International Journal of Architecture, Engineering and Construction
Vol 4, No 3, September 2015, 126-139

# A Methodology to Ensure the Consideration of Flexibility and Robustness in the Selection of Facility Renewal Projects

Miriam Esders[1,*], Nicola Della Morte[2] and Bryan T. Adey[1]

[1]Department of Structural, Environmental and Geomatic Engineering
Institute of Construction and Infrastructure Management, ETH Zurich, Switzerland
[2]Ernst Basler und Partner AG, Zurich, Switzerland

**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

**DOI:** 10.7492/IJAEC.2015.013

## 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.

*Corresponding author. Email: esders@ibi.baug.ethz.ch

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.

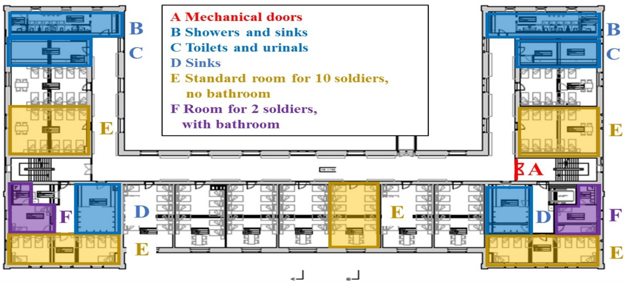


**Figure 1.** Project 0: Sanitary facilities and room types per floor

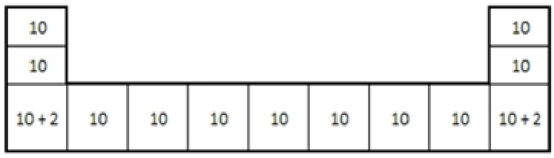


**Figure 2.** Room capacities of regular floor in the barracks building in persons

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;<br>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;<br>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.

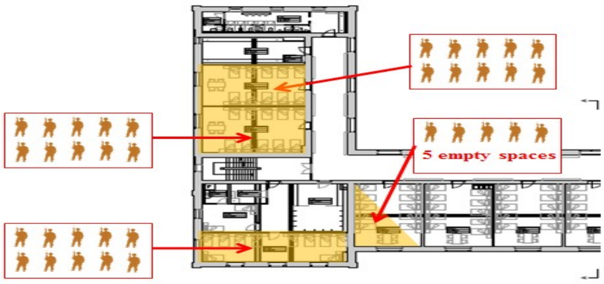


**Figure 3.** Example of empty spaces with a platoon of 35 soldiers

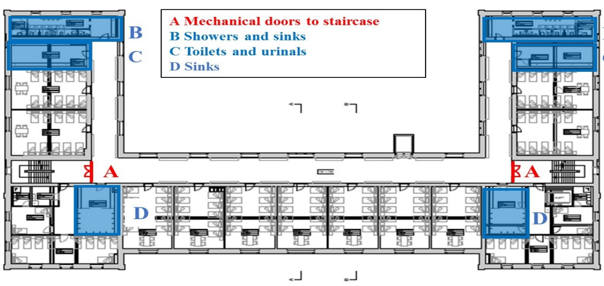


**Figure 4.** Access to sanitary facilities on floor

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).

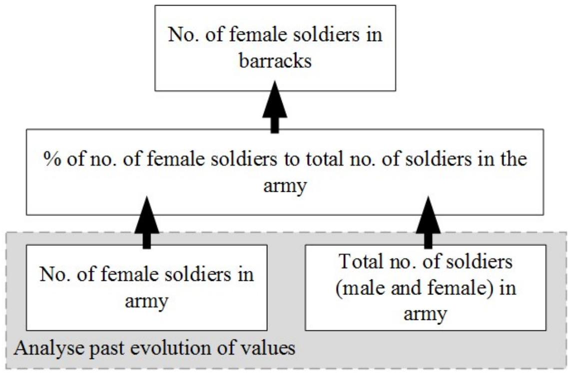


**Figure 5.** Illustration of the dependency of the no. of female soldiers in the barracks

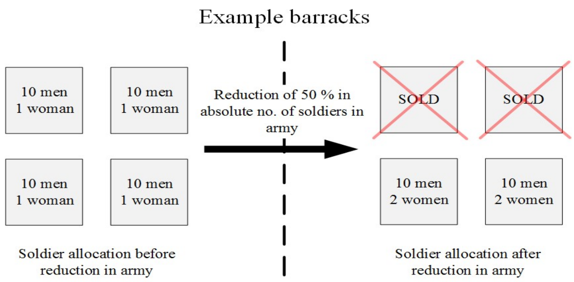


**Figure 6.** Example of the influence of a reduction of total no. of soldiers in the army on no. of female soldiers in the barracks

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.

*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)

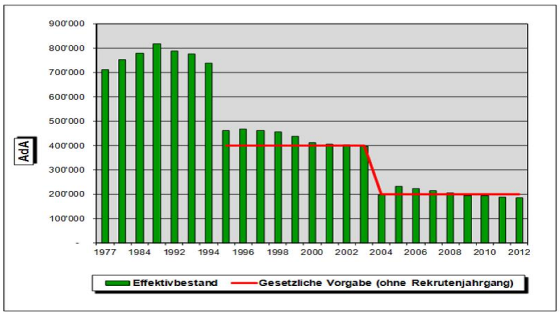


**Figure 9.** Historical data about the total number of soldiers (active soldiers and reserves) (Walser 2010)

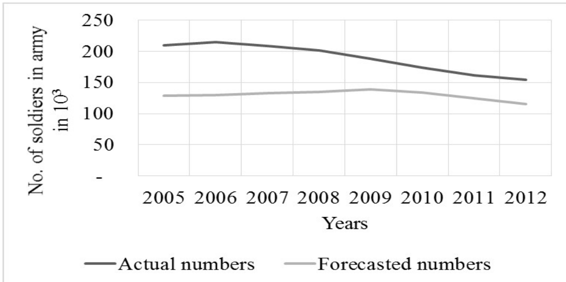


**Figure 10.** Development of soldiers number in the Armee XXI (only active soldiers) (Walser 2010)

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 $\alpha$ is the drift factor with $\alpha$=1+1/37, i.e. $\alpha$ 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; $\varepsilon_t$ is assumed to be normally distributed with the standard deviation $\delta$ , 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 $\lambda$ 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 $\lambda$ |
|---|---|
| 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:

$$NB = \sum_{t=0}^{T} \left( (1+r)^{-t} \left( OC_t - IC_t \right) \right) - MC \tag{4}$$

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.

$$x_t^B = (1+\lambda) \cdot \frac{x_{t=2012}^B}{x_{t=2012}^F} \cdot x_t^F \qquad (6)$$

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; $\lambda$ is the probability of reduction of the army (Table 6).

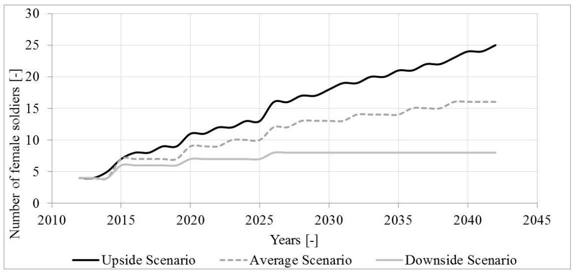


**Figure 11.** Three example scenarios of the evolution of the no. of female soldiers in the barracks

## 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;<br>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);<br>Build individual bathrooms into each room;<br>Turn current sanitary facilities into accommodation rooms. | Reduction of empty spaces through less empty spaces in rooms;<br>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;<br>Highest costs of all three projects for future interventions. |
| 2 | Robust | Turn rooms with showers (1 in Figure 4) into complete bathrooms;<br>Turn rooms with toilets and urinals into accommodation rooms (2 in Figure 4);<br>Turn rooms with sinks (3 in Figure 4) and half of adjacent rooms into complete bathrooms (G in Figure 13);<br>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);<br>Add water pipes and ventilation for en-suite bathrooms;<br>Add separation wall and electronic doors to create 3 sectors (A in Figure 13). | Reduction of empty spaces;<br>Increase in the number of spaces that could be rented;<br>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);<br>Provide space for additional ventilation for corner bathrooms for 5. | | | |
| 3 | Robust | Turn rooms with showers (1 in Figure 4) into complete bathrooms;<br>Turn rooms with toilets and urinals into accommodation rooms (2 in Figure 4);<br>Turn rooms with sinks (3 in Figure 4) and half of adjacent rooms into complete bathrooms (G in Figure 13);<br>Turn remaining half of corner rooms into rooms for five (C in Figure 13);<br>Add separation wall and electronic doors to create 3 sectors (A in Figure 13);<br>Add separation wall in long corridor to create 6 sectors (A in Figure 13);<br>Add individual bathrooms in corner rooms for 5 (C in Figure 13);<br>Add water pipes and ventilation for individual bathrooms (C in Figure 13); | None | Reduction of empty spaces in comparison to project 2;<br>Obtainment of more rentable sectors in comparison to project 2;<br>Increase in the number of spaces that could be rented;<br>Overall expenses for project are lower than for project 1; | High, certain costs for additional renewal project now. |

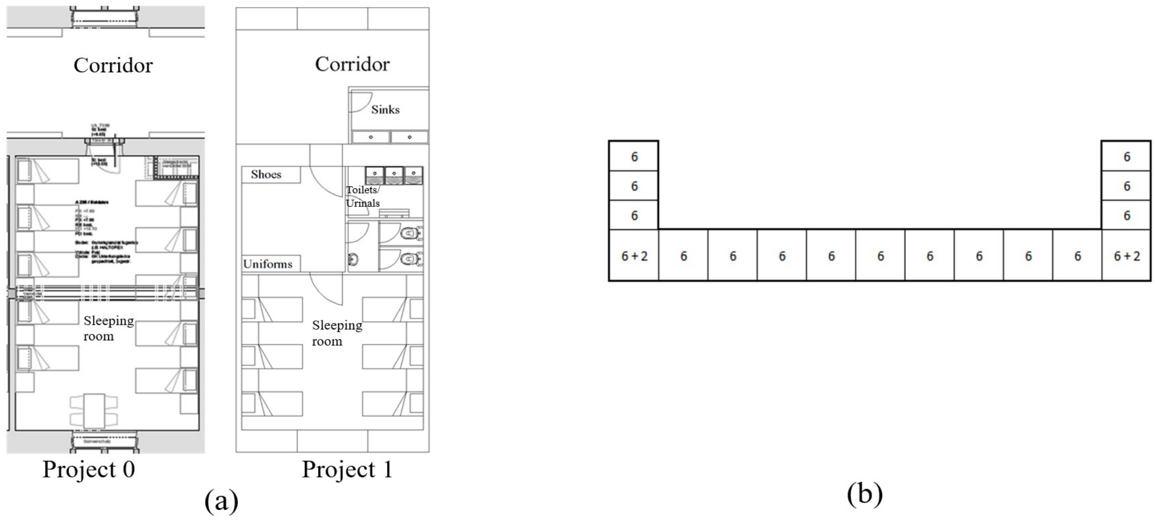


**Figure 12.** Project 1: (a) Detail standard room in comparison to Project 0, (b) Floor layout (comp. Figure 2)

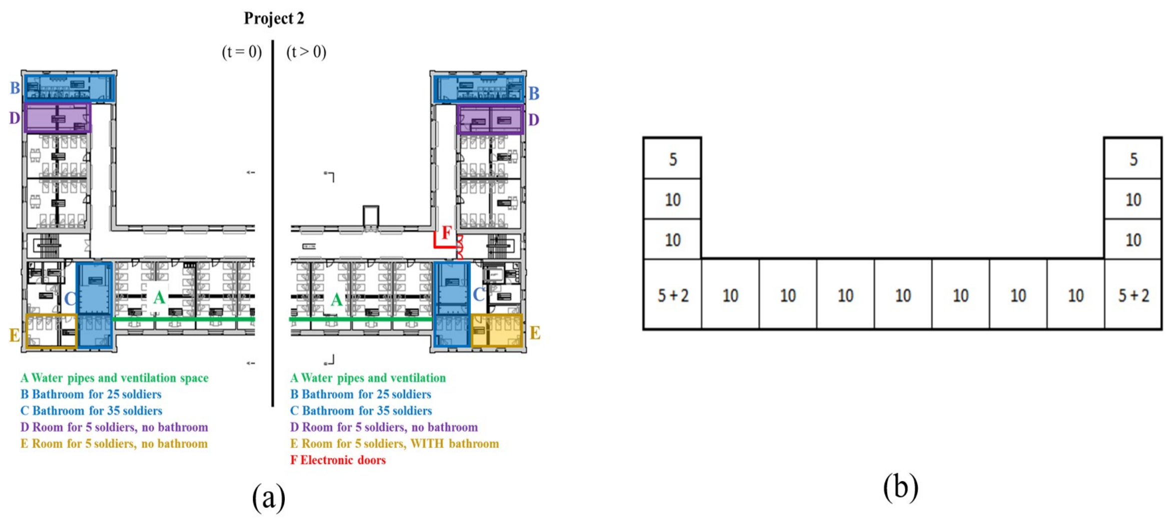


**Figure 13.** Project 2: (a) Detail of floor in comparison to Project 0, (b) Floor layout (comp. Figure 2)

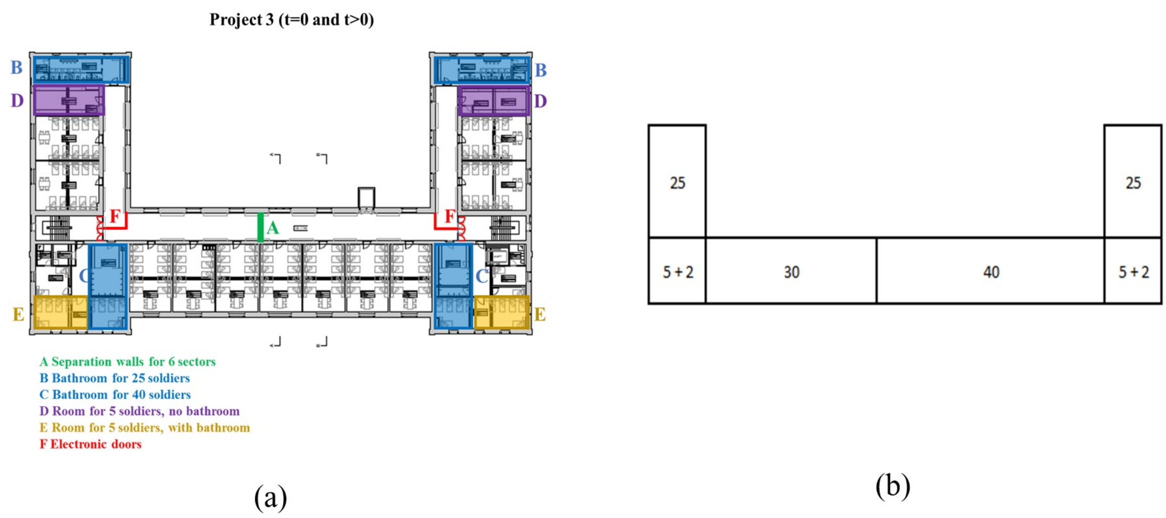


**Figure 14.** Project 3: (a) Detail of floor, (b) Floor layout (comp. Figure 2)

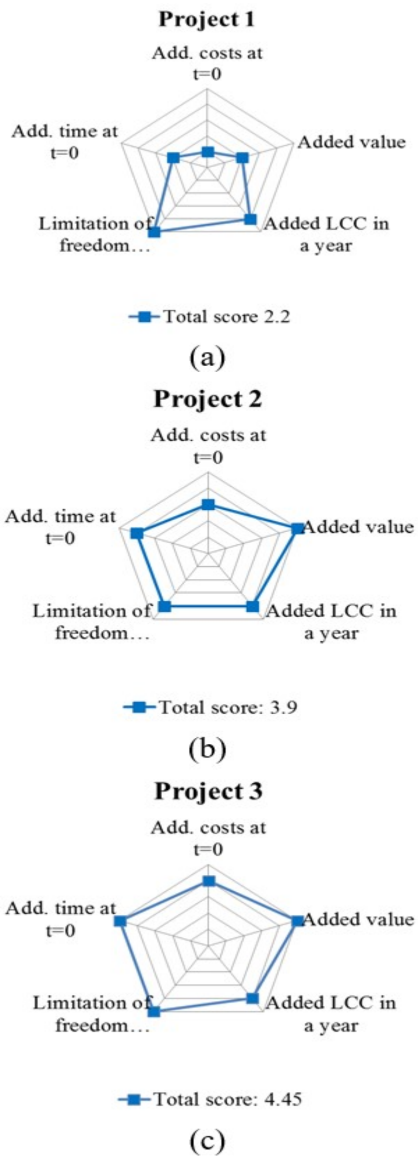


**Figure 15.** Radar charts for each project

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 $1.8 \times 10^6$ 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.

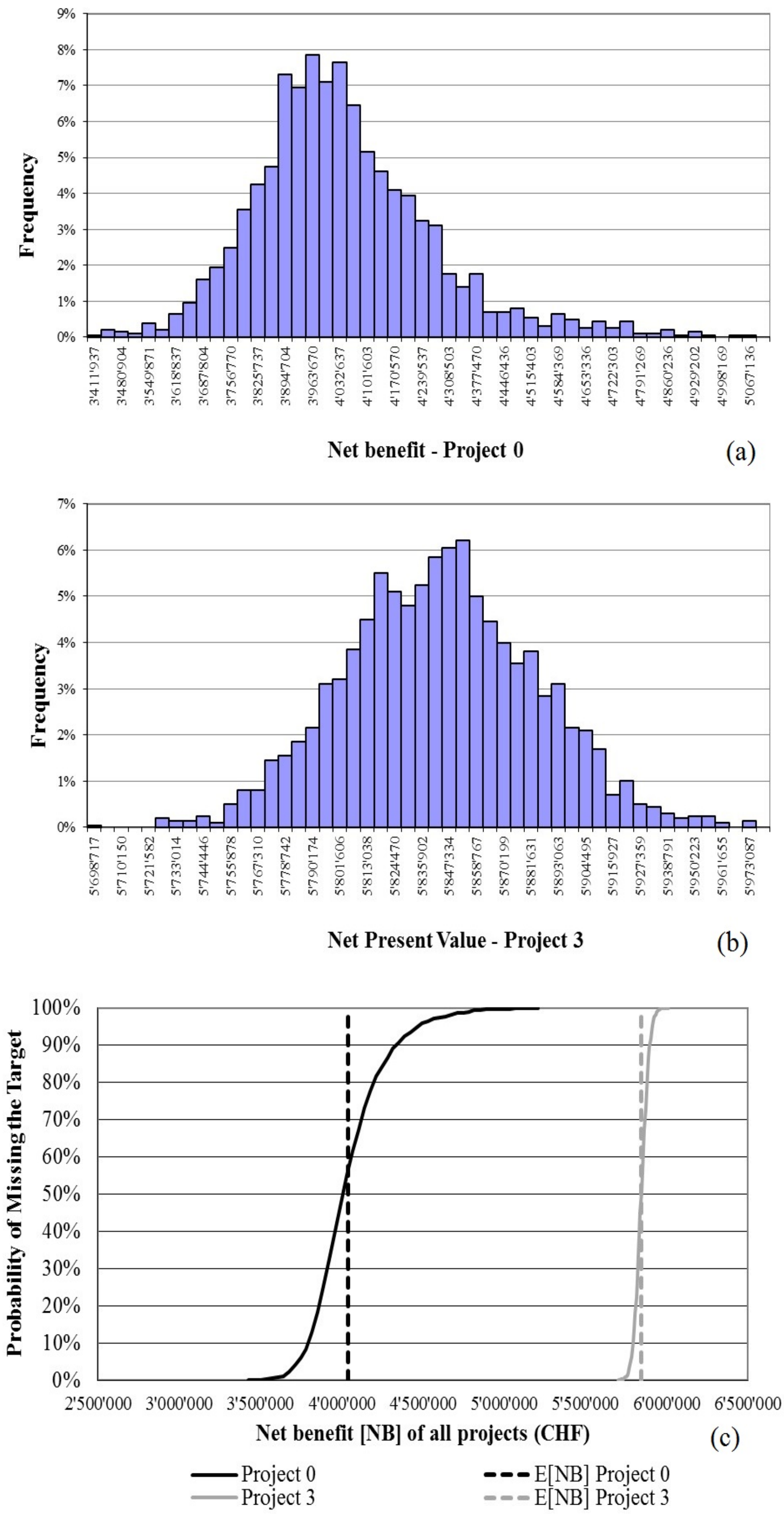


**Figure 16.** (a) Density function of net benefit of Project 0, (b) Project 3, (c) Comparison in cumulative distribution function

## 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.

## ACKNOWLEDGMENT

This work was only possible with the support of Dipl. Architekt Rolf Dauer, Federal Department for Defense, Civil Protection and Sport VBS Armasuisse Immobilien, Division Construction management East, who was the construction manager of the barracks' renovation; the input given by Mr. Jürg Lüdi, HEST, Department IMMO, and Mr. Fritz Blindenbacher concerning important details of the flexibility analysis is highly appreciated. We also thank Dr. Peter Staub from POM+ for his recommendation of the project.

## REFERENCES

Allehaux, D. and Tessier, P. (2002). "Evaluation of the functional obsolescence of building services in european office buildings." *Energy and buildings*, 34(2), 127–133.

Cardin, M.-A. and De Neufville, R. (2008). *A Survey of State-of-the-art Methodologies and a Framework for Identifying and Valuing Flexible Design Opportunities in Engineering Systems.* Available at <http://ardent.mit.edu/>.

Carthey, J., Chow, V., Jung, Y.-M., and Mills, S. (2011). "Flexibility: Beyond the buzzword practical findings from a systematic literature beview." *HERD: Health Environments Research & Design Journal*, 4(4), 89–108.

Cryer, J. D. and Chan, K.-S. (2008). *Time Series Analysis With Applications in R. 2008*. Springer.

De Neufville, R. and Marks, D. (1974). *Systems Planning and Design: Case Studies in Modeling, Optimization, and Evaluation*. Prentice-Hall.

De Neufville, R. and Scholtes, S. (2011). *Flexibility in Engineering Design*. MIT Press.

Della Morte, N. (2012). "Analysis of flexibility in building renovation - case study: Barracks herisau." M.S. thesis, ETH, Zurich, Switzerland, ETH, Zurich, Switzerland.

Dixit, A. K. and Pindyck, R. S. (1994). *Investment under uncertainty*. Princeton University Press.

Hu, J. and Poh, K.-L. (2011). "A sensitivity-based approach for identification of flexible design opportunities in engineering system design." *Lecture Notes in Engineering and Computer Science: Proceedings of The World Congress on Engineering and Computer Science*, San Francisco, USA.

Immobilien, A. (2011). *Preisliste.* Available at <http://www.ar.admin.ch/>.

Kotaji, S., Schuurmans, A., and Edwards, S. (2003). *Life-Cycle Assessment in Building and Construction: A state-of-the-art report, 2003.*

Walser, H.-P. (2010). *Armeeauszählung 2010 Kurzfassung.* P13, Available at <http://www.offiziere.ch/wp-content/uploads/>.

Wang, N., Chang, Y.-C., and Nunn, C. (2010). "Lifecycle assessment for sustainable design options of a commercial building in shanghai." *Building and Environment*, 45(6), 1415–1421.