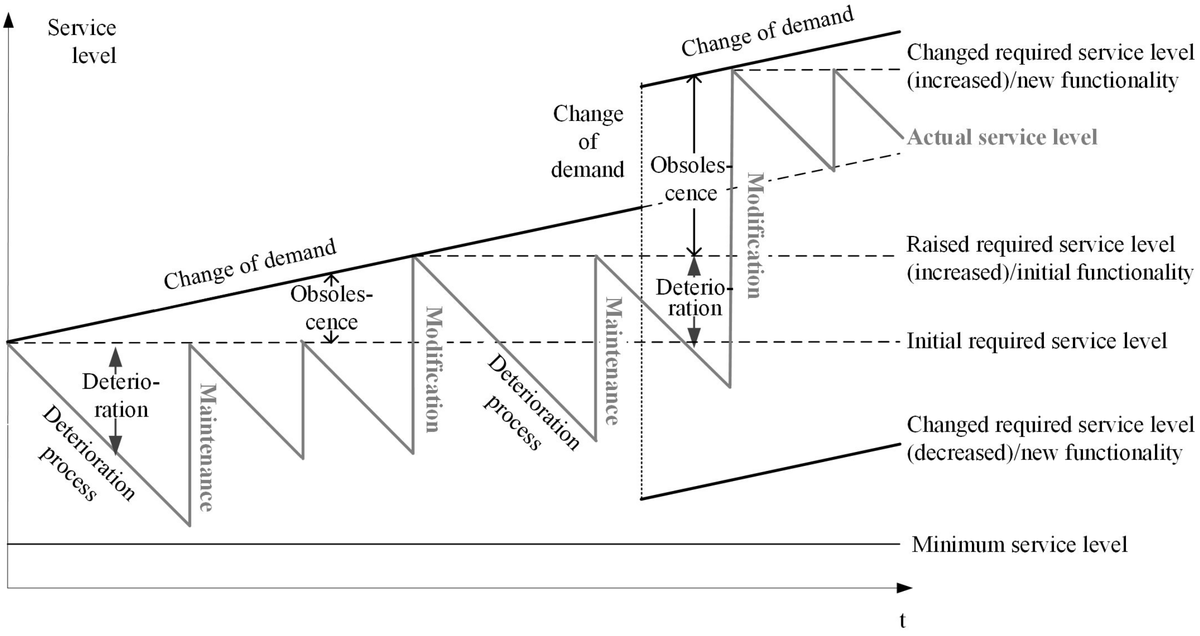

Figure D.6: Intervention categories in service level of a building (based on (EN, 2006; Douglas, 2006; Jones and Sharp, 2007))

D.1.6 Basic concepts of methods supporting determination of intervention programs

This thesis focuses on the determination of intervention programs, i.e. step 3b “Construction of intervention programs” of the infrastructure management process in figure D.3 in section D.1.2, in greater detail. An intervention program is herein defined as a list of interventions that are to be executed over the investigated time period. Intervention strategies are determined as a basis for intervention programs.

D.1.6.1 Intervention strategies

Intervention strategies are defined on building component level, without consideration of the actual state of nature, but for many possible states. Also, for intervention strategies, external constraints, e.g. through other buildings in the same network, are not considered. A maintenance intervention strategy defines the interventions that are necessary to bring a component to the initially required service level, e.g. by defining the appropriate intervention on a floor cover when the original colour of the floor cover has altered noticeably through constant wear; a modification intervention strategy defines the interventions that are necessary to bring a component to a changed required service level, e.g. by defining the appropriate intervention on the windows when the original windows do not comply with the required heat transmission coefficients anymore (example figure D.7).

The determination and evaluation of intervention strategies requires the consideration of the effects of an intervention on both the present and the future condition of a component. It also involves the estimation of the costs and other impacts on the long-term net benefit from the building, caused by the intervention costs, the disruption from their execution, the effects on future service levels, i.e. the probability of the building functioning as required or not (Adey, 2015). The determination of a feasible set, and also a manageable number for evaluation, of intervention strategies requires expert knowledge with thorough knowledge of, for instance, the components function in the overall system, material properties and interactions with other components (Adey, 2015). Examples for evaluation models for intervention strategies for building and infrastructure maintenance can be found in (Lethanh et al., 2015; Allehaux and Tessier, 2002; Lethanh and Adey, 2014b; Boyles et al., 2010; Asadi et al., 2012). An intervention

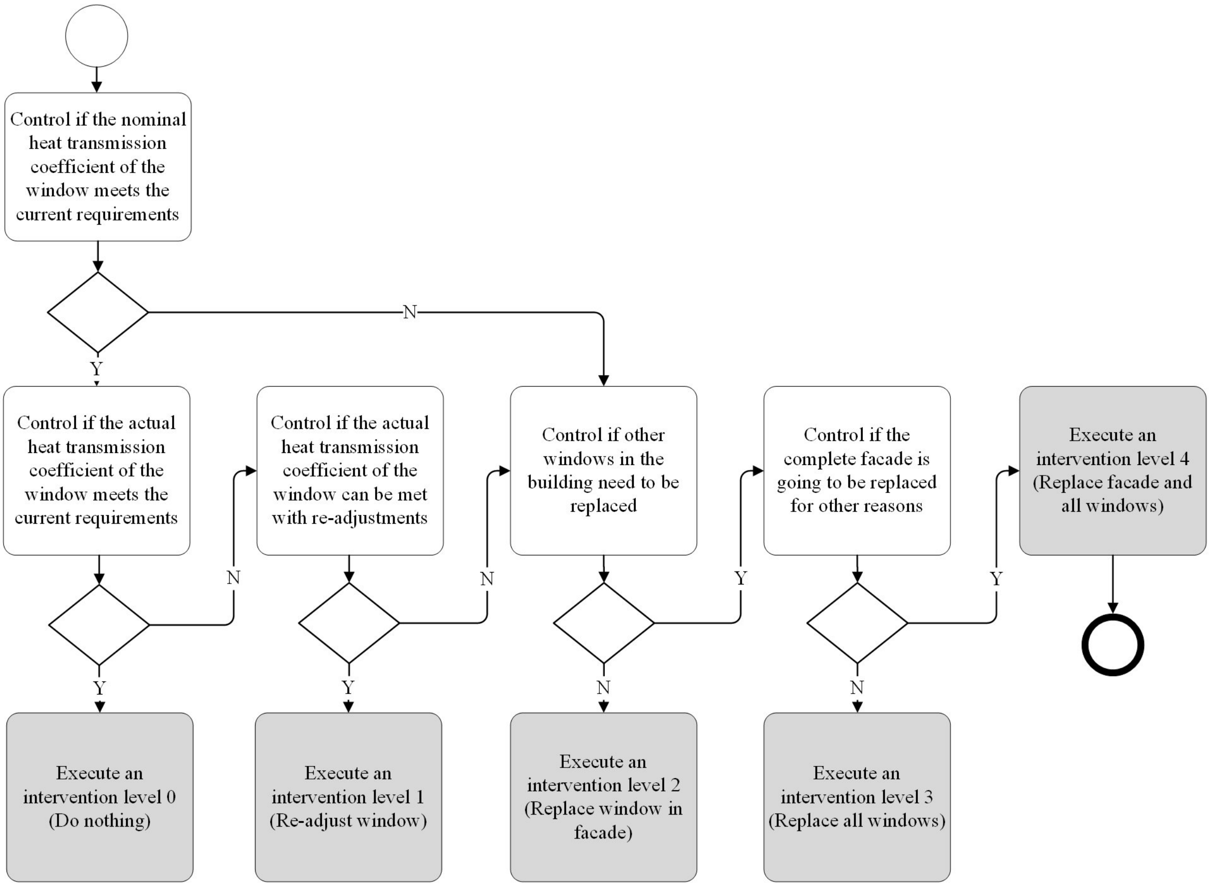

Figure D.7: Example for a modification intervention strategy

strategy supports a building manager in his decision making in future points in time, when the actual state of nature, i.e. the service level provided by a building, the required service level and constraints, can be observed, by providing recommendation in the form of conditional statements. It does not, however, give the decision maker any indication on which of the possible interventions will be executed over the investigated time period, nor at what time.

D.1.6.2 Intervention programs

It can be desirable to determine intervention programs for an investigated time period, i.e. to determine the list of interventions that should actually be executed and their timing over the investigated time period. This knowledge of future interventions to be executed is necessary to ensure that interventions executed today or in the near future, i.e. over the next 2 to 5 years, are optimal with regard to the interventions over a longer time period of 20 years or more. If for example, the decision maker can decide today about a short-term maintenance intervention program for a building facade over the next 5 years, and can decide between a costly maintenance intervention program 1, keeping the facade in a very good condition, or a low-cost maintenance intervention program 2, leading to a constant decrease of the façade's condition, it might be necessary to know the long-term intervention program. If a replacement of the facade is scheduled in the long-term intervention program in year 6, the low-cost intervention program 2 might be sufficient. If, however, a replacement of the facade is only scheduled in 20 years, the costly intervention program 2 might be more beneficial. An example for an intervention program is given in table D.3.

The intervention program to be executed is often based on an intervention strategy and the actual state of nature, under consideration of the required service level and constraints (Adey, 2015). Intervention strategies can support the decision maker in the determination of a possible set of candidate intervention programs, of which the optimal one is chosen.

Table D.3: Example intervention program

Component	**Year of intervention**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Windows (W)	Do nothing	Clean	Do nothing	Clean	Do nothing	Do nothing	Clean
Insulation (I)	Do nothing	Do nothing	Paint	Do nothing	Do nothing	Do nothing	Do nothing
Complete facade (W + I)	Do nothing	Do nothing	Do nothing	Do nothing	Do nothing	Replace	Do nothing

D.1.6.3 Decision making in the construction of intervention programs

In any decision problem, and thus also in making decisions about which intervention program to chose, three components are necessary: (1) The state of nature[3] (including constraints), (2) the sets of candidate solutions, and (3) the utility function defining the goal of the decision. These components translate, in the decision making about the desirable intervention program, into

1. models for predictions of service level (both actual and required) and applicable constraints,
2. set of candidate intervention programs, and
3. the objective function defining the optimal intervention program.

The objective function represents a decision maker's preferences regarding the candidate solutions under the actual state of nature. If the rationality of decision making is given, the optimal decision a^* is the one that maximizes the level of service (LOS)(a,c(· ,a)); i.e.a^*= argmax a∈A LOS(a,c(· ,a)). The decision alternatives are subject to constraints defined by the state of nature, and the maximization of the service level has to be done within these constraints. In this thesis, this assumption of rational decision making are taken as a basis of the decision to be made, even if in reality, individuals might not follow these assumptions. The objective function in this context of the determination of intervention programs describes the optimization of the chosen service level, with examples discussed in chapter D.1.3.

D.1.6.4 Models for predictions of required and actual service levels and constraints

Many models can be used for prediction of the relevant state of nature in the determination of intervention programs over the investigated time period, i.e. the required and actual service level, and relevant constraints. Distinction has to be made between gradual and sudden processes. Manifest processes describe changes in the state of nature over a longer time period so that there is enough time to react, e.g. by executing an intervention to reduce the consequences of the change for the service level. An example for a manifest process is the deterioration of a wooden facade due to exposure to humidity and temperature changes. Typical models for the prediction of manifest processes are mechanistic-empirical models, regression models, Markov models, neural network models, and Bayesian networks. Sudden processes describe changes in the state of nature in a very short time period so that there is not enough time to react, e.g. by executing an intervention. An example for a latent process is the failure of a wooden beam due to excessive loading. Typical models for the prediction of latent processes are event trees and fault trees. Depending on the modelled process and the intended use of the model, changes can be modelled continuously or in discrete steps (Adey, 2015). Latent processes will often be modelled with discrete steps.

Models for changes in the state of nature over an investigated time period can be deterministic or probabilistic, both with advantages and disadvantages. With deterministic models,

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[3] In the context of the determination of intervention programs, the expression "state of nature" will be used for the state of all relevant factors that are subject to change, such as the actual service level, the required service level of a building and its components, and all other relevant constraints and factors.

the impression is given that the state of nature is known with certainty at every time t over the investigated time period. These models give very precise, but most likely not very accurate predictions. Examples for such models are mechanistic models, empirical models, and mechanistic-empirical models. With probabilistic models, the probabilities for each state of nature at every time t are given. These models result in less precise predictions than deterministic models but may be more accurate. Examples are regression models and Markovian models (Adey, 2015). Models for latent processes and changes in demand are often probabilistic rather than deterministic, as they are often subject to uncertainty.

D.1.6.5 Methods for the construction of intervention programs

There are different methods for the construction of optimal intervention programs when the set of possible interventions or intervention strategies, the constraints and the models for prediction of the state of nature are established. These methods can be applied for both the generation of candidate programs and their analysis, evaluation and optimization, combining components 2 and 3 of the general decision making steps described in section D.1.6.3. The used methods can be divided in the following general groups: (1) Mathematical programming and (2) Heuristic methods.

Mathematical programming delivers exact solutions for an optimization problem and include e.g. linear and non-linear programming and dynamic programming methods. Mathematical programming includes a number of methods used to solve decision-making problems, for which an objective function and set of constraints can be represented in mathematical form. Both the objective functions and the constraints are formulated with decision variables and fixed parameters (see e.g. (de Neufville, 1990; Sinha, 2006)).

Heuristic methods are very common in the actual practice of intervention planning, especially for large and complex problems. Heuristic methods do not necessarily deliver optimal intervention programs, as the set of candidate intervention programs is, for example, determined through expert opinion, and not necessarily complete. Heuristic methods for the analysis and evaluation of candidate programs can be supported, opposed to solely being based on expert opinion, by systematic methods such as incremental benefit-cost analysis, genetic algorithms and artificial neural networks (Sivanandam and Deepa, 2008; Mohamed et al., 1995; Adeli, 2001; Revelle and Whitlach, 1996).

D.1.6.6 Constraints on intervention programs due to other building components and other buildings in the network

The focus in this work lies on the determination of intervention programs for building components, and does not consider a complete building or a building network. The determination of intervention programs for building components has to be done under the consideration of external constraints by the building and the building network, such as the interventions on other building components and even other buildings in the building network, other types of infrastructure, and budget or time constraints for the building or its network. The consideration of external constraints leads to other optimal intervention programs than would be considered optimal if only the single building component without the constraints would be considered. The optimal intervention program for the independent building component might be altered due to its position as part of a building or a building network, e.g. if a building component is not scheduled for a maintenance intervention but on a network level, an intervention is required that affects this component, an intervention on the component might be executed anyway. The development of optimal maintenance and modification intervention programs for multiple components of a building thus depends on the location of the components in the building. It will require making trade-offs between the benefits of one intervention program for one component and the benefits of the intervention program of another building component. This will result in different programs for the single components of the building than the ones that would be determined if they had been developed considering each component individually (Adey, 2015).

D.2 Uncertainty and the construction of intervention programs in the context of risk

In building management, the information that decisions are based on is almost always subject to uncertainty. The exact state of nature at a given point in time is not known for certain. This uncertainty affects the building manager's decisions about which intervention programs to follow. Both the actual current state of nature and the predictions for the future state of nature are uncertain. There can also be uncertainty about the effect of made decisions and other factors in the decision making process. The uncertainty about the future state of nature is often considerably higher than the uncertainty about the current state. This uncertainty is also the more relevant in the construction of intervention programs.

de Neufville and Scholtes (2011) emphasize that it is almost impossible to make point predictions about the future state of nature. They stress that point predictions, or predictions of the average values, are always wrong. Such predictions are based on the assumption that average values of the influence factors lead to an average value of the desired output variable. This, however, is not necessarily the case. This “flaw of averages” results from the fact that the effects of the symmetric influence factors are asymmetric, i.e. the effect of a very high value of one influence factor is not necessarily mirrored by the effect of a very low value of the same influence factor (de Neufville and Scholtes, 2011). Predictions are often based on the application of trends, e.g. by extrapolation of historical data. These forecasts can quickly be overthrown by trend-breakers like economic crises, political shifts or new technologies. de Neufville and Scholtes (2011) conclude that forecasts can only be made in terms of ranges but not by point-predictions. Frangopol et al. (2001) underline the necessity to consider uncertainty in the prediction of future scenarios of the state of nature in the determination and evaluation of intervention programs for infrastructure objects.

D.2.1 Risk and risk management

Uncertainty leads to risk, which is defined as “the effect of uncertainty on objectives, i.e. the deviation from an expected outcome, either positive or negative” (according to (International Organization for Standardization, 2009b)). Faber and Stewart (2003) define the technical risk R as “the sum over the possible consequences multiplied by the corresponding probability of occurrence”.

$$R = \sum_{i=1}^{\infty} p_i c(E_i) \tag{D.1}$$

where $c(E_i)$ are the consequences of event E_i. All consequences and their probability of occurrence must be well defined and quantified. In the determination and evaluation of intervention programs, the considered risk concerns the required service levels, e.g. the expected net benefits from the operation of the building or the reliability of the building function, and results from the uncertainty about the state of nature (regarding changes in demand and deterioration in the present and the future) and the consequences, e.g. the effect on the service level.

Examples for uncertainties relevant for intervention programs are the uncertainty over the extent of deterioration of a wooden building facade with the consequence of a change in the actual service level, i.e. of a breach of the building envelope and a possible loss of the heat insulation, or the uncertainty about changing constraints regarding the heat insulation coefficient of the building envelope that is required by law, leading to the consequence of a change in the required service level, i.e. the functional obsolescence of the building envelope. Consequences in the context of intervention programs often concern the actual and required service levels or relevant constraints.

The international standard ISO 31000 (International Organization for Standardization, 2009a) suggests a risk management process with the risk assessment (grey frame) and risk treatment (Figure D.8). The ISO GUIDE 73:2009 defines (1) risk identification as “the process of finding, recognizing and recording risks" (International Organization for Standardization, 2009b, 3.5.1), (2) risk analysis as the process of "developing an understanding of the risk" (International Organization for Standardization, 2009b, 3.6.1) by determining the level of risk according to equation D.1, and (3) risk evaluation as "comparing the level of risk found during the analysis process with risk criteria" (International Organization for Standardization, 2009b, 3.7.1) that have been defined during the context analysis. This comparison is the basis for the correct risk treatment.

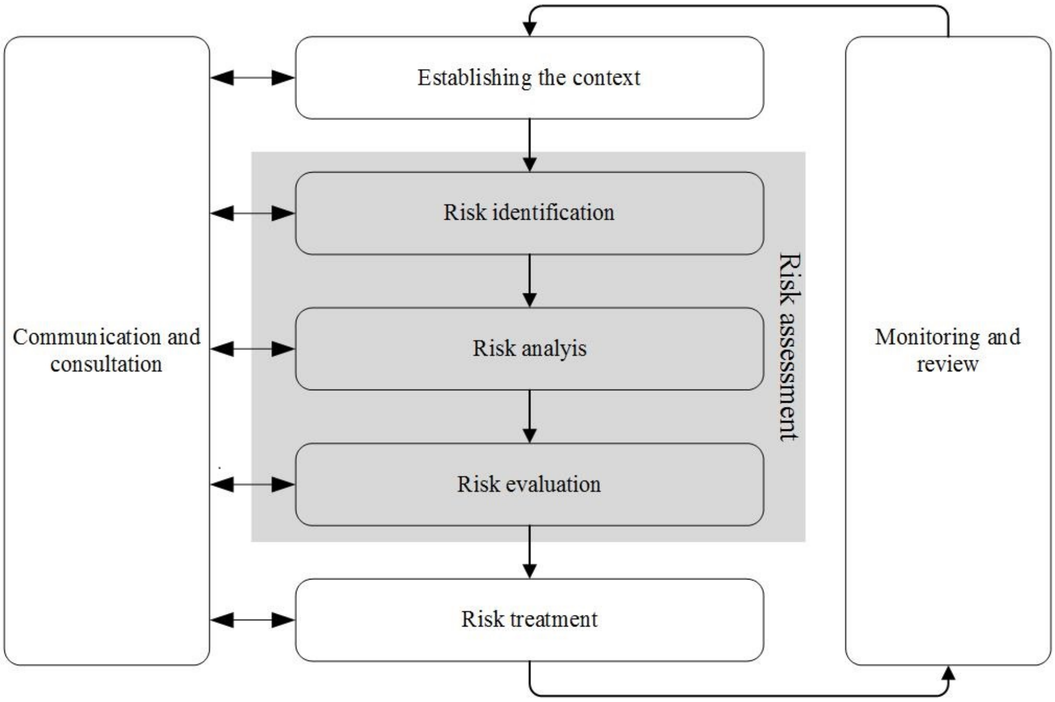

Figure D.8: Risk management process according to ISO 31000 (International Organization for Standardization, 2009a)

This process of risk management can give valuable inputs for the building and infrastructure management and can support the decision maker in the identification of adequate interventions and in the determination and evaluation of intervention programs. Concepts and methods for risk assessment can support the decision maker in the identification, assessment and modelling of the uncertain state of nature, and the concepts and methods of risk treatment can support the decision maker in the determination and evaluation of intervention programs.

D.2.2 Risk assessment in the construction of intervention programs

The uncertainty in predictions for the state of nature, i.e. the actual and required service level and constraints, and their consequences are relevant for the construction of intervention programs. This uncertainty results from uncertainties in the influence factors, changes of demand and deterioration processes, their effects and the required service levels and the causal relations between them. Considering these uncertainties and their relations, a decision maker can build probabilistic models for the prediction of the relevant future state of nature to be used in the construction of intervention programs. This process of making predictions for the state of nature is also called scenario planning. Bishop et al. (2007, p.3) describe "a scenario [as] a product that describes some possible future state and/or that tells the story about how such a state might come about".

Next to expert opinion, there are different techniques for risk assessment that can be used for the identification of uncertainties in predictions of the state of nature relevant for a building and its management over its life cycle and the consequences for the building and its functionality. Examples are brainstorming, structured and semi-structured interviews, the Delphi-Method and the scenario analysis (Martani, 2015). Martani (2015) offers a nearly comprehensive overview over existing tools and techniques, with an evaluation of each technique's applicability to risk assessment.

Event trees and fault trees are well-known methods to assess the type and probability of possible relevant states of nature and their consequences.These methods allow for a good understanding of causes and effects and, after the estimation of the probability, an estimation of the resulting risk according to equation D.1. It can be useful to distinguish between uncertainties based on their origin: (1) Uncertainty associated with *randomness or inherent natural variability*, which refers to the fact that many influence factors for a desired output are to some degree random, i.e. vary with a certain range, with some values occurring more frequently than others, that can be determined by measurements and observation, (2) *uncertainty associated with imperfect modelling* or model uncertainty, which results from incomplete knowledge and faulty comprehension on the analysts part and (3) *statistical uncertainty* (Ang, 2011).

Probabilistic models are used in risk assessment for scenario planning, and can also be used in the construction of intervention programs. Models that are often used in the construction of intervention programs are Monte Carlo simulation (see e.g. (Marseguerra and Zio, 2000; Asadi et al., 2012)), Bayesian networks (see e.g. (Ching and Leu, 2009; Cai et al., 2009)), neural networks (see e.g. (Mohamed et al., 1995)), Markov models (see e.g. (Lounis and Vanier, 2000; Zhang, 2006)), statistical regression (see e.g. (Chai et al., 2015)), Weibull hazard models (Kobayashi and Kaito, 2010), Poisson models (see e.g. (Ching and Leu, 2009)), and combinations of these models.

D.2.3 Risk treatment in the construction of intervention programs

When the extent of the uncertainty and the resulting risk for the service levels is established, the question arises how to consider or treat it in the building management process. Depending on the situation, the decision maker can decide if and how the building manager needs to treat the risk. If the uncertainty in the state of nature is low or if there are no or little consequences, the risk from this uncertainty and its consequences can be ignored, and the best available estimate can be used for the prediction of the future state of nature (while considering the possible flaw of average). If the existing uncertainty and its consequences lead to a considerable risk for the building manager's decision, there are two ways to reduce the risk that apply to the determination of intervention programs:

1. Reduce the uncertainty about the state of nature, in the present or the future, by improving models and gathering more data[4].
2. Reduce the consequences from the uncertainty about the state of nature, i.e. the consequences from the possible future scenarios of the state of nature.

In the area of building management, consequences from an uncertain state of nature regarding deterioration and changes in demand can be reduced by (1) improving the building design and (2) by executing interventions on the building. As the improvement of the building design can decrease, the consequences for the service level of the building over its life-cycle to only a certain extent[5], the execution of interventions and thus the construction of intervention programs leading to the highest service level is an important part of risk treatment for buildings.

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[4] With reduced uncertainty and the same consequences, the overall risk is reduced

[5] Improving the building design to decrease the consequences for the service level over the life cycle is possible, e.g. by choosing materials that are less likely to deteriorate, or by providing a building that is of a size that can accommodate future changes in demand with regard to that size. These improvements, however, will often exceed the constraints of the real world, e.g. space and, especially, budget constraints. It is also not always possible to consider all possible future states of nature in one design, as the changed demands from different changes in the state of nature are in conflict to each other. For example, a building cannot have a design that accomodates both the future demand for bigger room units and the future demands for smaller room units without the execution of a modification intervention.

D.3 Decision making about intervention programs under consideration of uncertainty

In the previous section, it was shown that the decision about which intervention program to follow has often to be made under consideration of the uncertainty in the future state of nature, based on the presently available information about the present and future state of nature. In section D.1.6.2, it was elaborated that long-term intervention programs have to be determined to be able to choose the best interventions over a short period of time to optimize the service level. Over a long time period of 20 years and more, the uncertainty about the state of nature is significant. There are many methods for the construction of intervention programs considering these uncertainties over longer time periods (see selection in chapter 2). With these traditional methods for the construction of intervention programs, however, it is assumed that the possible candidate intervention programs are inflexible, i.e. will not be changed over the investigated time period. From this set of inflexible candidate intervention programs, the intervention program is chosen as optimal that provides the expected optimal service level over the investigated time period, i.e. under consideration of all possible scenarios for the uncertain state of nature, the execution of the interventions according to this intervention program and their probability of occurrence.

These inflexible intervention programs could be seen as robust intervention programs, as they are selected to be the optimal solution for all possible ranges of all future considered parameters and demands. According to de Neufville and Scholtes (2011); Ellingham and Fawcett (2006), there are two ways to improve a system's design, which are also applicable to the construction of intervention programs, to reduce the consequences from uncertainty in a systems state over an investigated time period:

1. Robustness, which describes the design of the system in a way that all possible ranges or conservative estimates of all future considered parameters and demands can be accommodated, or

2. Flexibility, which describes the design of a system in a way that it accommodates current demands but can be modified in the future should it be necessary through interventions.

D.3.1 Decision flexibility in intervention programs

The concept of flexibility is also applicable to intervention programs, as in reality, a building manager will choose to change a so far optimal intervention program if it was beneficial according to the actual state of nature at a later point in time, i.e. she would execute her decision flexibility. *Decision flexibility* is the ability of a decision maker to postpone a final decision to a later point in time when more information about the actual state of nature is available. In intervention programs, this decision flexibility refers to postponing the decision about time and type of the intervention to be executed.

The construction of an intervention program considering only inflexible intervention programs, i.e. assuming that interventions will be executed over the investigated time period regardless of the actual state of nature, might not lead to the selection of the optimal intervention program and thus the selection of the optimal intervention today, because the possibility of a change in decision in the future is not considered. The consideration of decision flexibility in the evaluation of intervention programs, as of systems, can also lead to a higher expected value than with the assumption of inflexible decision making (e.g. elaborated in (de Neufville and Scholtes, 2011; Ellingham and Fawcett, 2006)). This decision flexibility allows for executing an intervention only if it is beneficial, and not to execute it, and thus save costs, if it is not beneficial. In summary, the consideration of decision flexibility over the investigated time period, i.e. flexible intervention programs instead of inflexible ones, might lead to other intervention programs and (2) a higher service level than with the construction of intervention programs with a traditional method, i.e. without the consideration of decision flexibility.

D.3.2 Building flexibility as a prerequisite to decision flexibility in intervention programs

Significant interventions on an existing building are not always possible without the provision of flexibility in the initial building design itself. This building flexibility is not always inherent in the initial building design i.e. if a building design only considers the presently required service level, many interventions might not be possible at a later point in time or be so costly that it is cheaper to tear down the building and rebuild it. The decision flexibility in intervention programs is sometimes connected to an increased building flexibility, but not always. Flexibility in the building design, in the remaining text referred to as *building flexibility*, makes it possible to design a building according to current demands and to adapt the building to future demands only if necessary, avoiding costs, and leaving the possibility for the required adaptation open. There is a great body of references in literature of examples for flexibility in the initial building design (e.g. in (Plagaro Cowee and Schwehr, 2008; van Reedt Dortland et al., 2012; Ellingham and Fawcett, 2006; de Neufville and Scholtes, 2011; Carthey et al., 2011)). A selection of examples for building flexibility are presented in table D.4.

Table D.4: Examples for flexible building design

Name	**Description**
Standardised ceiling heights	Ceiling heights suitable for different uses
Standardised, adaptable rooms	Rooms with layout and equipment for different uses
Open corridors	Corridors with their ends facing an outside wall towards an expansion area for access to future extension of the building
Double floors	Space for installations below the walking level, enabling rearrangement of wirings and pipes
Additional load bearing capacity	Additional reinforcement of load bearing structure, e.g. foundations, columns, ceilings, to allow for vertical expansion of the building
Additional equipment capacity	Additional capacity of air conditioning, water pumps, heating system to allow for expansion
Modular floor layout	Floor layout with central media distribution that can easily be partitioned to functional units of different sizes
Flexible wall and pile grid	Load bearing structure of a floor with small number of load bearing elements like walls and piles
Building zones	Vertical separation of zones, i.e. one zone of the same use on one floor, allowing for easy expansion or movement on the same floor
Separation of building elements	Separation of permanent and non-permanent building elements in primary (structural), secondary (walls and ceilings) and tertiary (furniture and interior fitting) building elements
“Soft” areas around hot spots	Soft areas like offices and waiting rooms are easy to move and to adapt and allow for expansion or change of hot spots with specialised use
Option on buying additional land	Contract with option to buy additional construction area to expand building
Additional area for rotating use	Area in or close to building network, available for intermediate use during interventions on a building in the network

D.4 Real Options Analysis and Decision Tree Analysis in building and infrastructure design and management

The decision flexibility described in section D.3 is not considered in traditional methods for the construction of intervention programs, even though decision flexibility is inherent in many situations. Real option analysis and decision tree analysis are two well known methods considering decision flexibility in the evaluation of engineering projects. The basics of these two methods and their difference will be presented in the following section, followed by a short overview of the main method types that were applied in engineering problems.

D.4.1 Decision Tree Analysis

Decision Tree Analysis[6] considers decision flexibility by taking into consideration multiple uncertain parameters, the utility related to the multiple possible future scenarios, and the ability of the decision maker to decide at certain points in the future as to what is to be done. To model the ability to make decisions, decision nodes are introduced. To model the probability of the decisions being made, it is convenient to discretise the values of uncertain parameters. This results in the so-called "trees" where every event node signifies multiple possible values of the uncertain parameter, branching from this node. For each branch originating from an event node, a probability of occurrence has to be estimated.

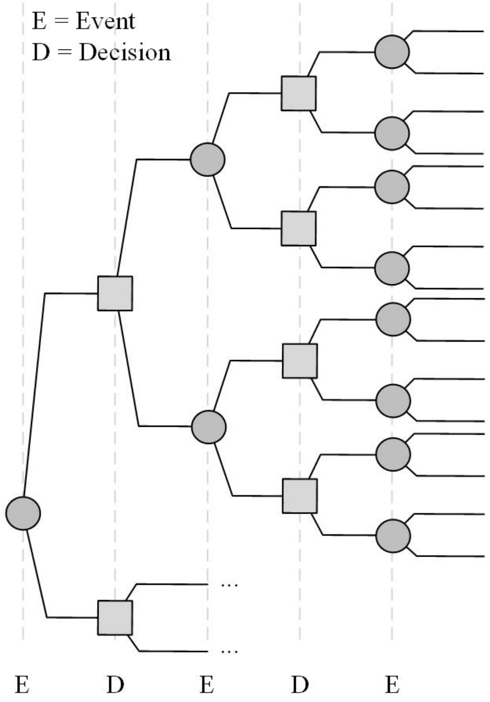

Figure D.9: Principle of decision tree

The decision nodes in the tree allow for the modelling of decision making based on the known outcome of the single or the multiple uncertain parameters. The values of the parameters are assumed to be observable at the event nodes before the decision node, and on the expected development of these uncertain parameters after the decision. That means that future decisions are made only after some of the uncertainty related to the considered parameters is removed when the state of nature is known. However, even though the state of nature is known, the decisions are also made based on the expected utility of this decision under consideration of possible uncertain development after the decision (Benjamin and Cornell, 1970). If the expected utility is estimated using costs and benefits (as it is the case for most intervention programs)

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[6] Also referred to as Bayesian decision theory (Benjamin and Cornell, 1970)

and if these costs and benefits occur over an investigated time period greater than 0, they must be discounted back to the decision time with an appropriate discount rate.

This Bayesian decision making requires the introduction of *conditional probabilities*, i.e. the conditional probability of event E given that event F has occurred, $P(E|F)$. If $P(E, F)$ is the *joint probability* of event E and F occurring together, and $P(E)$ is probability of event E and $P(F)$ is the probability of event F, then Bayes' theorem states

$$P(E|F) = \frac{P(E, F)}{P(F)} \tag{D.2}$$

D.4.2 Real Options Analysis

The ROA has its origins in the evaluation of financial options, i.e. the calculation of the expected value of options on stocks in financial markets (e.g. (Dixit and Pindyck, 1993; Trigeorgis, 2001; Copeland and Antikarov, 2001)), and has been adapted for the use evaluation of flexibility of engineering systems and projects.

An option is defined as "the right but not the obligation" to make a decision. A financial option gives an investor the right but not the obligation to buy a stock at a defined price, C, if it is favourable for her to do so, i.e. if the stock price S is above C; if the stock price S is below the purchase cost C of the stock, the investor can wait to a later point in time and decide again about buying the stock at price C. This decision situation can also be applied to "real option" deals, i.e. to investments with options-like characteristics, even though these investments are not traded in financial markets (Neely and de Neufville, 2001).

Similar to the decision tree analysis, financial and real option analysis assume that decision can be made in the future, considering that the state of nature is known at this time. The uncertain parameters considered in financial options are often financial parameters, i.e. stock and resource prices, which change continuously over time. Real options, however, also consider uncertain parameters which change suddenly, e.g. the sudden increase of patient numbers in a clinic with the introduction of a new treatment.

Trigeorgis (1995) shows the simple example of how ROA can be used to evaluate the investment in an building project. The value of the real option, i.e. to invest or not to invest, varies according to the oil price with each year over two years, i.e. the value of the buildingn project increases by 80% or decreases by 40% each year. The option, or flexibility in the decision making, that can be made here, is whether to invest in the project today or to wait and make the decision at a later time. Figure D.10 shows a two-period event tree for the modelling of the uncertain value of the building project (values on the left side in brackets, e.g. 180).

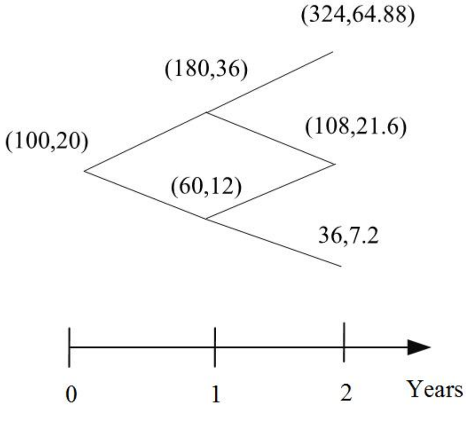


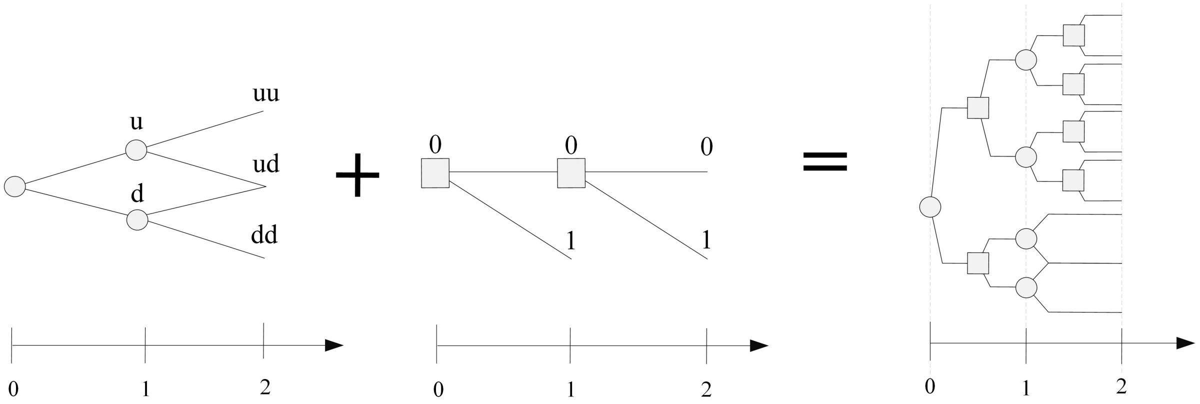
Figure D.10: Real Option valuation - example for building project (Trigeorgis, 1995)

As usual in the real option valuation, the decision nodes are not presented separately, but are included in the event nodes; only the value of the optimal decision, X, at each node is shown (value on the right side in brackets, e.g. 36). X is determined assuming that the decision is made to optimise the objective function, and takes the general form of:

$$X = max\left[0, S - C\right] \;\; for\ European\ type\ options \tag{D.3}$$

$$X = max\left[pX^{+} + (1-p)X^{-},\ S - C\right] \;\; for\ American\ type\ options \tag{D.4}$$

By omitting the decision nodes, and a further branching of the decision tree for each decision node, the ROA allows for the analysis and presentation of complex decision problems while keeping the complexity of presentation low. Figure D.11 shows the representation of the event tree in figure D.10 (left hand side) with possible decisions in each year as a decision tree (right hand side).



Event tree (ROM) Possible intervention decisions Decision tree (DTA)

Figure D.11: Representation of trees for ROA and DTA

D.4.3 The risk-adjusted approach of the ROA in comparison to DTA

The ROA is very similar to DTA. According to (Trigeorgis and Mason, 1987, p. 50), DTA is "*correct in principle [for the use on financial and real options] [. . .]. Its main shortcoming, however, is the problem of determining the appropriate discount rate to be used working back through the decision tree. [Option pricing] can be seen operationally as a special, though economically corrected, version of DTA that recognizes market opportunities to trade and borrow.*" The issue with financial options is that they are subject to market risks and concern values traded in markets, which affects the perspective of the decision makers and their attitude towards risk. The attitude towards risk is often expressed by the chosen discount rate, r, that is used in the backward optimisation in the decision/event tree. This discount rate is chosen as the sum of the risk-free interest rate, ir, that an investor could gain by investing in risk-free stock on the market, e.g. government bonds, and a risk premium, rp, appropriate for the situation and the investor's risk attitude (Trigeorgis and Mason, 1987). DTA can consider the perspective of any decision maker (building manager, owner, public etc.). This decision maker's attitude towards risk can be represented by the individual utility function and the making decisions based on axioms of consistent, rational behaviour (as defined by (von Neumann et al., 1944)). Thus, a discount rate equivalent to the risk free interest rate is appropriate for DTA.

ROA assumes the evaluation out of the perspective of a stockholder or an investor in a market[7], i.e. the decision is based on market equilibrium (Trigeorgis and Mason, 1987). The optimal decision about an investment[8] is not always made according a subjective utility function,

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[7] In this context, the building manager can be seen as an investor, or making decisions as a representative of the investor, e.g. the owner of the building, in an intervention as a beneficial investment in the building, which in turn is a part of a market.

[8] In this context, this is the investment in the intervention on the building to generate additional benefit from the improved service level of the building.

but rather according to its market value or the additional market value that is generated with the decision. Here, the attitude towards risk of the market can be relevant, and is considered in the risk premium in the discount rate used to discount future cash-flows. This risk premium must consider the additional return on the investment that could be gained by investing in a similar stock or investment with similar risk, as the investor has the possibility to trade and borrow in the market to diversify their risks. In the context of building management, the building manager, as a representative of the building owner, could diversify the risk of executing an intervention by deciding to invest in other, similar projects to gain additional benefits, which are identical to the ones expected from the execution of an intervention, e.g. by buying additional office space on the market, using borrowed money, with the desired service level instead of executing an intervention. If such a diversification of risk is possible, the evaluation of financial and corresponding real options, using the risk-free interest rate and the real probabilities might not capture the value of the option fully. There are several methods to adapt the DTA to enable the evaluation of such options. One of the most widely used method to adapt the DTA is the Contingent Claim Analysis (CCA), which is for example presented in Trigeorgis (1998), together with a comprehensive explanation why DTA might not capture an investment value fully if the open market conditions are not considered appropriately.

In summary, it can be said that if the possibility of a replicating portfolio and open market conditions for an investment, e.g. an intervention, exists, or the decision maker is interested in the market value of his decisions[9], the risk-adjusted approach has to be chosen. If an uncertain parameter, however, is independent from the market, real probabilities can be used and future cash-flows can be discounted with the risk-free rate ir (Copeland and Antikarov, 2001). If, in a project, it is necessary to use both types, Neely and de Neufville (2001) suggest a hybrid approach, using the ROA first for market risks, i.e. adjusting the probabilities, and then integrating it with DTA for project risks, so that both risks can be discounted with the risk-free rate, i.e. the market risks with the risk-adjusted probabilities and the project risks with the real probabilities.

D.4.4 Methods for the evaluation of decision and building flexibility

Even though ROA and DTA are very similar, ROA has been applied so far more extensively. The reason might be that the ROA is focussed on evaluation of flexible decision making under explicit consideration of uncertain processes over an investigated time period, which corresponds to the situation for most engineering projects and investments. More importantly, the ROA provides already some method types for appropriate evaluation situations, which offer a simpler and more efficient way of evaluation than the DTA. Martins et al. (2013) show a comprehensive overview of the main method types for evaluating real options: (1) Black-Scholes option pricing model, (2) binomial-option pricing model, (3) risk-adjusted decision tree analysis, (4) Monte Carlo simulation, and (5) hybrid real option approach.

The risk-adjusted decision tree analysis, the hybrid real option approach and the Monte Carlo simulation are the method types best suited for the application in the evaluation of intervention programs, while the Black-Scholes option pricing model and the binomial-option pricing model are only applicable under very specific conditions and more for investments in the context of financial markets.

The risk-adjusted decision tree analysis and the hybrid real option approach describe very similar method types, namely the use of decision trees with or without risk adjustments, or a combination of both in case of the hybrid approach. This corresponds to the method used in this thesis. These two method types allow for the application on intervention programs with successive execution of interventions and for insight on the decision making in each decision interval, which are two very important points for the consideration of decision flexibility in

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[9] Trigeorgis (1995, p. 19) state that “real options may, in principle, be valued similarly to financial options even though they may not be traded, since in capital budgeting we are interested in determining what the project cash flows would be worth if they were traded in the market, in other words, their contribution to the market value of a publicly traded firm.”

intervention programs. The Monte Carlo simulation could also be used to account for these aspects, while the application is less intuitive than with the risk-adjusted decision tree or the hybrid real option approach.

Appendix E

Changes in demand, influencing factors and effects

The following tables show the main types of changes in demand, together with their effects, i.e. the resulting obsolescence types. For each, several examples from literature are given.

Table E.1: Changes of demand, effects and examples (Function)

Changes of demand	**Function group** *Floor space layout and size* The required layouts and sizes of residential and office space change over time. *Space type* The demand for different space types evolves over time when new functions appear. *Room measures* Room measures like required corridor width and ceiling heights change according to required uses. *Infrastructure* The changing functionality of space types require a certain infrastructure
Effect (Obsolescence type)	**Functional obsolescence** Functional obsolescence occurs when the building does not fulfill the changed requirements for function anymore. This can apply to the whole building or just parts of it. A building or its components do not fulfil its function anymore when the usage objectives have changed.
Examples	Demand for apartments suitable for single-person households rises (Douglas, 2006)
	Demand for apartments suitable for single-person households rises (Douglas, 2006)
	Demand for apartments suitable for growing elderly population (Douglas, 2006)
	Demand for more space in residential and working buildings (Bahr and Lennerts, 2010)
	Demand for flexible office layouts rises (open space office, single office) (Bahr and Lennerts, 2010; Bottom et al., 1999; Sarja et al., 2006)
	Demand for office space in residential apartments and buildings increases (Douglas, 2006)
	Demand for certain functions decreases, e.g. huge computer rooms as the size of personal computers decrease (Douglas, 2006)
	Demand for greater diversity of retail outlets, e.g. bars and internet cafés (Douglas, 2006)
	Demand for new infrastructure to suit demands in space types like electrical ducts and wireless LAN for homes and home offices, pipes and air conditioning for new retail and sports facilities
	Demand for leisure facilities like fitness-centers, cinemas, restaurants (Douglas, 2006)

Table E.2: Changes of demand, effects and examples (Environment)

Changes of demand	**Environmental group** Changes in demand for environmental protection are often supported by laws and price politics. The aspects mentioned here are rather caused by a change in awareness of problems and general thinking. *Energy efficiency* The demand for more energy efficiency in buildings increases lately. *Waste reduction* The waste produced by the users of the building needs to be reduced.
Effect (Obsolescence type)	**Environmental obsolescence** Environmental obsolescence occurs when the building does not fulfill the changed requirements for the protection of the environment anymore. Requirements of environmental protection increase due to a raised awareness of the problems, not the increase of problems as such.
Examples	Demand for energy efficient electronic devises rises Demand for MINERGIE certified houses and similar systems rises. The rent revenue for energy efficient houses rises. Glass façades represent a deadly obstacle for birds that collide with them Infiltration of water is prevented on surface sealed by buildings and the surrounding facilities like parking spaces, etc. Influence on surrounding system Buildings have a direct influence on systems surrounding them, e.g. biological systems of flora and fauna, hydrologic cycle or wind circulation Lightning pollution is entering general awareness lately

Table E.3: Changes of demand, effects and examples (Economy)

Changes of demand	**Economic group** *Maintenance and modification costs* Demand for lower maintenance costs rises *Energy costs* Demand for lower energy costs increases, mostly for energy efficiency. *Efficiency of space* Demand for using existing space efficiently rises.
Effect (Obsolescence type)	**Economic obsolescence** Economic obsolescence occurs when using the building or one of its components is not economic anymore, i.e. if there are possible changes to improve its efficiency.
Examples	Demand for a higher insulated façade to reduce energy consumption Demand for new building components in general that are more easily maintained (Spilker and Oswald, 2000) Demand for more efficient office space use by introducing flexible working stations that can be used by more than one employee Demand for different building types because market conditions in the area of the building have changed, e.g. demand for more residential space than office space (Reed and Warren-Myers, 2010) Demand for new windows to reduce maintenance costs of the old ones (Spilker and Oswald, 2000)

Table E.4: Changes of demand, effects and examples (Health&Comfort/Social)

Changes of demand	**Health & Comfort/Social group** *Air quality* The quality of the indoor air condition becomes more important. *Lighting conditions* The illumination of working and living spaces is an important part of indoor comfort *Acoustic comfort* Demand for acoustic comfort in buildings, i.e. optimization of noise levels and types, increases *Ease of movement* Persons with movement *disabilities* need to be supported *Facilities* Adequate facilities for the comfort of the building users need to be provided *Adaptation of technical equipment* The demand for flexible and adjustable technical equipment increases as users want to influence the indoor quality actively or expect the building to adapt to changing external conditions, e.g. temperature and insolation
Effect (Obsolescence type)	**Social obsolescence** Social obsolescence occurs when the standards of the conditions for health and comfort influenced by the building are received as non-sufficient.
Examples	Demand for intelligent or “smart” buildings increases Demand for easier influence on indoor conditions rises (Bottom et al., 1999) Demand for building layouts for disabled and elderly increases (Bottom et al., 1999) Demand for easy movement from stairs or elevators to destination increases (Bottom et al., 1999) Demand for adequate catering and vending machines for employees (Bottom et al., 1999) Demand for adequate acoustic control in buildings increases (Bottom et al., 1999)

Table E.5: Changes of demand, effects and examples (Aesthetic)

Changes of demand	**Aesthetic group** Aesthetic demands change frequently over time. This is especially relevant for representative buildings like hotels. Changes in aesthetic demands have often an impact on the interior finish of buildings. These demands are very subjective and depend heavily on the taste of the user and/or owner Bahr and Lennerts (2010).
Effect (Obsolescence type)	**Aesthetic obsolescence** Aesthetic obsolescence occurs when the appearance of the building and its components does not comply with the standards of the building users and owners anymore.
Examples	Demand for new carpets and wall colour (Bahr and Lennerts, 2010) Demand for replacement of interior due to user changes, e.g. when space in an office building is rented to a new tenant

Table E.6: Changes of demand, effects and examples (Technical)

Changes of demand	**Technical group** When new technologies with better performance evolve, the demand for this better performance will rise equally. These demand changes are often manifested in the change of the state of practice.
Effect (Obsolescence type)	**Technical obsolescence** Technical obsolescence occurs when through the advance of technical development and innovations, parts of a building do not comply with the state of the art anymore. Elements will be replaced with newer products with better performance.
Examples	The increasing use of internet causes an increase in demand for improved internet connections in all areas of our daily live, especially wireless LAN. Therefore, demand in the corresponding installations changes over time. The structure of the building has to allow for wireless LAN (Reed and Warren-Myers, 2010) Demand for more efficient heating and ventilation systems arises (Sarja et al., 2006) Demand for more flexible control systems for heating or cooling arises, e.g. smart building technology or user controlled systems. Users want to control lighting, heat, cooling etc. (Bottom et al., 1999; Douglas, 2006; Sarja et al., 2006) Demand for the integration of new information and communication networks, e.g. computer networks, increases (Sarja et al., 2006) Demand for better sound and impact insulation increases (Sarja et al., 2006) Demand for better thermal insulation of building envelope rises (Sarja et al., 2006) Demand for new developments because replacement elements for the maintenance of technical equipment is no longer available (Bahr and Lennerts, 2010) Demand for more flexible systems, e.g. in IT connections, electricity supply, lighting etc., increases. These systems should be adapted to changing user demand on the short run (Bottom et al., 1999; Douglas, 2006)

Table E.7: Changes of demand, effects and examples (Political/Legal)

Changes of demand	**Legal group** Political decisions can trigger demand for different changes in houses. This demand is often made mandatory by the passing of corresponding laws and rules. But also legislation about the allocation of maintenance and modification costs can cause certain interventions.
Effect (Obsolescence type)	**Legal obsolescence** Legal obsolescence occurs when the performance of the building and its components does not correspond to legal standards anymore.
Examples	Demand for building modification when an urban area is changed or renewed (Spilker and Oswald, 2000) Modernization costs can be allocated to the tenant (at least in Germany), general maintenance on the other hand has to be paid by the owner. This leads to early modernization of building components (Spilker and Oswald, 2000) Changes in standards for heating, sound proofing and fire protection lead to early modification of building components (Bahr and Lennerts, 2010)

Table E.8: Influencing factors on changes in demand (Part 1)

Influence factor category	**Description**	**Examples**
Demographics	Growth of population Aging population Increase of small households Increasing demand for comfort	
Lifestyle changes	Increasing wealth of society Increasing demand in higher and further education (Manewa et al., 2009) Increasing use of information technology at home (Douglas, 2006) Increasing demand for comfort (Georgiadou et al., 2012) New working and living habits (Georgiadou et al., 2012)	
Environmental	Climate change (Georgiadou et al., 2012) Waste reduction (Sarja et al., 2006) Pollution reduction(Sarja et al., 2006) Growing awareness of necessity of environmental protection (Bahr and Lennerts, 2010)	Increasing temperature (Georgiadou et al., 2012) Urban heat island effects (Georgiadou et al., 2012)
Innovation	Development of state of practice for works and equipment in buildings (Bahr and Lennerts, 2010) Development of design standards (Reed and Warren-Myers, 2010) Development of mechanical systems(Reed and Warren-Myers, 2010) Development of construction materials(Reed and Warren-Myers, 2010)	Novel energy efficient measures for technical equipment (Sarja et al., 2006; Georgiadou et al., 2012) New fuel types and renewable energy resources (Georgiadou et al., 2012) New construction practices (Georgiadou et al., 2012) New method to accurately measure energy consumption (Georgiadou et al., 2012) New information and communication systems like computers (Sarja et al., 2006) Technical development in better material for sound and impact insulation (Sarja et al., 2006) New materials for better thermal insulation of building shell (Sarja et al., 2006) Abandoning of spare part production (Bahr and Lennerts, 2010)

Table E.9: Influencing factors on changes in demand (Part 2)

Influence factor category	**Description**	**Examples**
Political	Supply security objectives Objectives of environmental protection Safety targetsBuilding regulations(Georgiadou et al., 2012) Planning policies for cities and their districts (Georgiadou et al., 2012) Government support programs (Bahr and Lennerts, 2010)	Energy security (Georgiadou et al., 2012) Development plans (Bahr and Lennerts, 2010) New standards for heating demand in Germany (Bahr and Lennerts, 2010) Allocation of modernization costs to the tenant (Spilker and Oswald, 2000) Changes in Tax and tenancy law(Bahr and Lennerts, 2010) Built heritage conservation (Bahr and Lennerts, 2010) Possibilities for depreciation (Bahr and Lennerts, 2010)
Economic	Conjuncture data (Bahr and Lennerts, 2010) Economic growth (Georgiadou et al., 2012) Growth of manufacturing and industrial sector (Georgiadou et al., 2012) Moving of production sites (Bahr and Lennerts, 2010) Change in areal competition (Spilker and Oswald, 2000) Metropolitan growth (Brown, 2008) Management decisions(Brown, 2008) Design ideas (Brown, 2008) Price developments Resource developments Incentives (investments, funding, subsidies) (Georgiadou et al., 2012)	Growth of hotel and catering industry (Butt et al., 2010) Energy price development (Georgiadou et al., 2012) Fuel poverty (Georgiadou et al., 2012) Funding for improvement of energy efficiency of a building (Spilker and Oswald, 2000; Douglas, 2006; Georgiadou et al., 2012) Funding for low carbon technologies (Georgiadou et al., 2012) Oversupplied market (Reed and Warren-Myers, 2010)
Occasion	Bundling of interventions(Bahr and Lennerts, 2010) Empty space (Spilker and Oswald, 2000)	

Appendix F

Real world example

F.1 Simplifications

The two key parameters, patient numbers for existing treatment and patient numbers for new treatment, are modelled simplified in this real world example. The assumptions for the simplifications are explained in the following sections.

F.1.1 Probabilistic model for uncertain parameter 1 - Patient numbers for existing treatment

Over the investigated time period of 40 years, it is possible that the existing application for the localisation of cancer cells and tumors (UP1) will be replaced by another application with the same purpose. Possible consequences from such a replacement are:

1. A *new and better tracer* is developed for injection to the patient. Possible consequences for the PET center: (1) The new tracer has a longer half-life, i.e. the time limitations for a regular shift (until 2pm) could be extended, increasing the regular treatment capacity of the PET center. (2) The new tracer requires a more complicated application process to the patient, leading to an extension of required time per patient, decreasing the regular treatment capacity of the PET center.

2. A new and better tracer is developed for injection to the patient and requires a *different device*, e.g. a replacement for the PET/CT. Possible consequences from such a replacement are: (1) A new device, such as a PET/MR, are required for this new application, requiring the room of the PET/CTs, which in turn requires the modification of the rooms currently used for the PET/CTs (2) Less devices or smaller devices are necessary for this new application, leaving one of the rooms currently used for the PET/CTs empty and open for new use.

3. A *new application outside the clinic of nuclear medicine.* Possible consequences from such a replacement are: (1) Clinic of nuclear medicine looses main source of income and is significantly downsized, loosing the rooms of the PET center to another clinic for complete change of use. (2) Clinic of nuclear medicine introduces a complete replacement of the applications, making a major modification of the PET center necessary.

Changes with that magnitude, however, of consequences require

1. Significant success in research and development for a new application, a process which requires at least 10 to 12 years from the idea to introduction for patient treatment. However, to date, there was no indication of a relevant research and development process being underway.

2. The introduction of such a new application requires the support of the decision maker, in this case of the clinic head and the main physicians. Often, a change in application

requires a rotation of this head staff, i.e. through retirement of the former. According to the clinic head, this happens at most every 10 years. However, the head staff had, to date, just rotated, so that the next rotation can only be expected, earliest, in 10 years.

Taking these two points into account, it can be expected that, if the research & development process started today, a new application would be ready for introduction earliest in 10 to 12 years. A rotation in head staff, however, will likely occur before that and remain present for the following 10 years, i.e. making a change of the treatment possible earliest in year 20 of the investigated time period. That means that no change in application can be expected before that. The next opportunity for such an application change would then occur again, after the next rotation of the head clinic staff, in year 30 of the investigated time period. This one time possibility of change was not considered here, as the probability of occurrence is very low in comparison with the two considered uncertain parameters, and the consequences are very similar to the considered ones. As the combination of two uncertain key parameters considered already a high number of scenarios for patient numbers, this additional uncertain parameter was neglected in this example, to reduce the complexity of analysis. However, this topic could be subject to further investigation.

F.1.2 Probabilistic model for uncertain parameter 2 - Patient numbers for new application: Pre-screening for Alzheimer's

The simplification was made in chapter 6.2.3.2 that the uncertain parameter 2 - the patient numbers for the new application, the pre-screening for Alzheimer's - could be modelled as a jump or Poisson process, with a one-time jump between years 2 to 8, where the patient numbers would increase by 2000 and remain at that level until the end of the investigated time period. The latter is a simplification, as, according to the medical director and the experience with the introduction with other applications, it is more likely that, upon introduction of this new application, patient numbers would start around 1000 patients per year and then increase to a long-time plateau (similar to the patient no. development for UP1). Thus, the expected development of the patient numbers and their long-term behaviour will probably follow curves such as depicted in figure F.1, with an initial increase and then a variation around the long-term tableau, which could be modelled with a mean-reverting process similar to the one used for UP1.

The combination, however, of initial jump with following variation would have required to combine two different stochastic processes, a jump process and a mean reverting process, that would be complex for one jump. As there are four jumps possible between 2 and 8, such a detailed model for each jump would lead to a complex model in itself, even more so in combination with the uncertain parameter 1.

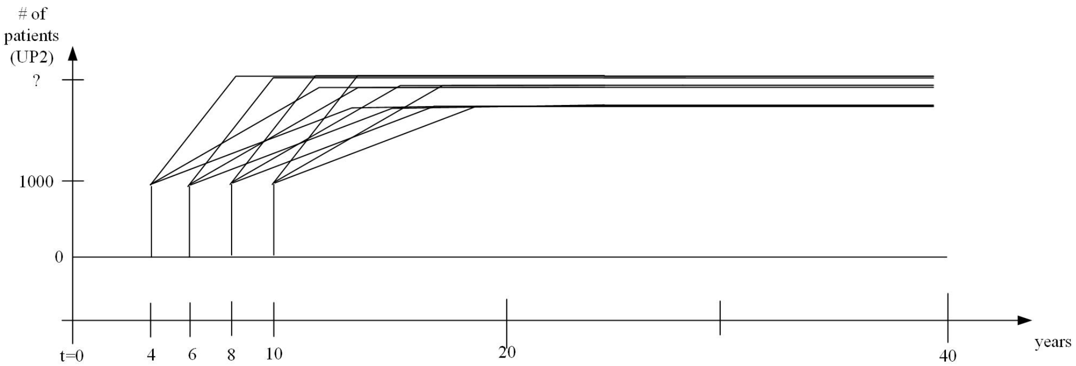

Figure F.1: Visualisation of possible paths for UP2 in extended model

Additionally, the time of increase, neither the long-term tableau nor the variation around this long-term tableau are known, and require a thorough and expansive analysis, e.g. as done in Forró et al. (2012) & Fievet et al. (2015); also, the consideration of such a jump process over several time intervals with a change of this process into a mean-reverting process would have caused a significant increase in complexity of the evaluation model. As the main focus of this work lay on the applicability of the evaluation method for intervention programs and not the complex modelling of uncertain parameters, it was assumed that the simplified model of a jump process would suffice for this purpose and could be expanded if necessary.

F.2 Assumptions

F.2.1 Relevant costs and benefits

Figure F.2 shows the relevant cost and benefit types of the clinic operation that could be affected by a change in patient numbers and the chosen interventions. Together with the stakeholders of the clinic of nuclear medicine, a selection was made out of this complete set with the most significant impacts on the expected net benefits for the use in the construction of intervention programs with consideration of decision flexibility.

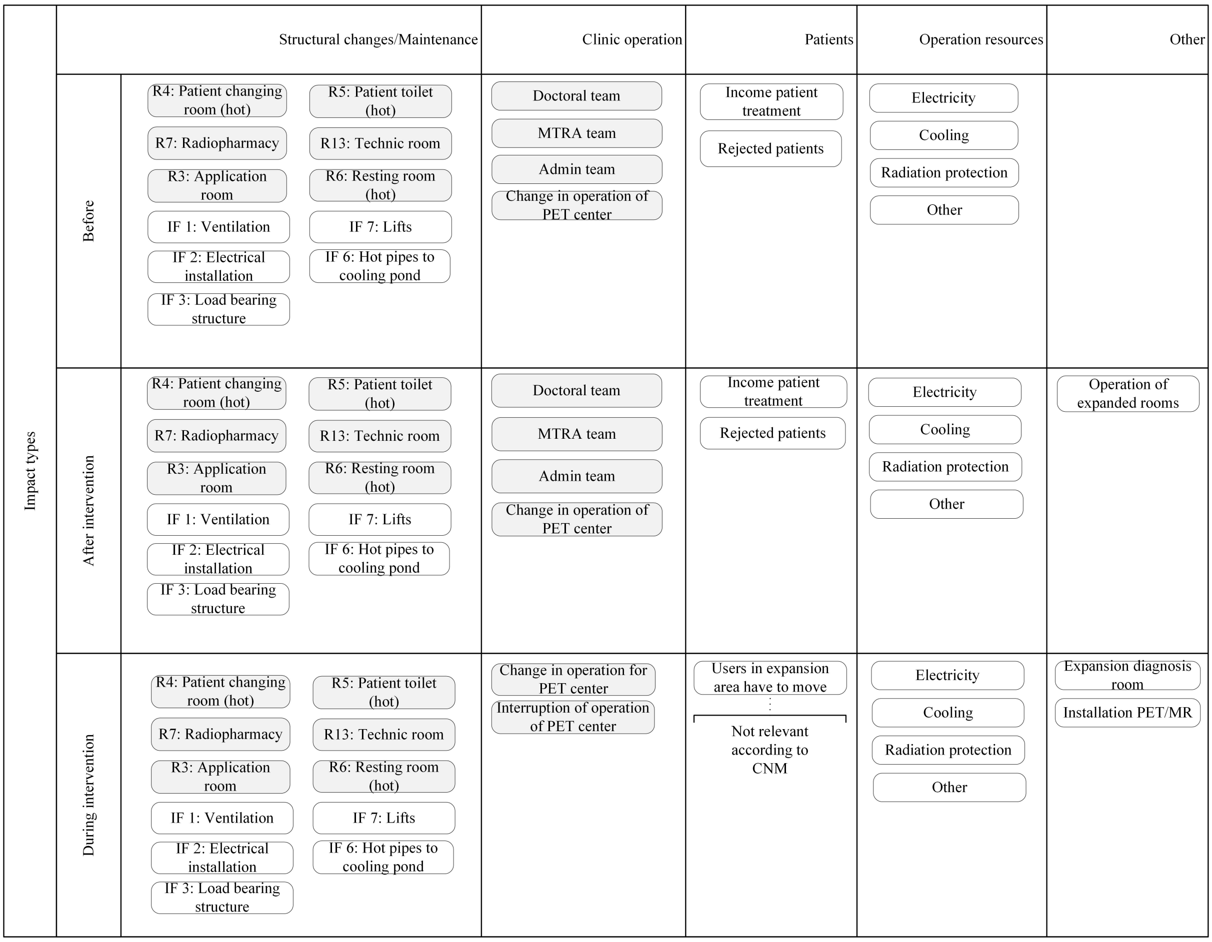

Figure F.2: Cost and benefit types for operation of the clinic of nuclear medicine

F.2.2 Team costs

For the evaluation of different intervention programs, more precisely for the estimation of the costs for the evasive measure 2, it is necessary to estimate the payroll for an additional medical to cover additional afternoon shifts. Currently, the PET center employs 1,5 medical teams to cover the regular morning shifts. The surplus is necessary to compensate staff shortage through sickness and vacation time. According to the head of the clinic of nuclear Medicine, one additional medical team would be necessary to run the afternoon shifts. The team costs were estimated based on the composition of the current team and the wages paid in Switzerland for the different positions. The position types in the team were identified as chief senior physician (Leitender Arzt), senior physician (Oberarzt), resident physician (Assistenzarzt), radiographer (MTRA), and admin staff. Each yearly wage was multiplied by 1.5 to account for additional administration costs per person.

Table F.1: Members of medical team with according wage estimations

Type	**Necessary FTE for additional afternoon shift**	**Current FTE in PET center**	**Swiss wages for position**	**Calculation**	**Payroll in CHF/year**
Chief senior physician	0.5	1	200.000	$200.000 \times 1.5 \times 50\%$	150.000
Senior physician	2	5	150.000	$150.000 \times 1.5 \times 200\%$	450.000
Resident physician	2	5	100.000	$100.000 \times 1.5 \times 200\%$	300.000
Radiographer	3	5	60.000	$60.000 \times 12 \times 1.5 * 300\%$	324.000
Admin staff	1	1 + 5 non-full-time positions	120.000	$120.000 \times 1.5 \times 100\%$	180.000
				Σ	1.404 Mil.

The cost of one shift was determined by dividing 1.4 Mil. CHF by 250 shifts/year. This leads to costs of 5’600 CHF/shift and team.

F.3 Sensitivity analysis

The example has multiple input parameters, with values often based on assumptions. These assumptions can be confirmed and in some cases improved with additional effort. A sensitivity analysis can help reducing this additional effort by showing which assumptions have a significant impact on the results and the validity of the general conclusions of the real world example. It is especially interesting to see if a variation of the input parameters leads to significant changes in

1. the value of a flexible evaluation, i.e. with the ROM AO, in comparison to the evaluation with the TM ($\triangle ENB - IP3 - FlexInitialTM$ in table 6.29), as the difference in the expected net benefits is small with the given input (0.5%),
2. the value of a staged execution of the interventions in comparison to a single-stage execution ($\triangle ENB - IP2 - AllInitial$ in table 6.29), as the difference in the expected net benefits is small with the given input (1.7%), and
3. the probability of execution of intervention 4 (table 6.29), as this probability is small (2% in total).

Other results that were tested were:

Table F.2: Tested results

Row name	**Description**
NoInitial - ENB in Mil. CHF	Expected net benefits in $t = 0$ without interventions
AllInitial - ENB in Mil. CHF	Expected net benefits with all interventions in $t = 0$
FlexInitial - Do nothing - ENB in Mil. CHF	Expected net benefits without interventions
FlexInitial - TM - ENB in Mil. CHF	Expected net benefits with all interventions with TM
τ_{TM} interv. 1 in years	Optimal year of execution of intervention 1 with TM
τ_{TM} interv. 2 in years	Optimal year of execution of intervention 1 with TM
τ_{TM} interv. 3 in years	Optimal year of execution of intervention 1 with TM
τ_{TM} interv. 4 in years	Optimal year of execution of intervention 1 with TM
FlexInitial - ROM AO - ENB in Mil. CHF	Expected net benefits with all interventions with DEM AO
τ_{AO} interv. 1 in years	First possible year of execution of intervention 1
$q^{ex}_{\tau_{AO}}$ in year t=1	Probability of execution of stage 1 in τ_{AO}
q^{ex}_{AO}	Sum of probability of execution of intervention 1 over T

Input parameters that will be varied in the sensitivity analysis are shown in table F.3. The reasons why these ranges were selected can be found in the sections below, where the results are presented.

Table F.3: Variation of inputs in sensitivity analysis

No.	**Parameter**	**Symb.**	**Initial value/ Calculation**	**Range**	**Unit**	**Discussed in section...**
1	Costs for additional PET/MR	$CPETMRd$	3	2.5 to 7	$Mil.CHF$	6.6.2
2	No. of additional patients UP2	$addUP2$	2000	1'000 to 5'000	$Patient/year$	6.6.2
3	Initial probability of introduction of Alzheimer screening	$pUP2$	0.8	0.2 to 0.8	-	6.6.2
4	Discount rate	r	0.06	0 to 0.16	-	6.6.2
5	Increase in variable costs for treatment above capacity on PET/CT	$delta_{TC}$	100	100 to 200	$CHF/patient$	F.3
6	Difference in capacity thresholds	dMx	5000, 6500, 7000, 7500, 8000	Increase difference by 100 to 300	$Patients/year$	F.3
7	Reduction in ratio of lost patients when send to external PET-center	$fdeltaUP2$	0.7	0.5 to 0.9	-	F.3
8	Variable yearly income (with operational costs staying the same)	Iv	2500	2'000 to 5'000 in 500 steps	$CHF/year*patient$	F.3
9	Fixed costs per Team per year	$ofmtrayear$	1.4	0.7 to 1.5	$Mil.CHF/year*team$	F.3
10	Difference in rent for highly specialised and normal area use	$ofrentDiff$	400	200 to 600	$CHF/year*m^2$	F.3

F.3.1 Variable costs for treatment above capacity - deltaTC

The variable costs, i.e. per patient, are based on an assumptions and were not confirmed by the clinic of nuclear medicine. Thus, it was varied up to an increase of 100% to test the impact on the results. The impact of the variation on the differences in expected net benefits between the ROM AO and the TM, and the AllInit and the FlexInitial design is negligible (around 0.1%). Thus, a possible variation has no impact on the results of the application and does not have to be considered further.

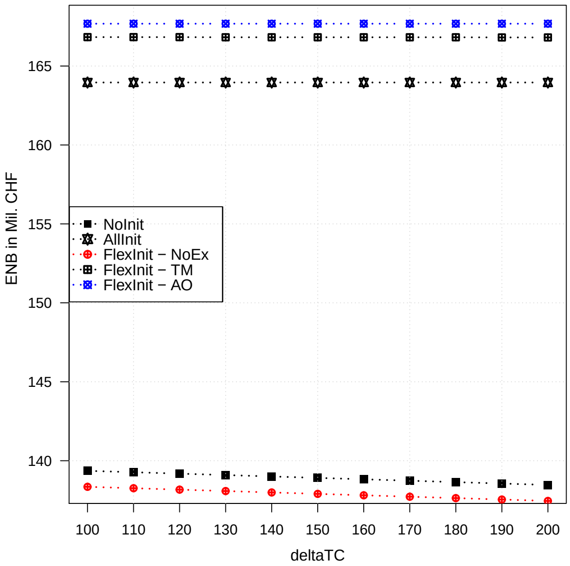

Figure F.3: SA: Costs for treatment over capacity deltaTC - All ENBs

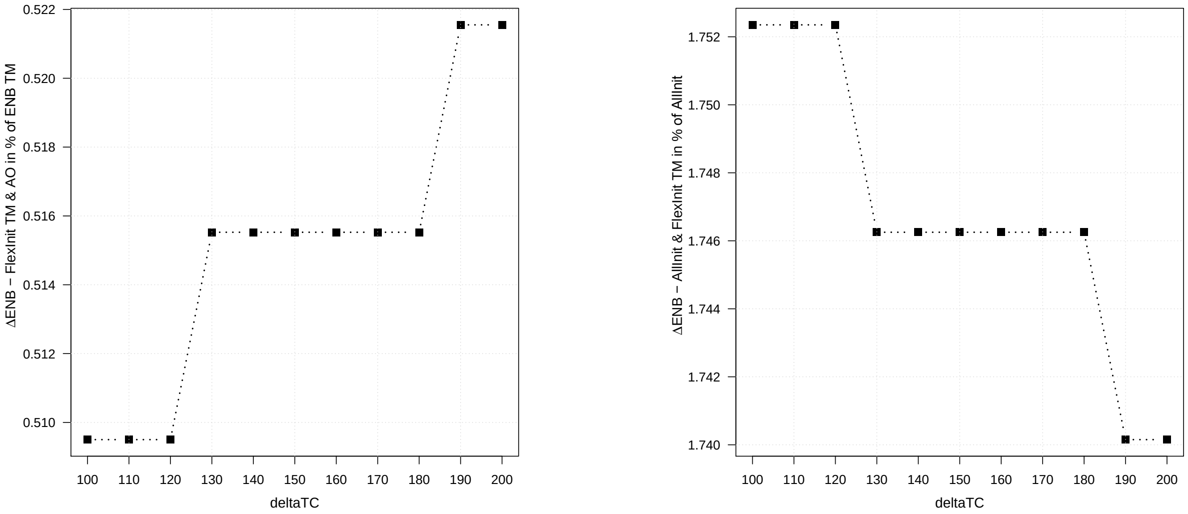

Figure F.4: SA: Costs for treatment over capacity deltaTC - ΔENB DEM AO - TM

Figure F.5: SA: Costs for treatment over capacity deltaTC - ΔENB FlexInit TM - AllInit TM

F.3.2 Increase in difference of capacity threshold for regular treatment of patients - dMx

Except for the capacity threshold before the execution of any intervention, the capacity thresholds after the execution of the different interventions and their differences are based on assumptions, made together with the clinic of nuclear medicine, and thus a certain variation is possible. The impact of the variation on the differences in expected net benefits between the ROM AO and the TM, and the AllInitial and the FlexInitial layout is negligible (around 0.1% and around 0.6%). Thus, a possible variation has no impact on the results of the application and does not have to be considered further.

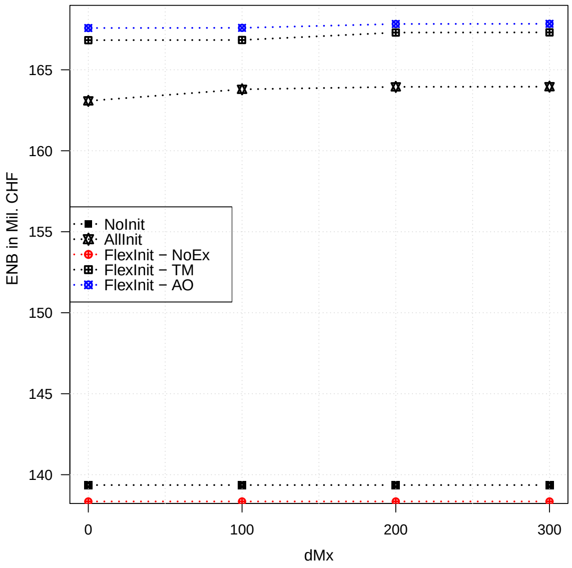

Figure F.6: SA: Capacity threshold dMx - All ENBs

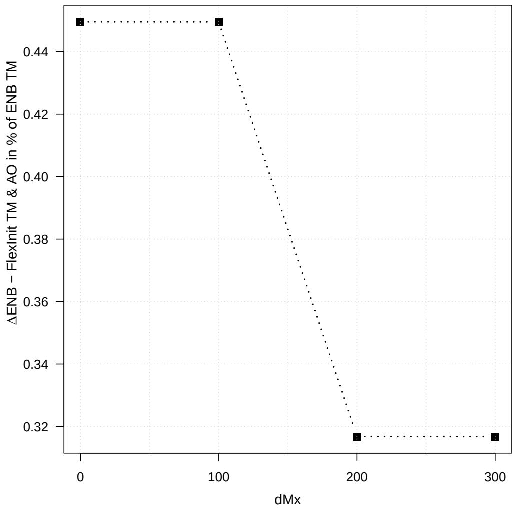

Figure F.7: SA: Capacity threshold dMx - ΔENB DEM AO - TM

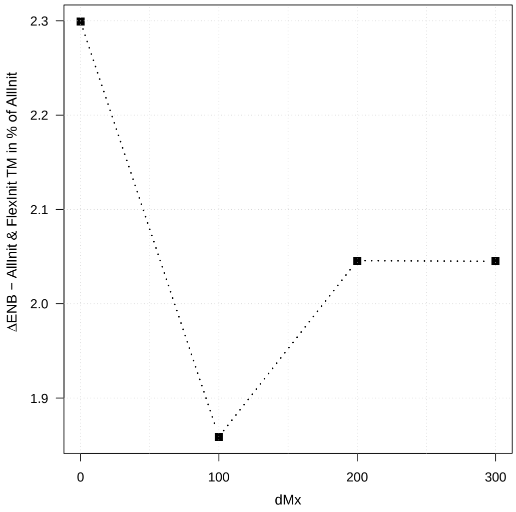

Figure F.8: SA: Capacity threshold dMx - ΔENB FlexInit TM - AllInit TM

F.3.3 Reduction in patient number when send to external campus - fdeltaUP2

The number of patients, who will move to another clinic in case they are sent to the clinic part of the Wagi areal is an assumption, as no historical data is available for such cases. The impact of the variation on the differences in expected net benefits between the ROM AO and the TM, and the AllInitial and the FlexInitial design is negligible (0%). Thus, a possible variation has no impact on the results of the application and does not have to be considered further.

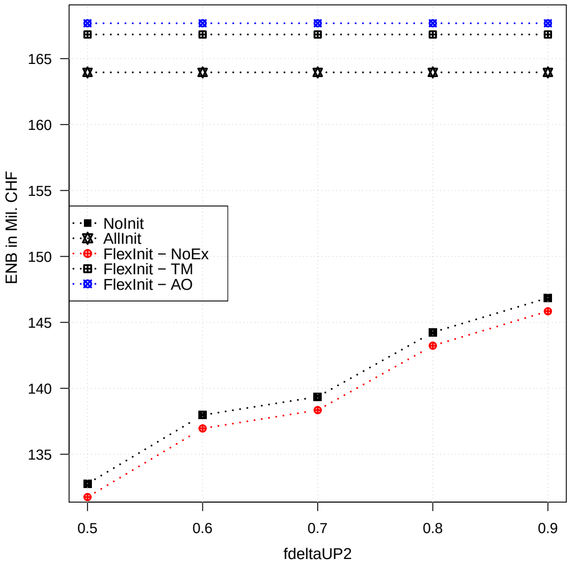

Figure F.9: SA: Reduction in patient no. fdeltaUP2 - All ENBs

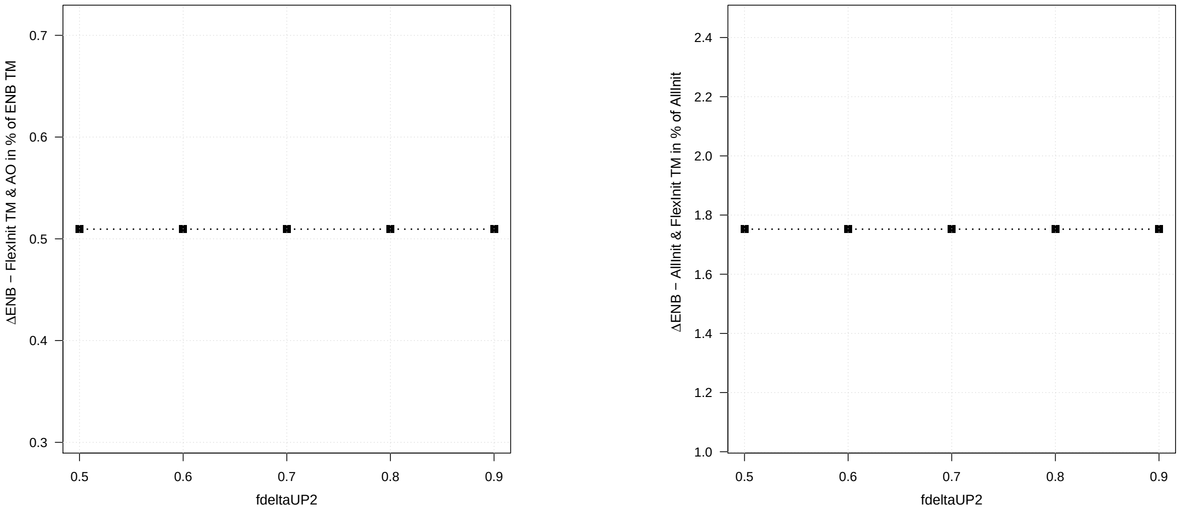

Figure F.10: SA: Reduction in patient no. fdeltaUP2 - ΔENB DEM AO - TM

Figure F.11: SA: Reduction in patient no. fdeltaUP2 - ΔENB FlexInit TM - AllInit TM

F.3.4 Yearly income - Iv

For the yearly income per patient, I_v, an average value was selected for the use here. This value was varied to test if there is an impact on the results by changing the ratio of costs to benefits of the interventions. I_v represents the benefit side of this ratio, as the number of treated patients increases after the execution of the interventions. The difference in percent between the expected net benefits from both the ROM AO and the TM for the FlexInitial layout and the differences between the expected net benefits from the TM for AllInitial and the FlexInitial layouts decrease with increasing I_v, because the overall expected net benefits increase, while the advantages of the flexibility (ROM AO vs. TM and FlexInit vs. AllInit) remain the same, i.e the absolute differences remain the same for all I_v (compare table F.4). This is due to the fact that the advantage of the ROM AO results from the costs savings from not executing an intervention, while the number of treated patients, which is depending on I_v, is the same for both ROM AO and the TM. The absolute differences remain the same for all I_v (compare table F.4). Thus, a possible variation has no impact on the results of the application and does not have to be considered further.

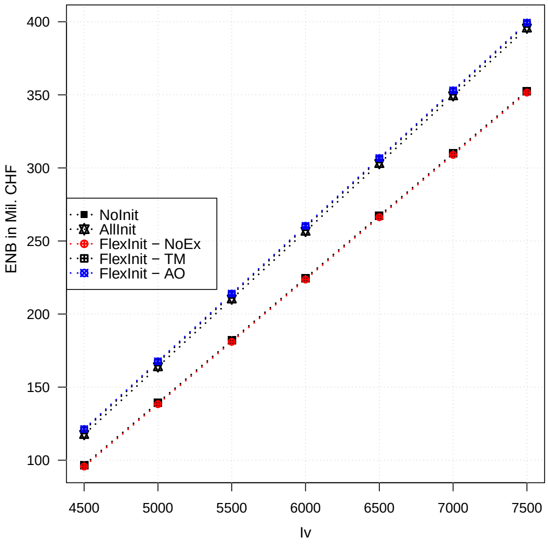

Figure F.12: SA: Yearly income Iv - All ENBs

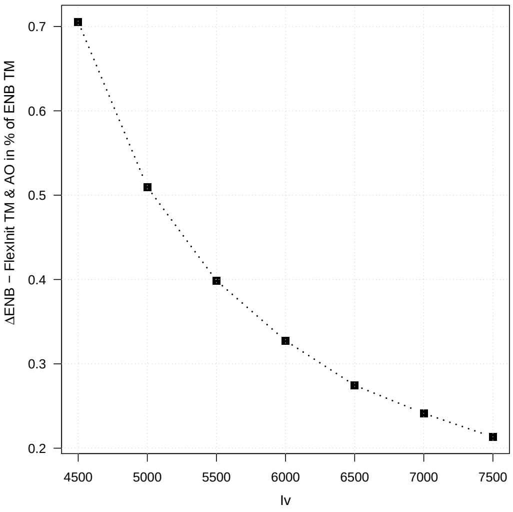

Figure F.13: SA: Yearly income Iv - ΔENB DEM AO - TM

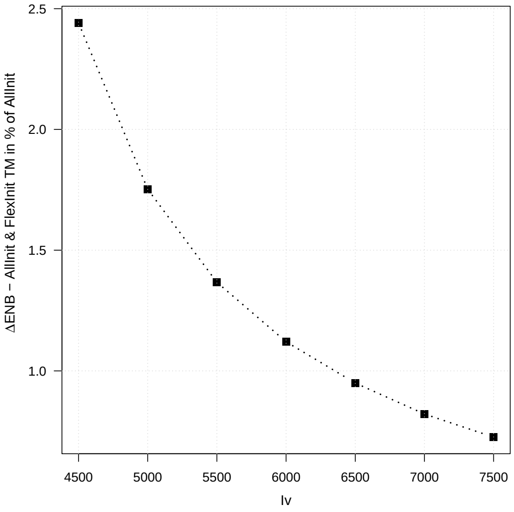

Figure F.14: SA: Yearly income Iv - ΔENB FlexInit TM - AllInit TM

Table F.4: Sensitivity Analysis - Change in I_v

Income per patient in CHF	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**	**7500**
NoInitial - ENB in Mil. CHF	96.71	139.36	182.01	224.66	267.31	309.96	352.60
AllInitial - ENB in Mil. CHF	117.61	163.96	210.31	256.65	303.00	349.35	395.70
FlexInitial - Do nothing - ENB in Mil. CHF	95.70	138.35	181.00	223.65	266.29	308.94	351.59
FlexInitial - TM - ENB in Mil. CHF	120.48	166.83	213.18	259.53	305.88	352.22	398.57
τ_{TM} interv. 1 in years	3.00	3.00	3.00	3.00	3.00	3.00	3.00
τ_{TM} interv. 2 in years	4.00	4.00	4.00	4.00	4.00	4.00	4.00
τ_{TM} interv. 3 in years	41.00	41.00	41.00	41.00	41.00	41.00	41.00
τ_{TM} interv. 4 in years	41.00	41.00	41.00	41.00	41.00	41.00	41.00
FlexInitial - ROM AO - ENB in Mil. CHF	121.33	167.68	214.03	260.38	306.72	353.07	399.42
τ_{AO} interv. 1 in years	2.00	2.00	2.00	2.00	2.00	2.00	2.00
$q^{ex}_{\tau_{AO}}$ in year t=1	0.37	0.37	0.37	0.37	0.37	0.37	0.37
q^{ex}_{AO}	0.99	0.99	0.99	0.99	0.99	0.99	0.99

F.3.5 Fixed costs for additional team - ofmtrayear

The costs for the yearly fix costs for one additional clinic team was varied, because the number of needed persons could vary depending on the organisational setup of the clinic. A possible range of costs for one team was tested. The difference in percent between the expected net benefits from the ROM AO and the TM for the FlexInitial layout increase with increasing ofmtrasyear by 0.2% in total, a negligible amount, because with the ROM AO, it is considered that more interventions can be executed to avoid the need for an additional team over the investigated time period, than with the TM.

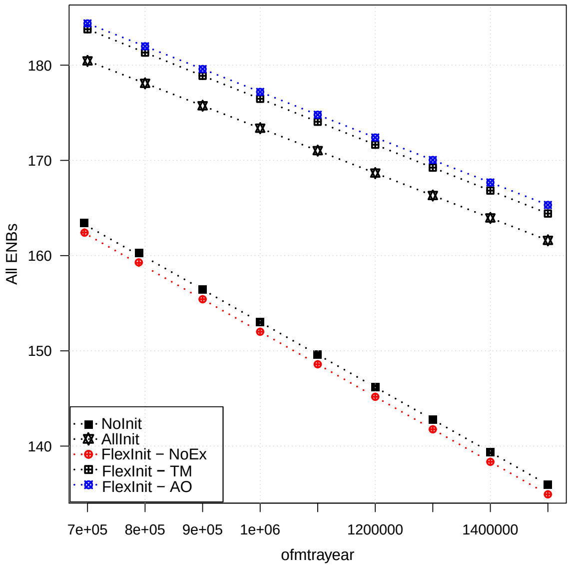

Figure F.15: SA: Fixed costs additional team ofmtrayear - All ENBs

The difference in percent between the expected net benefits from the TM for AllInitial and the FlexInitial layout decrease with increasing $ofmtrasyear$ by 0.1% in total, a negligible amount, because with the AllInitial layout, the increasing costs for an additional team are avoided with all possible means (which is not the solution with the overall highest expected net benefits, though), thus reducing the advantage of the FlexInitial layout. The differences in expected net benefits remain negligible, though, and, thus, a possible variation has no impact on the results of the application and does not have to be considered further.

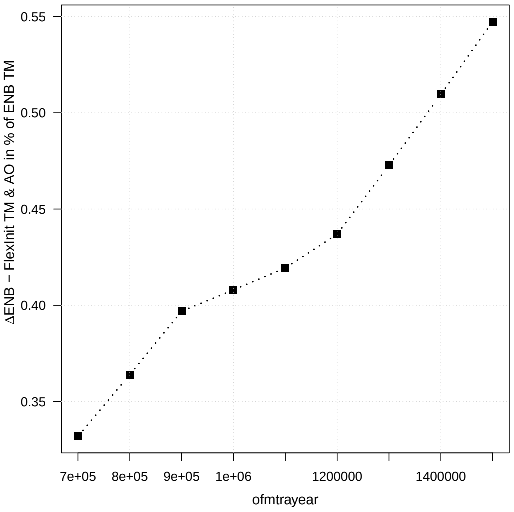

Figure F.16: SA: Fixed costs additional team ofmtrayear - ΔENB DEM AO - TM

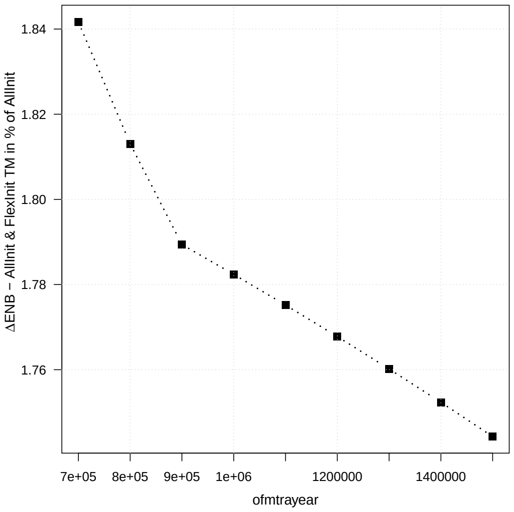

Figure F.17: SA: Fixed costs additional team ofmtrayear - ΔENB FlexInit TM - AllInit TM

Table F.5: Sensitivity Analysis - Change in ofmtrayear

ofmtrayear in 1000 CHF/year	**700**	**800**	**900**	**1000**	**1’100**	**1’200**	**1’300**	**1’400**	**1’500**
NoInitial - ENB in Mil. CHF	163.26	159.85	156.43	153.02	149.60	146.19	142.78	139.36	135.95
AllInitial - ENB in Mil. CHF	180.45	178.09	175.74	173.38	171.02	168.67	166.31	163.96	161.60
FlexInitial - Do nothing - ENB in Mil. CHF	162.25	158.84	155.42	152.01	148.59	145.18	141.76	138.35	134.93
FlexInitial - TM - ENB in Mil. CHF	183.77	181.32	178.88	176.47	174.06	171.65	169.24	166.83	164.42
τ_{TM} interv. 1 in years	3	3	3	3	3	3	3	3	3
τ_{TM} interv. 2 in years	-	-	4	4	4	4	4	4	4
τ_{TM} interv. 3 in years	-	-	-	-	-	-	-	-	-
τ_{TM} interv. 4 in years	-	-	-	-	-	-	-	-	-
FlexInitial - ROM AO - ENB in Mil. CHF	184.38	181.98	179.59	177.19	174.79	172.40	170.04	167.68	165.32
τ_{AO} interv. 1 in years	3	3	3	3	3	3	2	2	2
$q^{ex}_{\tau_{AO}}$ in year t=1	0.44	0.44	0.44	0.44	0.44	0.44	0.37	0.37	0.37
q^{ex}_{AO}	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00

F.3.6 Difference in rent for highly specialised and flexible use - ofrentDiff

For the moment, the exact value for keeping the additional space for expansion of the clinic, here defined as a difference in rent for “soft” use and “hard” use (see explanation in section 6.4.2 for FlexInit layout), is not known for certain. Thus, a variation was necessary. The difference in percent between the expected net benefits from the ROM AO and the TM for the FlexInitial layout and difference in percent between the expected net benefits from the TM for AllInitial and the FlexInitial layout increase both with increasing ofmtrasyear by 0.01% and 0.2% in total, negligible amounts, because with the ROM AO vs. the TM and the FlexInitial layout vs. the AllInitial layout, it is considered that the use of the additional space can be postponed if not absolutely necessary, thus avoiding the additional rent. The differences in expected net benefits remain negligible, though, and, thus, a possible variation has no impact on the results of the application and does not have to be considered further.

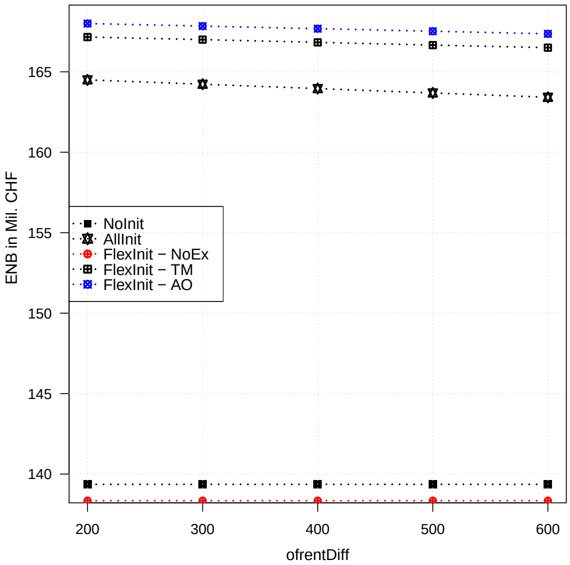

Figure F.18: SA: Rent difference ofrentDiff - All ENBs

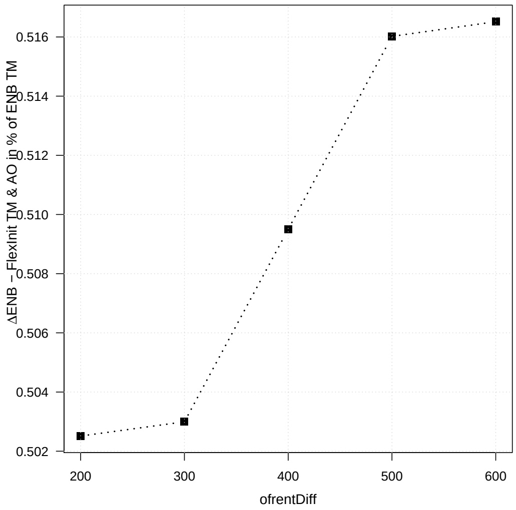

Figure F.19: SA: Rent difference ofrentDiff - ΔENB DEM AO - TM

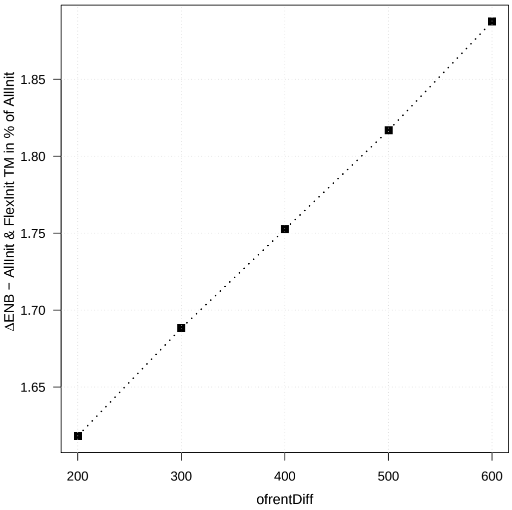

Figure F.20: SA: Rent difference ofrentDiff - ΔENB FlexInit TM - AllInit TM

Appendix G

Paper: “A methodology to ensure the consideration of flexibility and robustness in the selection of facility renewal projects”

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A Methodology to Ensure the Consideration of Flexibility and Robustness in the Selection of Facility Renewal Projects

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Abstract: Facilities are built to provide an adequate level of service over long periods of time. During these long periods of time, the required levels of service from facilities can change significantly, and these changes cannot be predicted with certainty. Having facilities that can be easily modified, or whose use can be easily modified, can increase the net benefit of facilities for owners over these long periods of time. This flexibility and robustness, respectively, should be adequately taken into consideration when designing and maintaining facilities, along with the myriad of possible futures that may occur and their associated probabilities of occurrence. In this paper, a systematic methodology is proposed that facility managers can use to identify possible changes in the required levels of service of facilities over specified time periods, to generate possible renewal projects to execute now and to evaluate these. The methodology is demonstrated by using it to determine possible projects to change a military barracks, to make it easier to use the barracks while accommodating future changes in the required amounts of space, and determining which of these yields the highest net benefit.

Keywords: Facility renewal, flexibility, robustness, project evaluation, decision making

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1 INTRODUCTION

Facilities are built to meet the needs of numerous stakeholders over relatively long periods of time. The ability of the facilities to meet these needs can change, however, due to changes in the values of external and internal influence factors, e.g. demand for space, space type or floor and room layout (Allehaux and Tessier 2002). These changes are not always known in advance, i.e. their future development is uncertain (De Neufville and Scholtes 2011; Dixit and Pindyck 1994).

Seeing that the future is uncertain, it can be advantageous to build or modify facilities now, so that they are either flexible, i.e. can easily be changed to accommodate possible future development if they occur, or robust, i.e. can easily accommodate possible future developments without being changed. The former is along the lines of the definition used by (Cardin and De Neufville 2008; Carthey et al. 2011). The latter is along the lines of the definition used by (Lin 2008). Having facilities built or modified so that they are either flexible or robust can help to ensure that facility managers avoid losses, e.g. by subletting space if initial demand decreases, and seize opportunities, e.g. by changing floor layout to accommodate new space demands (De Neufville and Marks 1974).

Unfortunately, many standard methods used by facility managers do not adequately take into consideration possible future developments and their associated probabilities of occurrence, when deciding what should be done with facilities (Kotaji et al. 2003; Wang et al. 2010). Keeping this in mind, a systematic methodology is presented in this paper, which is to be used by facility managers to help them do this. In more exact words, the methodology will help facility managers 1) to identify the possible changes in demand on facilities over an investigated time period, 2) to determine potential ways to build or modify facilities so that they are either flexible or robust, and 3) to evaluate these net benefits of these new or modified facilities.

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The methodology presented here builds on the comprehensive methodology presented by (De Neufville and Scholtes 2011) analysis of the flexibility and robustness of engineered systems. The modifications made are in many cases based on the work by (Cardin and De Neufville 2008) who conducted a comprehensive overview over the whole range of existing methods for the identification and evaluation of flexible or robust infrastructure. The methodology is demonstrated by using it to determine possible changes to a military barracks of the Swiss Army, to make it easier to accommodate possible changes in the demand for space, and determining which of these is the one that yields the highest expected net benefit. More details on the example can be found in (Della Morte 2012).

2 METHODOLOGY

The presented methodology can be divided in three main parts: 1) Model the system key parameters, 2) Identify possible projects, or ways to modify the facility, and 3) Evaluate the possible projects. These three main parts are presented in more detail in Table 1 and Table 2. Table 1 shows the sub-steps of Step 9 of the methodology in Table 2. The methodology can be followed at different levels, from using very simple qualitative methods to using very complex detailed estimates and assumptions, including the use of statistical methods for the interpretation of historical data and making forecasts, as demonstrated by (Cryer and Chan 2008), and the use of analytical methods for the identification of ways to modify the facilities, as demonstrated by (Hu and Poh 2011). The choice of level depends on the amount of time and effort availability of the facility manager and the requirements on the precision of the investigation.

3 CASE STUDY

3.1 Description of the case study

The case study is focused on the lodging building in an army barracks, built between 1862 and 1865 (the lodging building will in the following be referred to as "barracks"). The barracks area is used a training site with accommodations, training rooms, and parking spaces for troops. In the last 60 years only a few minor interventions have been executed on the barracks, leaving it in a relatively poor condition state. The owner would now like to adapt the barracks so that it can meet both current and future demands on it. It is assumed that the basic functioning of the building will not change, i.e. the building will be used for lodging, it will not be equipped with new types of equipment such as WLAN, different furniture, etc., and the amount of space soldiers will be given and the number of soldiers per room will not be changed.

The barracks can currently accommodate 278 soldiers during three separate periods of 12 weeks per year (spring, summer and winter); 134 persons per floor in regular beds, and 5 more persons per floor if necessary by introducing bunk beds. The lodging of soldiers is distributed over the 2nd and 3rd floors of the building. The current floor layout and room capacities are shown in Figure 1 and Figure 2. These are considered to be the floor layout and room capacities of the basic renewal project, herein referred to as project 0, which will be used later.

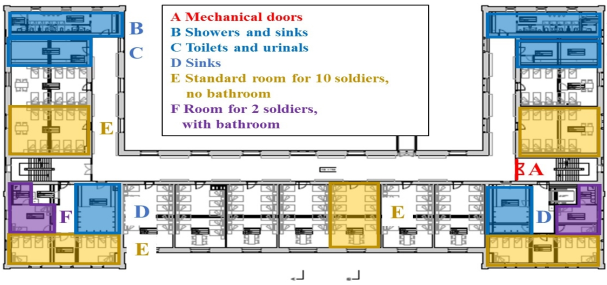

Figure 1. Project 0: Sanitary facilities and room types per floor

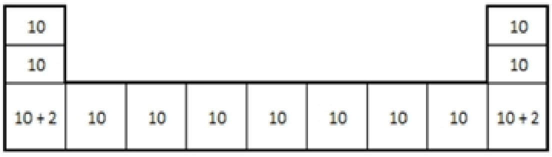

Figure 2. Room capacities of regular floor in the barracks building in persons

Currently, two companies are to be lodged simultaneously in the building during each of three 12 week periods per year. Each company consists of 160-180 soldiers in the winter school and 140-180 soldiers in the summer and spring schools. Each company is comprised of platoons of 20-60 persons. Companies and platoons consist of mixtures of men and women. To support group identification amongst soldiers and to avoid organizational problems, companies must all be lodged in one sector, and there cannot be persons from more than one platoon in a room. A sector is defined as an area having a bathroom and being separated from other sectors with doors. Currently, each of the two floors is one sector. For the main body of the companies, there are no bathrooms (defined as showers, sinks and toilets in one room), but separate sanitary facilities (see B, C and D in Figure 1). Female soldiers in the company must have access to different bathrooms than male soldiers. Currently, rooms for two with en-suite bathrooms in the corners of the floor are provided for the accommodation of female soldiers in a company (F in Figure 1).

3.2 Step 1: Assess level of service provided by and expected from facility

The level of service (LOS) to be provided by the barracks is to maximize the total net benefit of housing the

Table 1. Sub-process of Step 9: Identify possible projects

Sub-step	Description	Comments
9.1	Identify details of changes in facility use and operation (0,t]	The changes in facility use and operation over the investigated time period are to be structured so that it is easy to identify both the possible effects on the facility (i.e. with regard to interventions and operation) to maximize net benefit and the time that these should be done.
9.2	Identify necessary interventions and operations on facility in detail (0,t]	The necessary interventions and changes in operation on the facility are determined and organized in work programs (WP) and operation plans respectively, based on the general possible changes identified in the previous sub-step. These WPs include all interventions required to ensure that the general changes in use and operation will work and are planned in sufficient detail.
9.3	Construct possible renewal projects (t = 0)	The proposed renewal project is checked to see if it is well fitted to the possible future scenarios. In particular, it is checked to see if it is robust or flexible. Part of this process includes envisioning if the future possible changes to the facility would be better done now, or if the facility could be built differently now so that it would be easier to make the changes in the future if they were required.
9.4	Pre-screen possible projects	A prescreening is done to eliminate possible projects that are rather clearly not going to result in a maximisation of net benefit, i.e. either not flexible enough or robust enough. It is done to reduce the analysis effort in future steps. It can be done in many different ways. One is using a simple ranking based on expert opinion, and another is by defining a few basic critiera, and ranking these. The criteria can be weighted. If weighted, the sum of the multiplication between the score and weight will give the total score and will give insight into the most likely ways to change the facility to maximise net benefit. As this ranking is rather approximate, it is advisable to set a threshold where one can say which possibilities are to be considered further and which ones not.

required number of soldiers under consideration of all boundary conditions (see Table 3). Unused beds are to be avoided as fix costs, e.g. heating and cleaning costs, remain the same, without the benefit, e.g. rent, for a used bed for a soldier.

Table 3. Possible situation that might lead to inadequate LOS

No.	Description
1	Accommodate the required numbers of soldiers in two companies in each of the three schools every year in the barracks.
2	Accommodate all female soldiers
3	Male and female soldiers must have separate rooms and separate bathrooms.
4	Soldiers in a platoon must not share a room with soldiers of another platoon. They can, however, share bathrooms.
5	Soldiers in a company must all be accommodated within one sector.
6	Soldiers from a company are not allowed to pass through a sector that accommodates soldiers of another company, e.g. to reach a bathroom.
7	Persons from a third party are not allowed to pass through a sector that accommodates soldiers.

3.3 Step 2: Identify key parameters

The key parameters were generated by, first, identifying the situations where there was no way in which the required number of soldiers under consideration of all boundary conditions could be accommodated and, second, listing the possible reasons. This analysis was done with the help of facility stakeholders with knowledge of facilities situation and under consideration of the boundary conditions for the accommodation of companies and platoons, and both male and female soldiers (see Table 3). The possible situations would lead to inadequate LOS are shown in Table 4.

Table 4. Possible situation that might lead to inadequate LOS

Possible situation	Possible reason
Two companies cannot be accommodated	One company is too large for one floor; Platoons have an unfavourable number of soldiers and cannot be hosted in separate rooms without resulting in a large number of empty spaces.
Not all female soldiers can be accommodated	A company has more female soldiers than can be accommodated appropriately in the available space, i.e. in separate rooms.
Rooms are partially empty	Platoons have an unfavourable number of soldiers.
Sector is partially empty	One company has too many soldiers (male and female) for one floor and needs second floor; One company has too few soldiers (male and female) for one floor without resulting in a large number of empty spaces.

Table 2. Methodology steps

	No.	Step	Comments
Model system and key parameters	1	Assess level of service provided by and expected from facility	This step is done to obtain a general overview of how the facility is expected to function over the investigated time period. The expected function is defined in the level of service (LOS). This is to be done with taking into consideration how all of the elements in the facility work together. It often requires the involvement of stakeholders of the facility regarding their demands and processes in the facility.
	2	Identify key parameters	In this step all parameters whose values have a non-negligible probability of changing in a way that will have a large effect on the ability of the facility to provide an adequate LOS are to be identified. It is often useful to think of the processes that might lead to this changing, e.g. increases in fuel prices, the desire to have larger apartments. Thought then needs to be given as to which ones should result in a change to the facility.
	3	Analyse past evolution of values of possible key parameters	This step involves the collection and investigation of historical data for the most important key parameters to gain insight into which possible future scenarios may occur and with what likelihood.
	4	Analyse changes in trends	If there are changes in the trends observed in past data, the reasons why they have occurred and the factors that led to this need to be identified. This information needs to be used in the identification of such trend changes in possible future scenarios and in how likely they are.
	5	Develop models to predict likelihood of future scenarios	In this step models are developed based on the data, and the ability to use them to make future predictions is evaluated. The latter is done by verifying the ability of the developed models to make past predictions.
	6	Establish static model	An evaluation framework for system performance as a function of the key parameters is established. If it is assumed that the values of the key parameters can be predicted precisely, this is a static model. The development of an appropriate model requires an understanding of how the facility provides an adequate LOS, as well as how system performance is affected by a myriad of economic, environmental and social factors.
	7	Establish dynamic model	The static model is to be extended to represent the possible variations in the selected uncertain key parameters, the interactions between them and their influence on the system performance. If desired, the effect of variations in the values of the key parameters of the static model on future benefit are tested using a sensitivity analysis. The parameters with the largest effect on future benefit are to be included in the dynamic model, keeping in mind the amount of work associated with the evaluation of each scenario and the level of detail required in the analysis. Once the key parameters to be used are decided, the ranges of these parameters are to be determined and the uncertainty associated with their values needs to be modelled.
Identify renewal projects	8	Identify possible ways (for t > 0) to change the facility use or operation so that new LOSs could be provided	In this step, possible changes to facility use and operation to adapt the facility to different future scenarios with the potential to maximize net benefits are determined. The determination of facility use and operation often requires the definition of new LOSs, and explicit consideration of how it could change over the investigated time period. This step involves considerable brainstorming, and discussions with the stakeholders of the facility and process specialists.
	9	Identify possible renewal projects at t=0	In this step, possible interventions* over the investigated time period to enable the above determined changes to improve facility use and operation need to be defined. Then, special consideration should be given to the definition of possible interventions at t $= 0$, which are referred to here as renewal projects. The sub process is shown in Table 1.
Evaluate renewal projects	10	Estimate additional costs of each renewal project	In this step, the costs and benefits in each unit time for each investigated way to improve facility use and operation and way to change the facility are estimated. This is done for each investigated future, i.e. for each possible facility use and operation scenario and all possible values for the key parameters. This step is to be done without consideration of probabilities of occurrence of each possible future or the ability of the facility manager to change plans based on newly obtained information in the future.
	11	Estimate additional net benefits of each project	In this step, the cumulative costs and benefits of each identified possibility taking into consideration the probabilities of occurrence of the values of the key parameters in the future and the ability of a manager to change plans based on newly obtained information in the future. They are to be estimated relative to a reference way to modify the facility.

*An intervention is defined as all human activities undertaken during the operation of the facility to enable the facility to function at the required LOS. Interventions can also be executed while the facility is still, at least partially, functioning.

The key parameters deducted from the possible situations listed in Table 4 are given in Table 5, along with further explanation. It was considered that it would be unlikely that the variation in all other possible parameters would result in changes to how the building should be modified.

3.4 Step 3: Analyse past evolution of values of possible key parameters

The number of soldiers in a company in the barracks depends predominately on the internal regulations of the army and does not correlate with the number of soldiers per company in the past, i.e. the analysis of soldier numbers in the past is not useful for predictions about the future.

The number of female soldiers in the barracks depends on the percentage of female soldiers in the army compared to the total number of soldiers in the army. Thus, the number of female soldiers in the barracks depends, indirectly, on 1) the total number of soldiers (both male and female) in the army and 2) the number of female soldiers in the army (see Figure 5). The number of women joining the army and the total number of soldiers in the army vary independently from year to year.

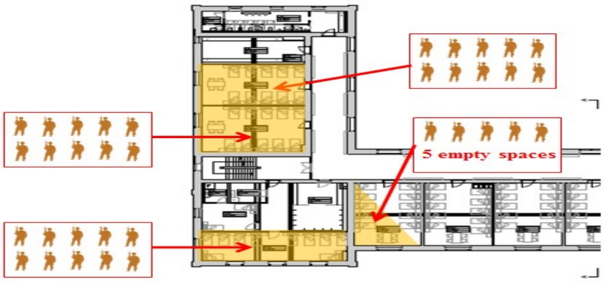

Figure 3. Example of empty spaces with a platoon of 35 soldiers

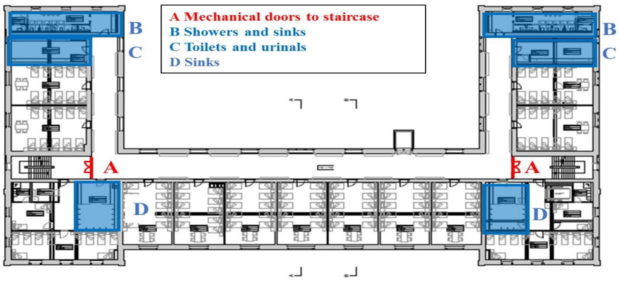

Figure 4. Access to sanitary facilities on floor

The influence of the total number of soldiers in the army on the number of female soldiers in the barracks is explained by the fact that if the number of female soldiers in the army is constant and the total number of soldiers in the army decreases, the army administration will decide to close some barracks and accommodate the remaining male and female soldiers in the remaining ones. If the number of soldiers in a company remains constant this will lead to an increase in the percentage of female soldiers in each company and, therefore in the barracks (see Figure 6).

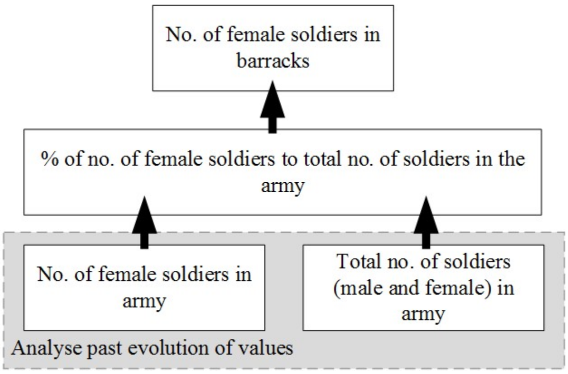

Figure 5. Illustration of the dependency of the no. of female soldiers in the barracks

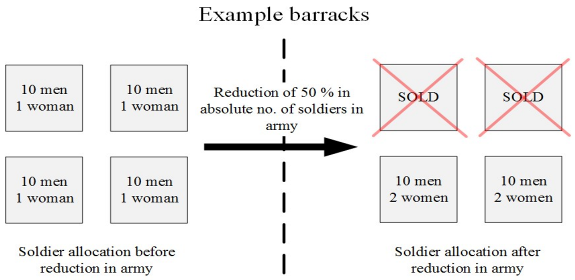

Figure 6. Example of the influence of a reduction of total no. of soldiers in the army on no. of female soldiers in the barracks

The conclusion is that, to gain accurate information about the number of female soldiers in the barracks, it is necessary to analyse the past evolution of the total number of soldiers in the army and the number of female soldiers in the army, and use this information to estimate the number of female soldiers in the barracks appropriately in the dynamic model in Step 7.

In Figure 7, the evolution of the number of female soldiers between 2005 and 2012 in the army is given in terms of absolute numbers and the percentage of the total number of soldiers in the army; in Figure 8 the evolution of the percentage of female soldiers to the total number of soldiers is given. Although not shown here it is interesting to note that women can voluntarily join the army since 1995.

Figure 9 shows the evolution of the total number of soldiers in the army from 1977 to 2012. Armee XXI* forced the total number of soldiers in the army to be reduced in 2004 from 350,000 to 200,000; thus, for predictions, the data prior to 2004 (Figure 10) is not relevant.

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*Armee XXI is a designation that denotes the current structure of the Swiss Army adapted to the current demands in Europe.

Table 5. Selected key parameters

Key parameter	Depends on	Reasons for choice
No. of soldiers in a company in the barracks	Internal army policies	As soldiers of two different platoons cannot be hosted in the same room, and rooms are to lodge a maximum of ten soldiers, platoons which are not multiple of ten soldiers will result in empty spaces (see Figure 3). As one floor cannot be used for more than one company, soldier needs to have access to the whole floor to reach all sanitary facilities (see Figure 4), and soldiers from other companies or persons from third parties are not allowed to enter a sector accommodating a company, it is not possible to rent eventual empty space to third parties or host members of a second company.
No. of female soldiers in the barracks	No. of female persons recruited in the army each year	As female and male soldiers need separate bathrooms and there are currently only separate bathrooms in two rooms provided for two female soldiers, i.e. the barracks capacity for female soldiers is only 4 per floor, if there are more than a total of 4 female soldiers in the two companies to be accommodated, it will not be possible to accommodate both companies.

Figure 7. Absolute number and percentage of female soldiers (Walser 2010)

Figure 8. Absolute number of soldiers and percentage of female soldiers (Walser 2010)

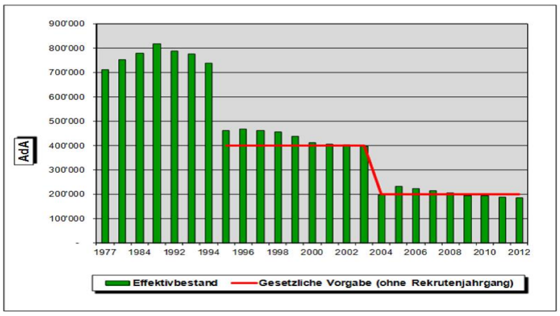


Figure 9. Historical data about the total number of soldiers (active soldiers and reserves) (Walser 2010)

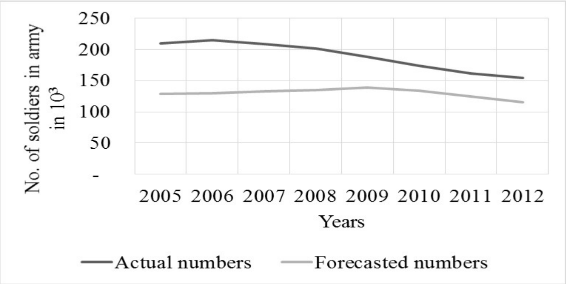


Figure 10. Development of soldiers number in the Armee XXI (only active soldiers) (Walser 2010)

It can be seen in Figure 10 that the actual total number of soldiers in the Swiss Army is decreasing over time and does not correspond to the forecasted numbers. Possible reasons for this decline could be the general decrease in persons who could be recruited, an increase in the number of persons doing civil service or deferring their obligatory service (e.g. due to going to university or due to work).

3.5 Step 4: Analyse changes in trends

As the number of soldiers in a company in the barracks depends predominately on the internal regulations of the army and does not correlate with the number of soldiers per company in the past, i.e. the analysis of soldier numbers in the past is not useful for predictions about the future, no trends were identified and thus no significant changes to this trend.

The significant changes in trends of the number of female soldiers in the barracks can occur depending on the size of the army as a whole (also compare Step 3), i.e. the total number of soldiers in the army. Politicians have been already discussing further reductions of the total number of soldiers in the Swiss Army to 80,000 active soldiers (from 200,000) (Walser 2010).

This corresponds to similar political decisions in the past (compare Figure 9). According to the managers of the barracks, the reduction will likely occur before 2027.

3.6 Step 5: Develop models to predict likelihood of future scenarios

The model to predict the future values of the number of soldiers in a company in the barracks is not based on past evolution of this number but on knowledge about possible company sizes, as the company size is defined by army administration for each year, and as it was concluded that the latter had much more weight than the former. The facility managers estimated that the yearly number of soldiers in each company could vary between boundaries of 160 and 180 for the winter school, and 140 and 180 for spring and summer schools. In addition the number depends directly on the number of soldiers in the platoons, in which the facility managers estimated could vary between the boundaries of 20 and 60.

As the number of soldiers in a platoon is relevant, the number of soldiers in a company was modelled indirectly through a model using the number of soldiers in a platoon (x_t^P in Equation 1), which was considered as an independent and identically distributed variable with a discrete uniform probability function for the occurrence of any time increment over the investigated time period (see Equation 1). The variable increments were chosen as 5, e.g. possible outcomes were 20, 25, 30, 35, 40, etc. The number of soldiers in a company was determined by summing the number of soldiers in platoons, up to the boundary for company size. It was assumed that each company consisted of four platoons.

$$x_t^P \in [20, 60] \quad with \quad P(x_t^P) = \frac{1}{n}, n = 9 \tag{1}$$

The number of female soldiers in the barracks (x_t^F in Equation 2) was modelled as a function of the number of soldiers and the number of female soldiers in the army, these two parameters were modeled (see dependency in Figure 5). The fluctuation per year was modelled using a random walk function with drift factor (see Equation 2).

$$x_t^F = \alpha \cdot x_{t-1}^F + \varepsilon_t \tag{2}$$

where α is the drift factor with α=1+1/37, i.e. α denotes the increase of the average value over time; x_{t-1}^F is the number of female soldiers in the army at time t-1; ε_t is assumed to be normally distributed with the standard deviation δ , i.e. the variation of the value around the average.

The model for the total number of soldiers in the army was simplified as a jump process of the form:

$$x_t^S = 200,000 + dq \tag{3}$$

where λ is the mean arrival rate of the reduction in the total number of soldiers in the army, i.e. the conditional probability of reduction (see Table 6).

This simplification was considered possible as it was believed that only a substantial reduction in the total number of soldiers in the army would have an influence on the number of female soldiers in the barracks, e.g. as it would require a political change in the army (see also Figure 6).

Table 6. Probabilities of reduction of number of soldiers in the Swiss army

Year of reduction to 80,000	Probability of reduction λ
2015-2019	50%
2020-2025	75%
$\geq$ 2026	100%

The number of female soldiers in the army was assumed to be constant regardless of the change in the number of soldiers.

3.7 Step 6: Establish static model

The static model to be used to determine the expected net benefit of each scenario at the beginning of the investigated time period is:

$$NB = \sum_{t=0}^{T} \Big((1+r)^{-t} \left(OC_t - IC_t \right) \Big) - MC \tag{4}$$

where OC_t are the operational costs and benefits for comparison, calculated per year (i.e. for all three schools); IC_t are the costs occurring for interventions during the investigated time period, calculated per year; MC are the costs for additional changes in the barracks today; t is the time in years; r is the discount factor.

The yearly operational costs (and benefits) are calculated as:

$$OC_t = \sum_{k=1}^{3} (UB \cdot x_{t,k} - UC \cdot y_{t,k}) \tag{5}$$

where UB are benefits in form of rent paid by the government per accommodated soldier in CHF/soldier*month (see Table 7); $x_{t,k}$ is the number of soldiers accommodated per month of school period, including female soldiers; UC are costs per provided bed space*month of school period (see Table 7); $y_{t,k}$ is the number of provided bed spaces per month of school period; k denotes the spring (1), summer (2) or winter (3) schools.

Table 7. Monthly unit costs and benefits

Operational cost parameter	Unit	Assumption
Costs	[CHF/bed space*month]	47*
Benefits	[CHF/soldier*month]	201*

*Source: (Immobilien 2011)

The net benefit for the case, where there are no changes in facility use and operation or the facility itself over the investigated time period, i.e. project 0, and the values of all key parameters are known with certainty and are given in Table 8, is 4.51 × 10^6 CHF.

Table 8. Parameter values used in the static model

Input parameters	Unit	Assumption
No. of soldiers in a company in the barracks in winter	[Bed spaces]	140
No. of soldiers in a company in the barracks in summer and spring	[Bed spaces]	135
Lost space per company	[Bed spaces]	10
Expiration date of the spring recruit school	[Year]	2017
Scenario for no. of female soldiers in a company in the barracks	[-]	Average scenario (compare Figure 11)
Discount rate	[%]	3

3.8 Step 7: Establish dynamic model

The dynamic model was created using the number of soldiers per company in the barracks and number of female soldiers per company in barracks as the variable independent parameters. The variation in the number of soldiers per company in the barracks over time was considered to be modelled through the number of soldiers in the platoons, as explained in section 3.6. The probability distribution of the number of soldiers in a platoon was assumed to be uniform, according to the definition in Equation 1.

The variation in the number of female soldiers in the barracks over time was modelled by combining the random walk model of the number of female soldiers in the army (Equation 2) and the jump process model for the total number of soldiers in the army (Equation 3) to determine the expected number of female soldiers in the barracks, as shown in Equation 6, i.e. when the future possible activities are executed. The example scenarios for the evolution of the number of female soldiers in the barracks are shown in Figure 11.

$$x_t^B = (1+\lambda) \cdot \frac{x_{t=2012}^B}{x_{t=2012}^F} \cdot x_t^F \tag{6}$$

Where x_t^B is the number of female soldiers to be lodged in the barracks in year t; x_t^F is the number of female soldiers in the army in year t; $x_{t=2012}^F$ is equal to 4; $x_{t=2012}^F$ is equal to 1050; λ is the probability of reduction of the army (Table 6).

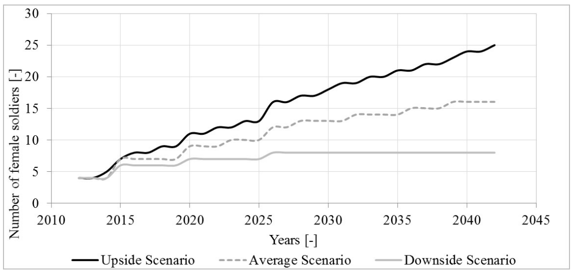


Figure 11. Three example scenarios of the evolution of the no. of female soldiers in the barracks

3.9 Step 8: Identify possible ways to improve facility use and operation

Keeping in mind the above stated LOS, any change to the building will be made to ensure that it can accommodate two companies over the investigated time period while minimizing the number of unused spaces. A brainstorming of experts lead to the possible changes to improve facility use as shown in Table 9.

Table 9. Possible changes in facility use and operation

No.	Changes in use and operation	Reason for choice
1	Provide more, but smaller, rooms	If more, but smaller, rooms were provided it would be easier to accommodate companies with larger variations in the numbers of soldiers in platoons without having empty spaces.
2	Divide floors into multiple sectors; Provide bathrooms to make separation in multiple sectors possible	If the floors were divided into multiple sectors, with the appropriate changes to the number of bathrooms, it would allow better redistribution of soldiers if they required more space than is provided by one floor, or if they were not large enough to occupy a whole floor. Space that was not occupied once two companies were housed, or even if only one company was housed, could be cordoned off and rented to third parties.
3	Provide more rooms with separate, en-suite bathrooms.	If more rooms with en-suite bathrooms were provided it would be more easily possible to accommodate more female soldiers or to distribute them differently within the barracks.

Table 10. Sub-process of Step 9: Identify possible renewal projects

No.	Sub-step	Description (short)
9.1	Identify details of changes in facility use and operation (0,t]	1. Provide more but smaller rooms; 2. Divide floors into multiple sectors (incl. bathrooms and entrances, separated by walls); 3. Provide bathrooms so separation of sectors is possible; 4. Provide separate rooms with separate, en-suite bathrooms.
9.2	Identify necessary interventions and operations on facility in detail (0,t]	1. Provide smaller rooms (e.g. for 5 beds) for housing female soldiers; 2. Install partitions that allow subdividing the sectors on each floor (e.g. by walls and doors, flexible or not); 3. Install bathrooms with showers, toilets and sinks in each sectors for each company; 4. Install extra bathrooms for female soldiers.
9.3	Construct possible renewal projects (t = 0)	The three new projects are explained in Table 11 and are illustrated in Figure 12 to Figure 14.
9.4	Pre-screen possible projects	The three new projects are evaluated using the following criteria: 1. the additional time required for modification in t = 0; 2. the additional cost required for modification in t = 0; 3. the additional life cycle impact for modification at t=0; 4. the limitation of the degree of freedom, and 5. the added value Each project was given a number from 1 to 5 for each criteria. These are shown for each project, along with the averages, in Figure 15.

3.10 Step 9: Identify possible projects

With the changes defined in Step 8, three possible projects for the barracks were identified with the help of the sub-steps in Table 10. Their rankings are shown in Figure 15. As project 3 is clearly preferred over the other projects it is selected to be the project implemented in the project.

3.11 Step 10: Estimate additional costs of each project

The additional costs at t = 0 of project 3 when compared to project 0 are shown in Table 12. They only include the modification costs as it is assumed that the change of bathrooms and the creation of four rooms for 5 soldiers leads to the same costs as the creation of two rooms of 10 soldiers and, thus, no additional costs at time t = 0.

Table 12. Additional project costs

Item	Unit	Unit cost [CHF]	Extent
Electric doors	No.	15,000	6
Mechanical doors	No.	500	6
Separation walls	m^2	150	50
Total			100,500

3.12 Step 11: Estimate additional expected net benefits of each project

The optimal renewal project with its interventions (in this case the choice is between project 0 and project 3) is chosen according to the expected additional net benefit ENB. The additional net benefit for each scenario is calculated according to Equation 7.

$$ENB = \sum_{t=0}^{T} \left((1+r)^{-t} \left(OC_{t,x}^{ci} - IC_{t}^{ci} \right) \right) - MC^{ci} \quad (7)$$

where ci is one of all possible combinations of renewal project and its interventions out of the complete set CI, in this case project 0 and project 3; MC^{ci} are the costs for additional changes in the renewal project in the barracks today (for project 0: 0 CHF, for project 3: see Table 12); IC_t^{ci} are the costs occurring for interventions during the investigated time period, calculated per year; $OC_{t,x}^{ci}$ are the operational costs and benefits for comparison, calculated per year (i.e. for all three schools); t is the time in years; r is the discount factor; s is the future scenario.

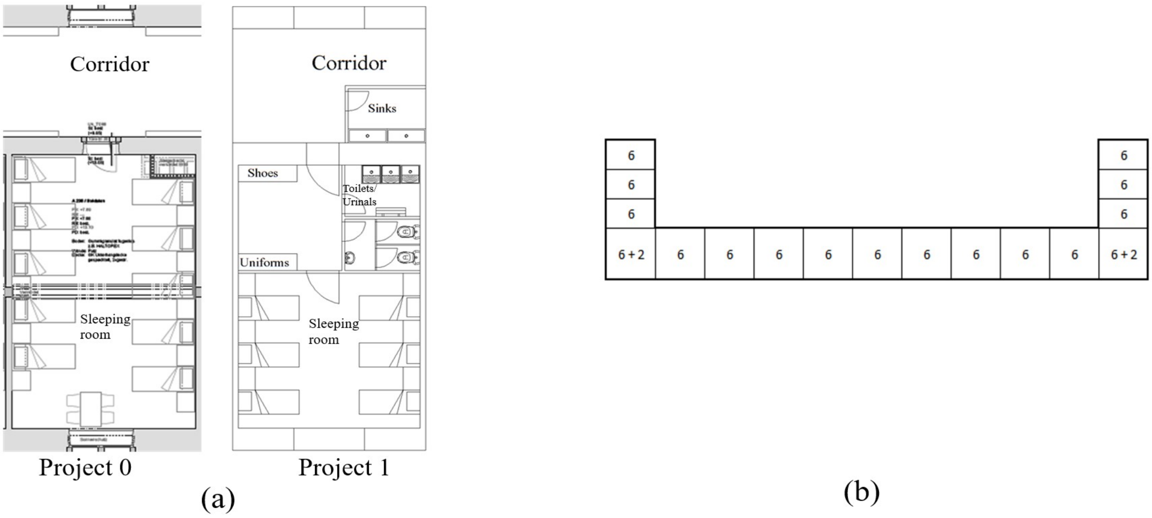
The yearly operational costs and benefits, OC, are calculated as:

$$OC_{t,s}^{ci} = \sum_{k=1}^{3} \left(UB \cdot (x_t^{REG} + x_t^{WK}) - UC \cdot y_{t,k}^{ci} \right) \quad (8)$$

where UB are benefits in form of rent paid by the government per accommodated soldier in CHF/soldier*month (see Table 7); x_t^{REG} is the number of soldiers in the regular recruit school in two companies accommodated per month of school period (model is described in section 3.6); x_t^{WK} is the number of soldiers in a platoon in the repetition course accommodated per month of school period (for project 0, x^{WK} is 0, as no third parties can be accommodated; for project 3, the model is assumed to be similar to the one in Equation 1); UC are costs per provided bed space and month of school period (see Table 7); $y_{t,k}^{ci}$ is the number of bed spaces (in this case 278); k denotes spring (1), summer (2) or winter schools (3).

Table 11. New projects

Project	Changes in the renewal project at t = 0		Possible interventions in the future	General advantages	General disadvantages
	Label	Description	When threshold values indicate that this would increase net benefit	In numerous future scenarios this would lead to	In numerous future scenarios this would lead to
1	Flexible	Add water pipes in the ceilings for individual bathrooms; Provide space for additional ventilation in the ceilings to enable en-suite bathrooms; Modify current bathrooms and toilets so that they can easily be turned into normal rooms.	Reduce spaces per room to 6 soldiers instead of 10 (Total no. in barracks: 248 soldiers); Build individual bathrooms into each room; Turn current sanitary facilities into accommodation rooms.	Reduction of empty spaces through less empty spaces in rooms; Increase in the number of spaces that could be rented since every room is “independent” (private bathrooms).	Reduction of the total number of available spaces; Highest costs of all three projects for future interventions.
2	Robust	Turn rooms with showers (1 in Figure 4) into complete bathrooms; Turn rooms with toilets and urinals into accommodation rooms (2 in Figure 4); Turn rooms with sinks (3 in Figure 4) and half of adjacent rooms into complete bathrooms (G in Figure 13); Turn remaining half of corner rooms into rooms for five (C in Figure 13).	Add individual bathrooms in corner rooms for 5 (C in Figure 13); Add water pipes and ventilation for en-suite bathrooms; Add separation wall and electronic doors to create 3 sectors (A in Figure 13).	Reduction of empty spaces; Increase in the number of spaces that could be rented; Overall costs for project are lower than for project 1.	Reduction of the number of empty spaces due to the relatively large sectors, but not to the same extent as project 1.
	Flexible	Provide additional water pipes for bathrooms in corner rooms for 5 soldiers (C in Figure 13); Provide space for additional ventilation for corner bathrooms for 5.			
3	Robust	Turn rooms with showers (1 in Figure 4) into complete bathrooms; Turn rooms with toilets and urinals into accommodation rooms (2 in Figure 4); Turn rooms with sinks (3 in Figure 4) and half of adjacent rooms into complete bathrooms (G in Figure 13); Turn remaining half of corner rooms into rooms for five (C in Figure 13); Add separation wall and electronic doors to create 3 sectors (A in Figure 13); Add separation wall in long corridor to create 6 sectors (A in Figure 13); Add individual bathrooms in corner rooms for 5 (C in Figure 13); Add water pipes and ventilation for individual bathrooms (C in Figure 13);	None	Reduction of empty spaces in comparison to project 2; Obtainment of more rentable sectors in comparison to project 2; Increase in the number of spaces that could be rented; Overall expenses for project are lower than for project 1;	High, certain costs for additional renewal project now.



(a)

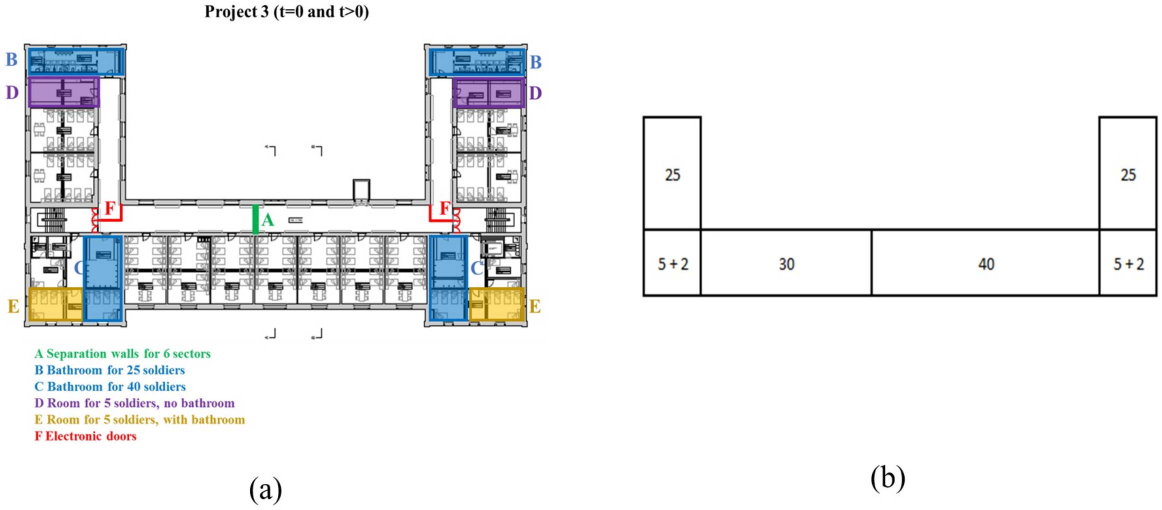
(b)

Figure 12. Project 1: (a) Detail standard room in comparison to Project 0, (b) Floor layout (comp. Figure 2)

(a)

(b)

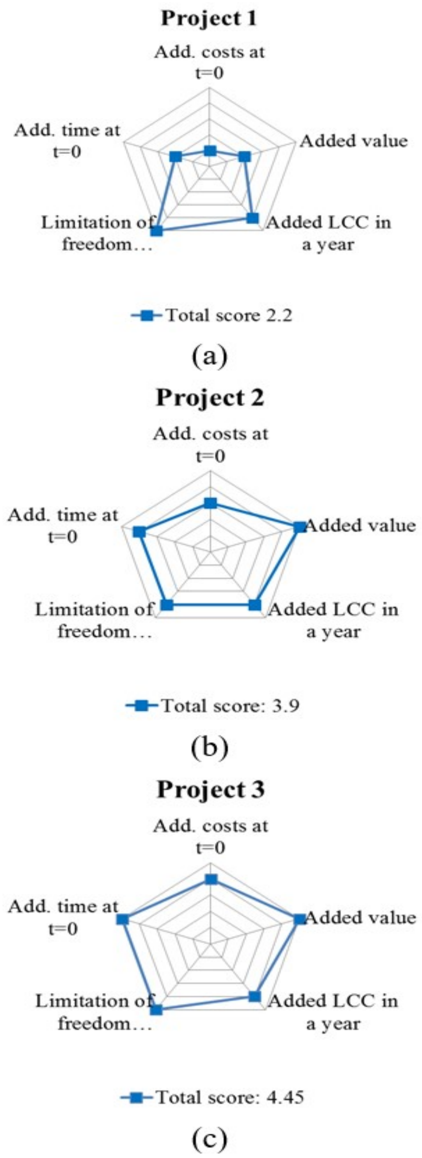
Figure 13. Project 2: (a) Detail of floor in comparison to Project 0, (b) Floor layout (comp. Figure 2)



(a)

(b)

Figure 14. Project 3: (a) Detail of floor, (b) Floor layout (comp. Figure 2)



(a)

(b)

(c)

Figure 15. Radar charts for each project

The objective function for the choice between renewal projects in set IC is:

$$\max_{ic \in IC} ENB \tag{9}$$

Figure 16(a), shows the results from the simulation of the expected net benefits for both project 0 and project 3 for different scenarios of the uncertain key parameters. These were estimated using equation 7, the probabilistic distributions for the key parameters given in Equation 1 and 3 and running 2000 Monte-Carlo simulations. Seeing that project 3 makes it easier to allocate female soldiers and any number of soldiers in a platoon and facilitates renting empty space to repetition courses, the additional net benefits may be seen as the value of the additional flexibility of project 3. The expected additional net benefits of project 3 over project 0 were estimated as 1.8×10^6 CHF. This was done by subtracting the net benefit of project 3 from the net benefit of project 0 (Figure 16).

4 DISCUSSION

In this paper, a methodology to ensure the consideration of flexibility and robustness in the selection of facility renewal projects is provided. Use of the methodology helps to ensure that appropriate consideration is given to the flexibility and robustness of the facility, and that appropriate consideration is given to the uncertain level of service required from the facility and how it might be changed to deal with these different possible levels of service.

The analyzed case study demonstrates how the methodology is to be used, and shows how its use can lead to the determination of a renewal project that may increase the net benefit of the facility manager by ensuring that she is better prepared for the future. Specifically, the proposed optimal project, project 3 for the case study, which divides the building in independent sectors, leaves the facility manager better able to respond to changes in the number of soldiers in a company and the number of female soldiers in the barracks, than the other considered projects. Project 3 was found to provide an added value of 1.8 Mio. CHF over the next 30 years, when compared to the reference project, i.e. an increase in of 45%.

The application of this methodology is heavily reliant on stakeholder knowledge about the things that might affect the required levels of service in the future, how the facility can be modified, how the use of the facility can be modified and how the facility itself may change over time; thus, the first step of facility analysis level 1 is the most time consuming part. To ensure that stakeholder knowledge is obtained as best possible, good stakeholder communication and management is essential.

The determination of the ranges of the values of the key parameters and their probabilities of occurrence is essential for the choice and the evaluation of flexible and robust projects; however, this quantification is not always straightforward, e.g. in case of political decisions which are hard to predict. Thus, the results of the evaluation have to be treated carefully, as they are based on simplifications and assumptions. Nonetheless, if made carefully, the general recommendations have a relatively high probability of being correct.

The application of the methodology in the case study has also shown that, even with simple situations as the one analysed, substantial simplifications are required to make the analyse tractable. Although simplification are unavoidable, they do need to be made with care so as not to exclude important key parameters and their projects.

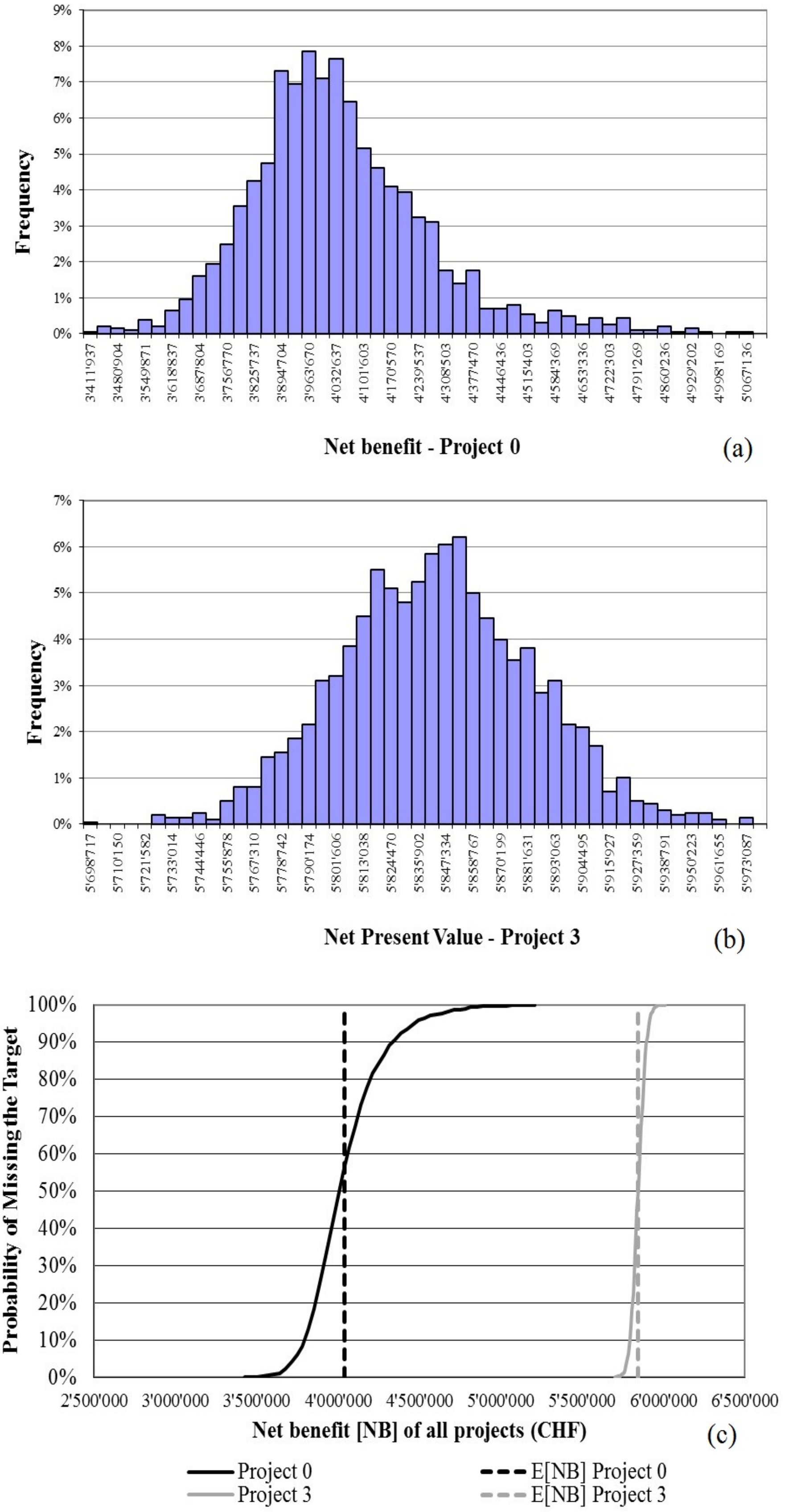


Figure 16. (a) Density function of net benefit of Project 0, (b) Project 3, (c) Comparison in cumulative distribution function

5 CONCLUSION

The presented methodology is a systematic way to ensure the consideration of flexibility and robustness in the selection of facility renewal projects. Its use in many cases is expected to lead to increases in the net benefits to facility managers. Future work will involve the testing of the methodology on other real world examples where renewal projects are to be identified that maximize the benefit of the facility manager, and on other real world examples at substantially different scales, e.g. the identification of the possible expansions to infrastructure networks to accommodate future city growth.

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Curriculum Vitae

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