THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

A systematic approach to strategic maintenance and renovation planning in multifamily buildings

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Abstract

The satisfactory lifetime performance of residential buildings is of critical importance to the acceptable energy performance of the real estate sector and the sustained social development of a modern society. Maintenance and renovation planning in multifamily buildings require considered analysis of both the building performance and the total cost accrued over the entire service-life. The lack of a proper long-term plan can lead to financial difficulties specially in older buildings in need of extensive maintenance and renovation measures. These difficulties are more pronounced in less-attractive markets where maintenance and renovation budgets are limited and there are socio-economic problems. Both market and internal deficiencies have made maintenance and renovation planning a complicated task for the housing owners (property managers). These plans should be devised while taking into consideration multiple and often competing criteria in terms of condition, energy demand and service-life cycle costs. Current planning tools/methods are not efficient or capable of addressing the complexity of the problem. This study therefore proposes a systematic approach to strategic maintenance and renovation planning that combines a modified deterioration function with a service-life cycle cost analysis and facilitates planning using a multi-objective optimization process. This multi-objective approach leads to a large pool of alternative maintenance and renovation solutions that helps decision makers in their choice of maintenance and renovation strategies in difficult market situations and/or under budget constraints.

Keywords: maintenance; renovation planning; multifamily buildings; energy efficiency; multi-objective optimization

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I would like to also say thank you to my family, who have loved and supported me unconditionally. I wouldn't be here, if it was not for you. Literally.

At last, I would like to say thank you to Hugo, Kisse, Mimi, Misse and Müsli for filling my life with joy and laughter.

Love and peace,
A.

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[1] The list is in an alphabetical order except for the last name for obvious reasons. If I have forgotten your name, please forgive me and know that your place is always in my heart if not in my brain.

List of publications

1- **Licentiate thesis:** Farahani, A. (2017). Maintenance, renovation and energy efficiency in the Swedish multi-family housing market (Licentiate). Chalmers University of Technology.

2- **Article 1:** Farahani, A., Wallbaum, H., & Dalenbäck, J.-O. (2018). Optimized maintenance and renovation scheduling in multifamily buildings – A systematic approach based on condition state and life cycle cost of building components. Construction Management and Economics, 1–17. https://doi.org/10.1080/01446193.2018.1512750

3- **Article 2:** Farahani, A., & Dalenbäck, J.-O. (2019). Optimizing the Life Cycle Costs of Building Components with Regard to Energy Renovation. Springer Proceedings in Energy, Cold Climate HVAC (pp. 265–274). Kiruna. https://doi.org/10.1007/978-3-030-00662-4

4- **Article 3:** Farahani, A., Wallbaum, H., & Dalenbäck, J.-O. (2019). The importance of life-cycle based planning in maintenance and energy renovation of multifamily buildings. Sustainable Cities and Society, 44. https://doi.org/10.1016/j.scs.2018.10.033

5- **Article 4:** Farahani, A., Wallbaum, H., & Dalenbäck, J.-O. (2019). Cost-optimal maintenance and renovation scheduling under budget constraints. Submitted to the journal of construction engineering and management. Submitted to the Journal of Construction Engineering and Management. (Submitted for publication, under revision)

6- **Article 5:** Naegeli, C., A., Farahani, A., Österbring, M., Wallbaum, H., & Dalenbäck, J.-O. (2019). A service-life cycle approach to maintenance and energy retrofit planning for building portfolios. Submitted to the Building and Environment Journal (Submitted for publication, under review).

In the first four articles (Article 1, 2, 3 and 4), Farahani, A. has been the first author of the publications.

The Fifth article, has been authored jointly by Naegeli, C., A., Farahani, A. and Österbring, M.
Naegeli, C., A. has contributed to the modelling, data handling, visualization and writing.
Farahani, A. has contributed to the modelling, data handling and writing.
Österbring, M. has contributed to writing and through data input.

In all the publications, the co-authors, Dalenbäck, J-O. (main supervisor) and Wallbaum, H. (Co-supervisor) have acted as sounding boards for developed approaches as well as reviewing articles.

Nomenclature

Symbols	
A	Present value annuity factor
C	Cost
Co	Condition state
E	Energy use
R	Rent
r_{in}	Inflation rate
r_c	The price growth rate in costs of services/materials
r_d	Discount rate
S	Energy savings
SW	Switch (The shift from phase 1 to phase 2 in the deterioration function)
t	Time
Abbreviations	
Alpha	Exponent defining the deterioration behaviour
ASCE	American Society of Civil Engineers
BE	Building and Environment
BSM	Building Stock Modelling
CEM	Construction Engineering and management
CNCF	Cumulative Net Cash Flow
CME	Construction Management and Economics
EAC	Equivalent Annual Cost
EE	Energy Efficiency
ESL	Estimated/Extended Service life
EPIQR	Energy Performance Indoor environment Quality Retrofit
GHG	Greenhouse Gas
INVESTIMMO	A building retrofit planning method
ISO	International Standards Organization
ISL/RSL	Initial/Reference service life
MATLAB	Is a multi-paradigm numerical computing environment and proprietary programming language developed by MathWorks
MARS	Maintenance And Renovation Scheduling
MERIP	A condition diagnostic method
NPV	Net Present Value
PABI	Practical adaptive budgeting of maintenance measures
PBL	Plan- och Bygglag (Planning and Building Act)
SABO	Sveriges Allmännyttiga Bostadsföretag (A Swedish association of public housing companies)
SCS	Sustainable Cities and Society
S-LCC	Service-Life Cycle Cost
STRATUS	A portfolio management tool
TOBUS	A decision-making tool for selecting office building upgrading solutions

Table of Contents

1. Introduction

1.1. Background

The residential building stock in Sweden is fairly old, with more than 70% of the buildings having been built before 1975, (SCB, 2018). The economic boom and social prosperity after the World War II (between 1945 and 1960) in Sweden, resulted in an unprecedented demand for housing as more and more people moved to bigger cities. Although during these years around 570 000 apartment units were built to address the housing situation, the age of the building stock, with its poor housing quality, and population growth, along with the quick urbanization, led to the housing shortage of the early 1960s. By 1960, in Stockholm alone, more than 100 000 people were on the waiting list for rental apartments, (Boverket, 2007). The poor housing conditions, on top of the ever-growing demand for housing at the time became a political burden for the leading political party. As a result, in 1965, the government decided on a holistic approach to dealing with the housing situation through which one million apartments[2] would be built in the following decade. The decision meant extra financial support to boost the already high rate of production where municipalities were given more support and thus extra responsibility for planning and construction, (Boverket, 2007; Hall & Viden, 2005; Roos & Gelotte, 2004). This programme was called the Miljonprogrammet (The Million Homes Programme).

In this period, municipal housing companies took on the majority of the construction work and owned the largest share of the apartments. Multifamily buildings were prioritized because of housing subsidy conditions such as: the tax-free status, favourable subsidies on mortgage interest rates, land acquisition and construction permits and for being more time- and cost-efficient on a large scale (Hendershott, Turner, & Waller, 1993).

Due to the conditional housing subsidies, for example, the land acquisitions, most of the buildings were built in the outskirt of bigger cities. The development of proper infrastructure was necessary to provide stimulating living environments in these areas, although it was often disregarded or given the least economic priority, (Hall & Viden, 2005; Johansson, 2012; Roos & Gelotte, 2004).

As a result, it did not take long for the suburban areas to lose popularity. Residents who could afford to leave, chose to move to more attractive central locations while in most cases little or no effort was made to improve the situation for the remaining inhabitants, (B. Roos & Gelotte, 2004). The high vacancy rates in the suburban areas created a challenging financial situation for the housing owners. These assets could only generate low revenue, which made it difficult for the owners to justify expenses, some buildings were demolished, and some were left with limited care. As of today, only 3% of the total multifamily stock in the country has been renovated to meet the current standards according to the requirements of Planning and Building Act (PBL). The remaining multifamily apartment units which were built before the record years, today in their 40s, are in need of extensive maintenance and renovation measures.

On the other hand, considering the current condition of the multifamily buildings and the need for extensive maintenance and renovation measures, the opportunity is presented to improve

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[2] Both in multi- and single-family buildings

the energy performance in multifamily buildings at marginal costs. A large share of the costs associated with energy efficiency measures are related to the adjustments and alteration of the buildings' envelope. Changing windows, insulating the envelope and, upgrading the heating and ventilation systems, depending on the design of the building, often are cost- and labour-intensive. These costs are partly accounted for in planning for already required renovation measures. If the opportunity is overlooked, considering the long service-life of respective components (e.g., windows, façade, roof, etc.), similar opportunities will not arise for another 30-50 years. Currently, residential buildings account for about 23% of the total energy use in Sweden, (Swedish Energy Agency, 2017) and so, neglecting the presented opportunity imposes a substantial financial burden on the housing owners if the national climate and energy goals are to be met[3].

Despite the government's effort to facilitate investments in energy efficiency, the opportunity is yet to be fully realized. Lack of knowledge and expertise amongst decision makers, as well asstructural and financial differences between organizations (housing owners), have most often led to associating high risks with energy efficiency investments which has had a noticeable effect on the extent of energy efficiency investment in this sector, (Högberg, Lind, & Grange, 2009).

The financial challenges and uncertainties involved in renovation and energy efficiency investments are more pronounced in less attractive markets where higher vacancy rates and lower revenue have made maintenance and renovation planning more complex and challenging for the housing owners. The majority of the multi-family buildings built within the Million Homes Programme are located in similar areas where tenants' composition comprises a large share with high price sensitivity, (Mattson-Linnala, 2009). In these markets, buildings have been left with limited care, maintenance measures are often neglected or postponed, and renovation is approached in an unsystematic way. In such areas, renovation planning must be approached not only systematically but also cautiously as incautious renovation decisions can result in serious social problems, such as segregation and gentrification.

In general, maintenance and renovation planning in the Swedish rental housing market is not systematic. It is mainly short-term and opportunistic with the focus on capitalization of reported and/or discovered renovation opportunities. The short-term planning approach has been shown to have a considerably negative financial impact on the housing owners and hence on the tenants in the long term, (Farahani, 2017). In order to address the complexity of the problems involved in strategic maintenance and renovation planning, there is a need for a systematic approach through which service-life cycle costs can be minimized and both the market's and the owners' requirements can be met. A long-term budgeting plan gives the owners the opportunity to foresee upcoming costs and the time to plan and distribute resources more efficiently.

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[3] The background to the current situation and the existing problems in maintenance and renovation of the multifamily building stock is extensively studied and presented in the licentiate thesis, (Farahani, 2017).

1.2. Research questions & the main objective

The research questions are formulated based on the initial literature study and problem description and are presented below:

1- How can the service-life cycle costs of building components be minimized under condition and time constraints[4]?
2- What are the economic effects of a service-life cycle approach in maintenance and energy-renovation planning?
3- Is it possible to impose yearly budget constraints in maintenance and renovation planning and yet meet the condition requirements of building components?
4- How does cost-optimal maintenance and renovation planning affect cost projections on a portfolio level?

The main objective of this PhD thesis is to develop a systematic approach for strategic maintenance and renovation planning under condition, time and/or budget constraints to address the posed research questions.

1.3. Research structure

At the beginning of this research project, an extended literature study was carried out to provide a complete overview of the current status of the Swedish housing market and its defining characteristics (mainly the rent-control system and the Swedish Union of Tenants). These characteristics together with existing internal[5] management deficiencies, were found to have formed some of the main underlying reasons behind the current difficult situation regarding the maintenance and renovation of multifamily buildings. This background provided the essential knowledge necessary for problem identification hence the initial method development, the results of which were published in the licentiate thesis, (Farahani, 2017). Following this stage, the method was developed and adapted to illustrate and address the common issues and difficulties in maintenance and renovation planning in multifamily buildings. Figure 1 shows the research structure, method development and the corresponding publications for each stage of the research.

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[4] Condition constraints secure the acceptable performance of building components throughout their service life whereas time constraints limit flexibility in the timing of renovation measures.

[5] Inside housing companies

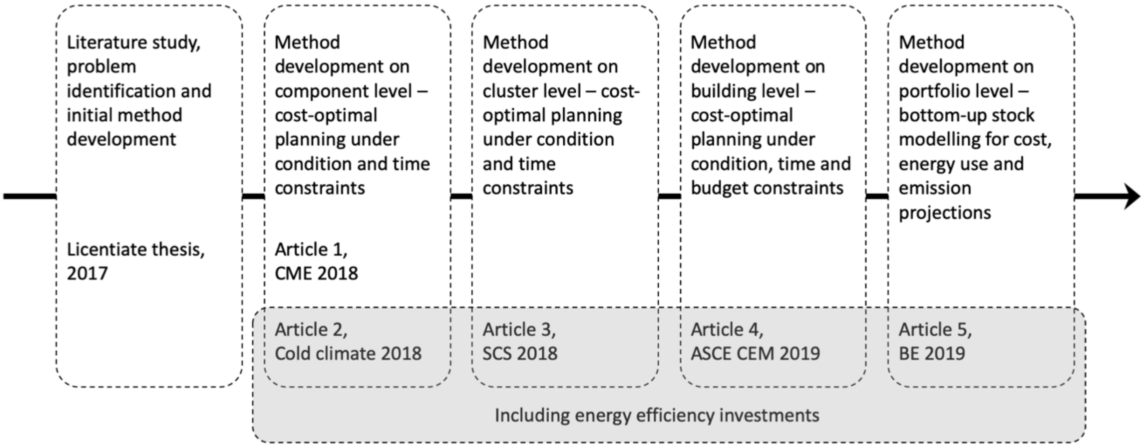

Figure 1. Research structure

The order of the articles as shown in the figure, indicates the steps taken toward achieving the main objective of this research study. Article 1 offers an introduction to the basics of the modified deterioration function and the service-life cycle cost analysis in the proposed method. Article 2 implements the costs and benefits of energy performance improvements in the service-life cycle cost analysis. Article 3 builds a cost-optimization process upon the knowledge presented in Articles 1 and 2 and enables the economic assessment of a service-life cycle approach in energy-renovation planning. Article 4 introduces the complete maintenance and renovation scheduling (MARS) method by using component clusters to enable energy performance improvement and cost-optimization in building level. Furthermore, it introduces a budget optimization process that enables cost-optimization under yearly budget constraints. And finally, Article 5 demonstrates the application of the method in building stock modelling and offers an overview of the expected maintenance/renovation costs, energy use and GHG emission reductions in two energy efficiency scenarios on a portfolio comprising more than 1800 apartment buildings.

1.4. Research method

The process by which this research project has been carried out defines the research method used in this study. In the beginning, research questions were formulated based on a literature study and a diagnostic problem description. Predictions were then made as logical consequences, which helped in specifying and developing the conceptual framework and the solution environment. In the next step, the theoretical framework was established which helped in addressing the posed research questions. Ultimately, the application of the resulting solution (the developed method) was demonstrated in practical applications and the findings were communicated through scientific publications.

1.5. Problem description

The ability to create a long-term maintenance and renovation plan gives property managers the opportunity to efficiently utilize resources and maintain acceptable building performance under lower budgetary pressure. To be able to create a long-term maintenance and renovation plan, the key parameter required is the life expectancy of building components. A reliable prediction of the life expectancy can however, be a complex and time-consuming process. Because the deterioration process is uncertain in nature, the prediction of the life expectancy can never be an exact science (Hovde & Moser, 2004).

Life expectancy in general can be estimated using either a deterministic or a probabilistic approach, (Kumar, Setunge, & Patnaikuni, 2010). The deterministic approach is relatively simple and gives a robust estimation of life expectancy that is widely used in the real estate and construction industries. As for the probabilistic approach, it uses time-performance data to estimate the deterioration behaviour of building components which is then used to estimate life expectancy. The probabilistic approach, which requires more input data, is more complicated and results in a probability distribution of life expectancy.

In the deterministic approach, life expectancy is estimated by incorporating the effects of in-use conditions[6] into a reference service-life value. In this approach, experts assign coefficient values to the in-use conditions, which are then multiplied by the reference service-life to calculate the life expectancy, (ISO15686-3, 2016). In the ideal case, the reference service-life is provided by a full deterioration model using a probabilistic approach (Hovde & Moser, 2004). The reference service-life values for building components can be obtained from various sources, for example, manufacturers, publications, local building codes and standards, etc.

Although the deterministic approach is widely used in the real estate and construction industries, studies on its application highlight the uncertainty of the estimated life expectancy, given that the outcome is a single value for the service-life (Bourke & Davies, 1997; Hovde & Moser, 2004; Marteinsson, 2003). To obtain more representative estimations of life expectancy, it has been suggested that both the effects of in-use conditions and the reference service-life in a deterministic approach should be given as probability distributions (the engineering approach) rather than single values, (Lounis & Lacasse, 1998). The main problem with probabilistic approaches however is that they are too inherently complex to be used by property managers, (Frangopol, Kallen, & Van Noortwijk, 2004; Lawless & Crowder, 2004; Nicolai & Budai, 2004; van Noortwijk, 2009). Moreover, they are mainly considered for assets where, unlike in residential buildings, sudden failure would be catastrophic or where mobilization costs are high, relative to the cost of a replacement, (Anthony Pajunas, Matto, Trick, & Zuluaga, 2012).

During the last few decades, several budgeting methods have been developed based on both deterministic and probabilistic approaches. These methods in the form of integrated decision-making tools have been designed to assist property managers (building owners) in budgeting and planning for maintenance and renovation. For example, the Energy Performance Indoor environment Quality Retrofit tool (EPIQR) is developed based on the MERIP method, for diagnosis and analysis of maintenance and refurbishment plans for residential buildings which includes sustainability criteria that describes the deterioration state of building components in the form of probability distributions, (Brandt & Wittchen, 1999; Flourentzou, Brandt, & Wetzel, 2000). INVESTIMMO (Balaras, Droutsa, Dascalaki, & Kontoyiannidis, 2005) is developed based on EPIQR‘s methodology to assess residential building renovation and refurbishment processes and to further investigate the effects of external factors on the deterioration and life expectancy of building components. TOBUS (Caccavelli & Gugerli, 2002) similar to INVESTIMMO, is developed based on EPIQR’s methodology but for commercial buildings. The Practical adaptive budgeting of maintenance measures method (PABI) is developed to facilitate budgeting for maintenance and renovation without an on-site assessment (Bahr & Lennerts, 2010). STRATUS is another widely used tool for maintenance and renovation budgeting which is developed based on Schroeder’s method (Christen, Schroeder, & Wallbaum, 2014; Schröder, 1989). The Schroeder method is based on a simple

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[6] In-use conditions as listed by (ISO15686-8, 2011) include: inherent performance level; design level; work execution level; indoor environment; outdoor environment; usage condition and maintenance level.

deterioration function that describes the deterioration behaviour of building components and is used to determine the depreciation value and condition status of the respective component in function of time.

Although these methods facilitate quick condition analysis and offer an estimation for future maintenance and renovation costs, they fail to address the complexity of the problem under condition, time and budget constraints. Whether the purpose is to plan and budget maintenance in new construction or to carry out major renovation work, to sustain the acceptable performance of the building components and to minimize the service-life cycle costs, timing is of crucial importance. To understand how timing of maintenance and/or renovation measures affect the performance of building components and the corresponding service-life cycle costs, the effects of maintenance on the condition/deterioration of building components should be taken into account separately from the rest of the in-use conditions.

Knowledge regarding the timing of actions can be used, for example to determine the economic effects of premature renovation or to evaluate the economic benefits in early but more frequent maintenance (over-maintenance) of a building component. The main reason behind an inability to address timing in existing methods is the difficulty of the assessment of the effect of maintenance on condition state (deterioration pace) and subsequently the life expectancy of building components.

The theoretical framework presented in this study presents a systematic approach to cost-optimal maintenance and renovation planning in multifamily buildings. The resulting MARS method tackles the problem by modifying the condition-deterioration function of the commonly accepted Schroeder method to take into account the effect of maintenance on the life expectancy of building components. The Schroeder method offers a simplified deterioration function that avoids the complexity involved in probabilistic approaches yet provides a prediction for life expectancy that is sufficient to meet the maintenance and renovation planning objectives. Combining the modified deterioration function of the Schroeder method with a complete service-life cycle cost analysis (including costs and benefits of energy performance improvements), the economic effects of timing can then be evaluated under different maintenance regimes. This allows for maintenance and renovation cost optimization under condition, time and/or budget constraints. The MARS method is intended to provide support for property managers (building owners) in the form of techno-economic assessment of possible maintenance and renovation scenarios.

1.6. Definitions and modelling assumptions

Considering the existing inconsistency in the use of the terms, maintenance and renovation, in the scientific community, it is important to identify what these terms mean and what they include in this study. The given definition regarding maintenance and renovation are according to the Swedish standard AFF 04 (Svensk Byggtjänst, 2004) and are specific to this study and placed so that the results and the intended message can be conveyed clearly.

Thereby, '**maintenance**' is considered as actions carried out to sustain and restore the original function of a managed item and is divided into proactive and retroactive maintenance measures. Retroactive measures only include the **reinstatement** of building components, whereas, proactive measures, in addition to the **reinstatement**, include actions carried out to sustain the proper working condition of the respective components and/or to prolong their service life.

The term ‘**renovation**’ is used if the substitute by the end of a component’s service life is a component with a better/higher quality (higher utility-value). And so, the term ‘**energy-renovation**’ is used when energy efficiency measures are implemented along with the replacement of a component. The terms ‘**renovation**’ and ‘**energy-renovation**’ however may be used interchangeably. In the fifth article, the term ‘**retrofit**’ has been used in exchange for energy-renovation.

The assumptions and model specifications used in this study are as follows:

- In deterioration, building components are mutually independent.
- The duration of proactive maintenance measures is negligible, and the maintenance effect is applied directly at the time of maintenance.
- The deterioration process includes the effects of ageing, wear and other cumulative damages and is the only cause of system failure.
- In-use conditions have no effect on overall deterioration behaviour. Deterioration is regarded as a component characteristic.
- Except for maintenance, the effects of in-use conditions are reflected in the size of time increments.
- Maintenance does not change the overall deterioration behaviour but restores the condition state of the respective component to a higher state and therefore decreases the deterioration rate.

2. Theoretical framework

2.1. Overview

The key complication in maintenance and renovation planning comes from the uncertainty of the deterioration process and so the difficulty in the estimation of life expectancy. Empirical studies show that the mean prediction of a deterioration process in time can be expressed in deterministic form by the power law (Cinlar, Osman, & Bazant, 1977; Ellingwood, 1993; Hoffmans & Pilarczyk, 1995; Noortwijk & Klatter, 1999). The expected deterioration can therefore be expressed by equation (1):

$$E\big(X(t)\big) = at^b \propto t^b \tag{1}$$

where $X(t)$ denotes the deterioration at time 't' for physical constants $a > 0$ and $b > 0$ at time t.

Similarly, Schroeder (Schröder, 1989) explained the deterioration behaviour of building components with a simplified condition/deterioration curve using equation 2. Schroeder's deterioration function is simple yet provides a prediction of the life expectancy that is sufficient for maintenance and renovation planning. Deterioration functions are necessary in maintenance and renovation planning as they enable real time condition assessment of building components.

Considering its simplicity and creditability (Christen et al., 2014), the Schroeder deterioration function is used as the principle deterioration function in this study. The proposed MARS method, unlike the existing planning methods, incorporates the effects of in-use conditions separately in the deterioration function allowing for *S-LCC* analysis and multi-objective optimizations.

In-use conditions as listed by (ISO15686-8, 2011) include: inherent performance level; design level; work execution level; indoor environment; outdoor environment; usage condition and maintenance level. Except for the effects of maintenance level, the effects of the remaining in-use conditions are generally not visible (cannot be inspected) immediately. For example, the effects of a worsening usage condition can only be inspected after certain period of time during which a component has been used under the new condition. The effects of maintenance level therefore cannot be incorporated into the deterioration function in the same way as the other in-use conditions. And so, to take into account the effects of all in-use conditions two different approaches which are presented in the following sections are used in the proposed MARS method.

Deterioration process is best described as a discrete-time Markov chain process. The main property of a Markovian process explains the condition characteristics of a system in time, that is, the condition of a system in the future depends only on the current condition state of the system (Gagniuc, 2017). This property of the deterioration process allows for incorporation of the effects of maintenance level in Schroeder's deterioration function.

2.2. Deterioration function

Schroeder divided deterioration into two phases, both of which are expressed by the power law. Phase one outlines an irreversible degradation process (from the beginning to t_{SW_i}, Figure 2), whereas the second phase outlines a degradation process during which the condition is retrievable by means of maintenance, equation (3). These condition/deterioration curves already include the effects of in-use conditions and so are presented for a range of in-use conditions, IP-BAU report, (IP BAU, 1995). Since the maintenance effect in Schroeder method is not separated from the rest of in-use conditions, its timing effect cannot be evaluated. This deficiency does not allow for service-life cycle cost (*S-LCC*) thus multi-component maintenance and renovation plan cost optimization.

$$Co(t) = 1 - t^{\alpha} \tag{2}$$

Where $Co(t)$ is the condition at time t; α is the exponent defining the shape of the condition/deterioration curve and t is time.

Maintenance increases a component's performance by improving its condition state. This effect as stated in the literature (Anthony Pajunas et al., 2012; Frangopol et al., 2004), is considered to be a non-repeating modification of the deterioration behaviour; meaning that the deterioration rate at the condition state, $Co_{i,j}(t_2)$, after a maintenance measure is carried out in a proactive strategy, is equal to the deterioration rate at the same condition state, $Co_i(t_1)$, on the deterioration curve in retroactive strategy, as seen in Figure 2. The retroactive deterioration curve is the deterioration curve when no maintenance measure is carried out. The maintenance condition improvement marks the shift from the retroactive to the proactive strategy, stage one to stage two in Figure 2.

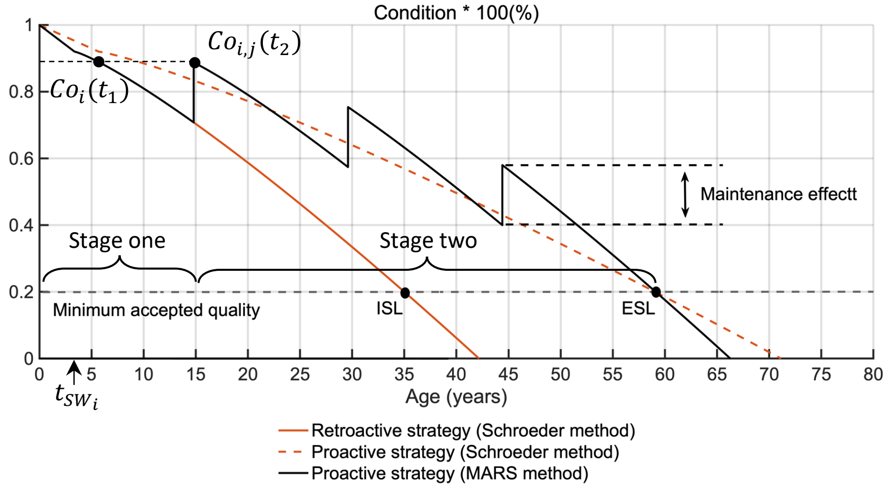

Figure 2. The condition/deterioration curves for retroactive and proactive strategies in both Schroeder and MARS methods. *ESL* is the Extended Service Life denoting the end of the service life in a proactive strategy whereas *ISL* is the Initial Service Life and denotes the end of the service life in a retroactive strategy.

Considering a building with n non-identical components, it is assumed that a component's condition state can be characterized by a physical variable Co_i with $i = \{1, 2, \dots, n\}$. Each component acquires one minimum accepted quality (minimum condition level) and $j = \{1, 2, \dots, m\}$ maintenance operations. Assuming $Co_i(0) = 100\%$ (in a new component), the deterioration function is used to calculate the future condition state, $Co_i(t)$, of a component at time t based on its current condition, equation (3).

$$Co_i(t) = \begin{cases} 1 - t_{sw_i}\left(\frac{t}{t_{sw_i}}\right)^{\alpha_{i,1}} & ,phase\ 1 \\ Co_i(t_{sw_i}) - Co_i(t_{sw_i})\left(\frac{t - t_{sw_i}}{Co_i(t_{sw_i})}\right)^{\alpha_{i,2}} & ,phase\ 2 \end{cases} \tag{3}$$

where: t_{sw_i} is the time when phase 1 ends and phase 2 begins (years); α_i is the exponent defining the shape of the condition/deterioration curve during each phase and; $Co_i(t_{sw_i})$ is the condition state at time t_{sw_i}. Since the first phase in Schroeder's deterioration function is considered irreversible, its respective deterioration behaviour is assumed linear regardless of the component type, $\alpha_{i,1}$ is always equal to 1.

Implementing the effects of maintenance, the corresponding added service life, $\delta t_{i,j}$ is calculated using equation (4). The maintenance effect can either be estimated with the help of an expert or calculated if a general maintenance guideline for the corresponding component is provided by the manufacturer, local guidelines or standards such as SABO's maintenance guideline for residential buildings, (SABO, 2013).

$$\delta t_{i,j} = \begin{cases} t - t_{sw_i}\left(\frac{1 - Co_{i,j}(t)}{t_{sw_i}}\right)^{\left(\frac{1}{\alpha_{i,1}}\right)} & ,for\ Co_{i,j}(t) \geq Co_i(t_{sw_i}) \\ t - t_{sw_i} - Co_i(t_{sw_i})\left(1 - \left(\frac{Co_{i,j}(t)}{Co_i(t_{sw_i})}\right)\right)^{\left(\frac{1}{\alpha_{i,2}}\right)} & ,for\ Co_{i,j}(t) < Co_i(t_{sw_i}) \end{cases} \tag{4}$$

where: $\delta t_{i,j}$ is the added service life to the component $'i'$ after maintenance measure $'j'$ is carried out (years); $Co_{i,j}$ is the improved condition state of the component $'i'$ after maintenance measure $'j'$ is carried out at time $'t'$.

A threshold minimum accepted quality $Co_{i,min}$ is identified for each component to determine the extended service life (ESL). When the condition state reaches $Co_{i,min}$, the component i is assumed unusable (reached failure). In order to identify properties corresponding to the minimum accepted quality, $Co_{i,min}$; performance requirements should be divided into three categories: safety; functional and aesthetic. The corresponding performance requirements should be specified for each component (Moser, 1999).

Using the deterioration function in equation (3), for a building component, condition/deterioration curves are simulated using both Schroeder and MARS methods, as in Figure 2. Retroactive and proactive strategies are both used to illustrate the differences between the two strategies in the two methods. The resulting deterioration curve for the retroactive strategy applies to both the Schroeder and MARS methods. As for the proactive strategy, in the MARS method, by incorporating the effects of maintenance, condition improvements start by the end of stage one and occurs at 15-year intervals, as seen in Figure 2. The effects of maintenance in the proactive strategy in the Schroeder method, however, are implemented evenly throughout the component's service-life by an increase in the time increment. The proactive deterioration curve in Schroeder's method is shown by the orange dashed line in Figure 2.

The shape of the condition/deterioration curve is defined by the α (alpha) value. The default values for α in this study are taken directly from the IP BAU report (IP BAU, 1995). These values however can be calibrated given that there are enough time-performance data available.

The points denoted as ISL (initial service life) and ESL (extended service life), mark the end of service-life in retroactive and proactive strategies, respectively. The ISL values are often available in datasets given by manufacturers, statistics, local standards/guidelines, etc. and the ESL is calculated using the modified deterioration function of the MARS method. By the end of the service-life components are replaced with a new component which resets the condition state back to an excellent state, $Co_i(0)$, and the deterioration process recommences.

Incorporating the effects of maintenance separately in the deterioration function, as in the MARS method, allows for adjustments in maintenance timing hence its frequency and the corresponding service-life cycle cost (*S-LCC*) analysis. This characteristic of the MARS method enables multi-objective optimizations in both individual component level and in building level.

2.3. Service-life cycle cost (*S-LCC*) analysis

The *S-LCC* analysis evaluates the total costs of a simulated maintenance plan throughout its calculated service life in order to determine economically optimum dates of maintenance and renovation. The total cost for each plan includes the costs of inspection, maintenance and reinstatement. Since changes in maintenance intervals result in different extended service life (*ESL*) values, the equivalent annual cost (*EAC*) method (Flanagan, 1989), is used for a better *S-LCC* evaluation, equation (5). The maintenance interval, which yields the lowest *EAC* is then considered as the economically optimal maintenance interval for the respective component.

$$EAC_{(i,j)m} = \frac{1}{A_{ESL_{(i,j)m},r_d}} \sum_{t=0}^{ESL_{(i,j)m}} \frac{C_{MR,t}^{est_{(i,j)m}} (1+r_c)^t (1+r_{in})^t}{(1+r_d)^t} \tag{5}$$

where: $A_{ESL_{(i,j)m},r_d}$ is the present value annuity factor for component i, with maintenance measure j in plan m, equation (6); $C_{MR,t}^{est_{(i,j)m}}$ is the estimated cost for the respective plan at year t, equation (7) ; $ESL_{(i,j)_m}$ is the extended service life for plan m; r_c, r_{in} and r_d are the price growth rate in costs of services/materials, the inflation rate and the discount rate, respectively.

The present value annuity factor is equal to:

$$A_{ESL_{(i,j)m},r_d} = \frac{1-(1+r_d)^{-ESL_{(i,j)m}}}{r_d} \tag{6}$$

$$C_{MR,t}^{est_{(i,j)m}} = C_{insp_{(i,j)m}} + \sum C_{pro_{(i,j)m}} + C_{rein_{(i,j)m}} \tag{7}$$

where: $C_{insp_{(i,j)_m}}$ is the inspection cost; $C_{pro_{(i,j)_m}}$ is the proactive maintenance cost (of different types) and $C_{rein_{(i,j)_m}}$ is the reinstatement cost.

The cost function $C_{MR,t}^{est_{(i,j)m}}$ includes all the costs identified for the maintenance and reinstatement/renovation of each building component. For example, for the heating system, the total service-life maintenance cost includes the costs of, for example proper controls (flue gas, etc.), cleaning, venting of the distribution system and the radiators, general repairs, replacing radiator valves, dismantling and cleaning radiators, replacing the burner and replacing pumps and valves.

In order to find the economically optimum dates of maintenance and renovation, it is necessary to realize the effects of changes in a maintenance regime in the total *S-LCC* cost. To utilize this effect, the MARS method subjects building components to maintenance regimes of different intervals and calculates the corresponding *S-LCC* which results in a cost profile similar to the one shown in Figure 3.

For this purpose, the shortest and longest intervals (simulation boundary) are set to t_{SW_i} (the time when phase 2 begins) and $t_{tech\ limit}$, respectively. The target cost-optimal plan for that respective component is defined by the interval, $t_{optimum}$, and its subsequent *ESL* that yields the lowest total *EAC* value. Here, $t_{tech\ limit}$, denotes the latest time[7] at which a measure is to be carried out to sustain acceptable performance level.

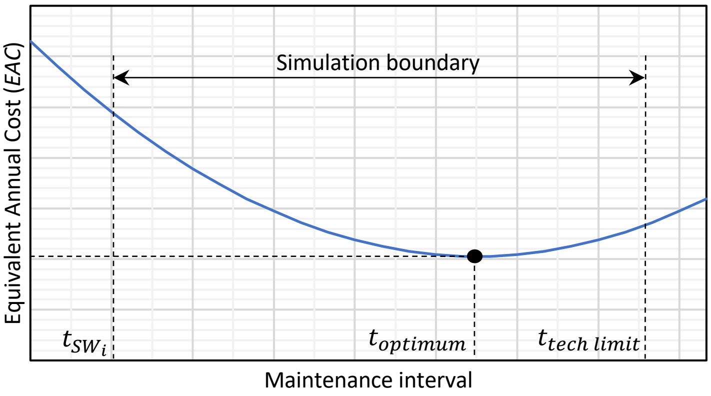

Figure 3. Exemplary maintenance interval – *S-LCC* relationship

In the MARS method, the total cost of maintenance and renovation is divided into two separate costs: the costs of material and labour and the associated fixed/logistic costs,for example scaffolding. The fixed/logistic costs can sometimes take a substantial share of the total costs. As a result, combining maintenance/renovation measures with sharing fixed/logistic costs (deep-renovation) is often preferable for the housing owners. The problem with this approach, however, is the potential loss of value due to the improper and unsystematic economic evaluation of the renovation projects. If the economic evaluations are not carried out in a service-life cycle perspective, this can result in a loss of value costlier than the potential benefits gained.

In the MARS method, in order to both realize the deep-renovation benefits and avoid the loss of value, components with sharing fixed/logistic costs are grouped into clusters where the simulated individual maintenance plans are coupled to find possible cost reduction opportunities throughout the calculated *ESL*s. Once the cost optimization is done in each cluster, the renovation year for each component is checked against the renovation year of the remaining components in the respective cluster to analyse the economy of premature renovation opportunities. Since the cost analysis is done in a service-life cycle perspective, the loss of value is already taken into account in premature renovation opportunities. This step in the cost

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[7] Or a condition state which can in return be converted into a time value.

optimization process allows for further potential cost reductions in maintenance and renovation planning. The resulting combined plan with the lowest *EAC* value is then selected as the cost-optimal plan for the respective set of components. Since the aim of maintenance is to keep building components at an acceptable performance level, maintenance negligence and/or delays are excluded from the results.

In Article 1[8], the deterioration function in equation (3) combined with the introduced *S-LCC* analysis are used to introduce the modified deterioration function of the MARS method and demonstrate its optimization process. In Article 1, the maintenance and renovation cost optimization process is carried out for two components in both individual and combined setups. Considering the volume of the data to be processed, a MATLAB code is developed and used to run the cost optimizations. The flowchart shown in Figure 4, presents the simplified simulation process used in Article 1. Here the end of stage one marks the shift from a retroactive to a proactive strategy.

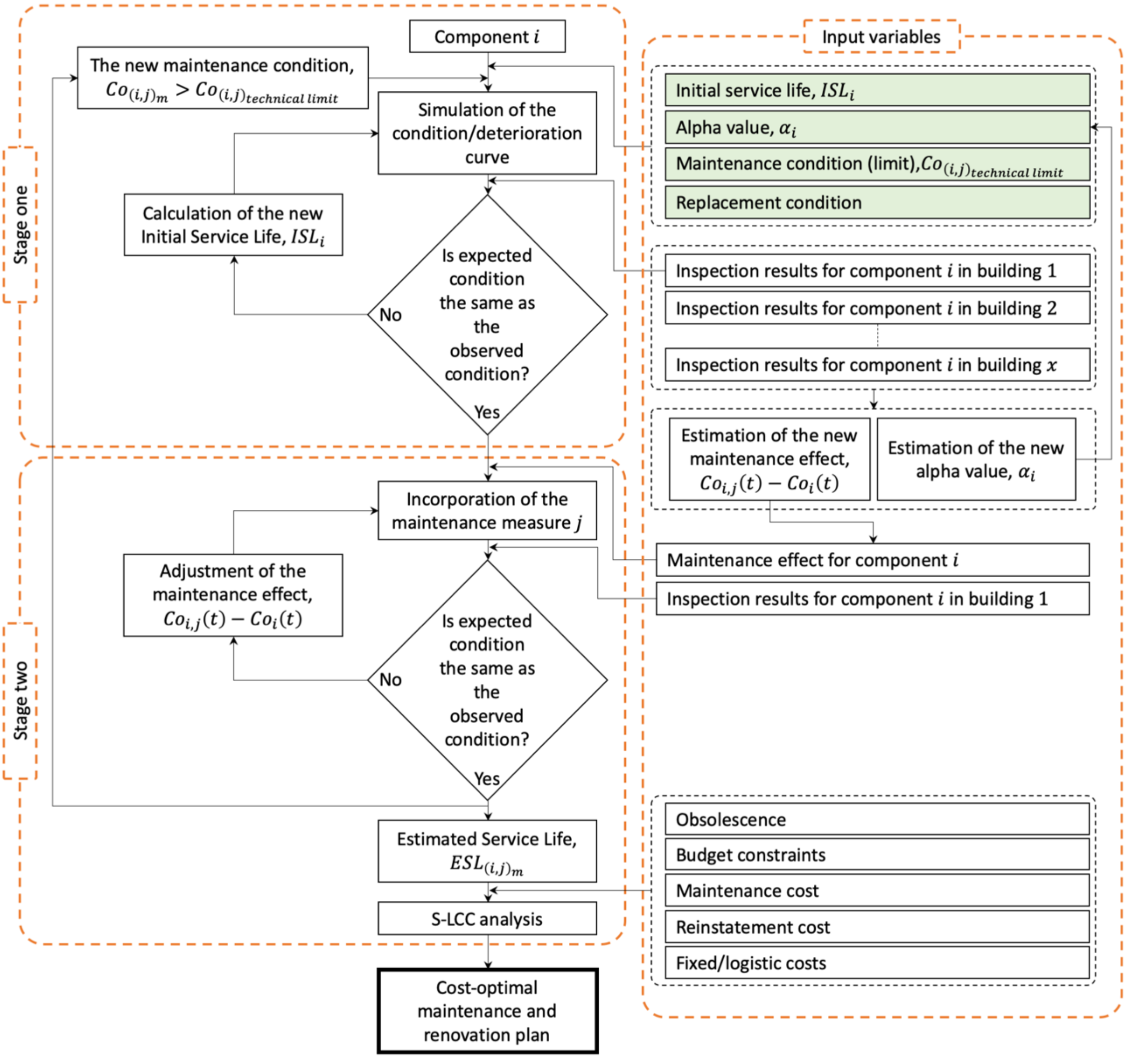

Figure 4. Modelling process flowchart used for a single component in Article 1. The green colour highlights the variables required to start the simulation.

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[8] "Optimized maintenance and renovation scheduling in multifamily buildings – a systematic approach based on condition state and life cycle cost of building components"

2.4. Inspection

Disregarding the method used in maintenance and renovation planning, inspections always play an important role in the accuracy and reliability of the devised plans. Inspections in principle are used to assess the condition state of building components. They are also used to observe and evaluate in-use conditions in order to detect changes in the effects of these conditions. The inspection results most often include an estimation of the condition state and time estimates for designated building components. While the condition state represents an evaluation of a component's performance in terms of functionality, safety and aesthetics, the time estimates identify the time at which a maintenance/renovation measure is to be carried out. In the proposed MARS method, the inspection results, in either form can be used to incorporate the effects of in-use conditions in the deterioration function and so the resulting extended service-life (ESL) of building components.

Considering that the deterioration behaviour is a characteristic of a component alone and is not dependant on time (discrete-time Markov chain process[9]), the effects of in-use conditions can be directly implemented in the deterioration function and be reflected in the size of time increments in condition/deterioration curves, as seen in Figure 5. The ratio of the new time increment to the original time increment is proportional to the ratio of the inspection time to the time on the simulated condition/deterioration curve at which the assessed condition state is equal to the expected condition state at the time of inspection, equation (8).

$$\frac{\delta t_{increment,new}}{\delta t_{increment,original}} \propto \frac{t_{inspection}}{t_2} \tag{8}$$

In Figure 5, δt is the time difference between the inspection time, $t_{inspection}$, and the time , t_2, at which the projected condition on the original condition/deterioration curve, at point 2, is equal to the assessed condition at inspection time at point 3, $Co_{i,assessed}$. In this example the assessed condition $Co_{i,assessed}$ is lower than the expected condition at inspection time $Co_{i,expected}$, representing the effects of a worsening in-use condition, resulting in a shorter extended service life, ESL-2 compared to the original extended service life, ESL-1.

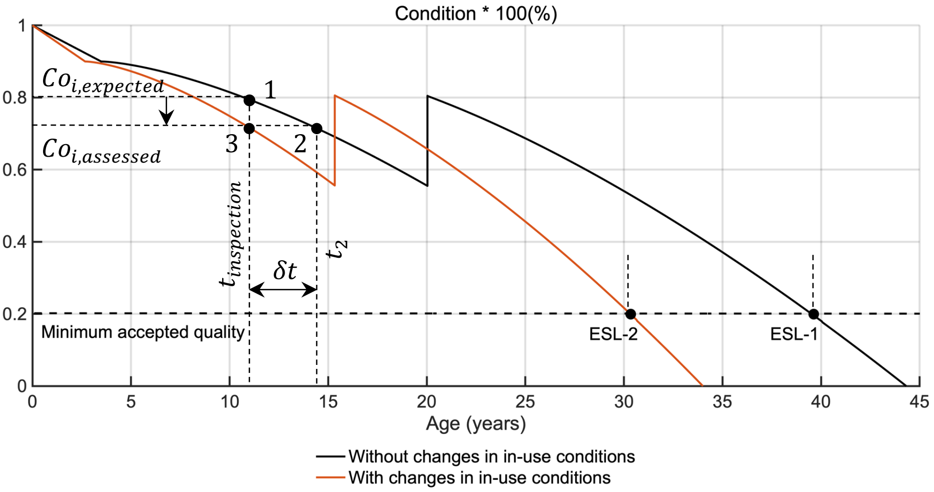

Figure 5. the effects of changes in in-use condition

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[9] Considering the uncertain nature of deterioration, it is best described by a discrete-time Markov chain process, (Gagniuc, 2017)

It is however important to note that changing the time increments does not affect the deterioration rate, α. The two deterioration/condition curves given in Figure 5, are simulated using the same alpha 'α' value but with different time increments.

The effects of in-use conditions and their implementation in the deterioration function is demonstrated by an example in Article 3[10]. Three components are combined for cost-optimal maintenance and renovation planning in both new and existing[11] buildings to illustrate the economic effects of timing and worsening in-use conditions.

Apart from incorporating the effects of in-use conditions into the deterioration function, the inspection results can also be used to improve the accuracy of the deterioration function, the estimated 'α' value, using the maximum likelihood estimation (*MLE*) method. For this purpose, the time-performance data must be gathered from a number of identical components (used under similar in-use conditions) during the first stage of the service life, as in Figure 2. Using identical components under similar in-use conditions filters the effects of in-use conditions (excluding maintenance) from the assessed condition state in respective components.

2.5. Energy efficiency

In general, implementing an energy efficiency (*EE*) measure imposes a considerable expense on the total service-life cycle costs of a building component. This expense can, however, be lowered substantially if the respective *EE* measure is carried out by the end of a component's service-life, when the costs of a reinstatement/renovation measure are already expected. By doing so, the required *EE* investment is lowered to a marginal cost that is equal to the difference between the original *EE* investment cost and the reinstatement/renovation cost. Considering the obvious economic benefits of combining *EE* measures with already required reinstatement/renovation measures, in the MARS method, *EE* measures are always planned together with reinstatement/renovation measures.

Replacing building components often changes maintenance/operation costs and so their life cycle economy. Similarly, improving the energy performance by implementing *EE* measures increases the investment required and changes the operation costs. The changes in the operation costs with regard to *EE* investments, however, always results in lower operation costs. The savings made through reductions in energy use are considered in the profitability assessments of *EE* investments but are seldom used in the evaluation of components' service-life cycle economy. To take these savings into account, in the MARS method, both the marginal *EE* investment costs and the respective lowered operation costs are incorporated into the *S-LCC* analysis of simulated maintenance and renovation plans.

Since in the deterioration function, the *EAC* method is used for the service life cycle cost (*S-LCC*) analysis, the addition of an energy efficiency criterion requires the costs and benefits of energy efficiency investments to be calculated using the *EAC* method.

In order to take the lower operation costs into account, the longest ESL amongst all components, is considered as the reference service-life. The savings made by the lowered operation costs are calculated against the reference service life and deducted from the total

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[10] "The importance of life-cycle based planning in maintenance and energy renovation of multifamily buildings"

[11] 'Existing buildings' refers to older buildings with no/limited prior maintenance care. The planning for existing buildings which have been maintained properly follows the same procedure as for new buildings.

service-life cycle costs of the respective components, equation (9). Here, the annuity factor of the savings is calculated using the reference service-life, whereas the annuity factor of the total maintenance and renovation costs for each simulated plan is calculated using the respective extended service-life (ESL).

The cost function $C_{MR,t}^{est_{(i,j)m}}$ includes all the costs identified for the maintenance and reinstatement/renovation of each building component plus the marginal costs of energy efficiency measures, equation (10). For example, for windows, proactive maintenance costs include the costs of frame adjustments, fixture of handles and hinges, new sealing and repainting of the sash and the frames. The reinstatement cost includes the total costs of installing an identical new window. And the energy efficiency cost becomes the difference between the total costs of the new more energy efficient windows and the reinstatement cost.

$$EAC_{(i,j)_m} = \frac{1}{A_{ESL_{(i,j)_m},r_d}} \sum_{t=0}^{ESL_{(i,j)m}} \frac{C_{MR,t}^{est_{(i,j)m}}(1+r_c)^t(1+r_{in})^t}{(1+r_d)^t} - \frac{1}{A_{ESL_{(i,j)_1},r_d}} \sum_{t=ESL_{(i,j)_{technical\ limit}}}^{ESL_{(i,j)1}} \frac{S_e.E.C_e(1+r_e)^t}{(1+r_d)^t} \tag{9}$$

where: $A_{ESL_{(i,j)_m},r_d}$ is the present value annuity factor for component i with maintenance measure j in plan m; $A_{ESL_{(i,j)_1},r_d}$ is the present value annuity factor for plan 1 ($ESL_{(i,j)_1}$ refers to the shortest maintenance interval thus the longest service life); $C_{MR,t}^{est_{(i,j)m}}$ is the estimated cost for the respective plan at year t; $ESL_{(i,j)_m}$ is the service life for plan m; S_e is the potential energy saving; C_e is the energy price; E is the total energy use; r_c and r_e are the price growth rate for costs of services and materials and the energy price growth rate and r_{in} and r_d are inflation rate and discount rate, respectively. The present value of the annuity factor is calculated using equation (6). And the cost function is calculated using the following equation:

$$C_{MR,t}^{est_{(i,j)m}} = C_{insp_{(i,j)m}} + \sum C_{pro_{(i,j)m}} + C_{rein_{(i,j)m}} + C_{EE_{(i,j)m}} \tag{10}$$

where: $C_{MR,t}^{est_{(i,j)m}}$ is the cost function for component i with maintenance measure j in plan m; $C_{insp_{(i,j)m}}$ is the respective inspection cost; $C_{pro_{(i,j)m}}$ is the proactive maintenance cost (of different types); $C_{rein_{(i,j)m}}$ is the reinstatement cost and $C_{EE_{(i,j)m}}$ is the marginal cost of the respective energy efficiency measure in plan m.

The energy efficiency improvements regarding the heat use, in general, are divided into two categories: the envelope heat loss reductions and the increased heating efficiency in the heating system. Considering that the envelope heat loss reduction measures are independent, their implementation order is important only when the energy renovation is also planned for the heating system. Equation (9) is used when the energy efficiency measures are applied only to the building envelope thus the order of implementation is not important. When combined with improvements in the heating system, energy use reductions can change depending on the time of implementation with respect to the time at which the heating system was upgraded. In this case, equation (11) is used for the calculation of energy savings made through the implementation of energy efficiency measures. The EAC value of the total savings can therefore be calculated using equation (12).

$$C_{ES_{(i,j)_m},t} = \begin{cases} \begin{cases} 0 & ,t \leq ESL_{(i,j)_m} \\ \left(\dfrac{S_h}{h_{e,initial}}.C_{e,h}.A\right) + \left(S_{el}.C_{e,el}.A\right) & ,t > ESL_{(i,j)_m} \end{cases} & ,t \leq t_{h,retrofit} \\ \begin{cases} 0 & ,t \leq ESL_{(i,j)_m} \\ \left(\dfrac{S_h}{h_{e,retrofit}}.C_{e,h}.A\right) + \left(S_{el}.C_{e,el}.A\right) & ,t > ESL_{(i,j)_m} \end{cases} & ,t > t_{h,retrofit} \end{cases} \tag{11}$$

$$EAC_{ES_{(i,j)_m}} = \frac{1}{A_{ESL_{(i,j)_1},r_d}} \sum_{t=ESL_{(i,j)_{technical\ limit}}}^{ESL_{(i,j)_1}} \left(C_{ES_{(i,j)_m},t}.\frac{(1+r_e)^t}{(1+r_d)^t}\right) \tag{12}$$

where: $C_{ES_{(i,j)_m},t}$ is the total savings made at year t, through implementation of energy efficiency measures; S_h is the heat loss reduction; $h_{e,initial}$ is the initial heating efficiency; $C_{e,h}$ is the price of heat; A is the heated floor area; S_{el} – is the change in electricity use; $C_{e,el}$ is the price of electricity; $h_{e,retrofit}$ is the improved heating efficiency and $EAC_{ES_{(i,j)_m}}$ is the equivalent annual cost of the total energy savings. Here $C_{ES_{(i,j)_m},t}$ if used only for the envelope is equal to $S_e.E.C_e$ in equation (9).

In Article 2[12] and Article 3[13], the deterioration function in equation (3) combined with the *S-LCC* analysis, given in equation (9), are used to illustrate the economic effects of timing in implementation of energy efficiency (*EE*) measures. This is done on both new and existing components to further illustrate the economic effects of worsening in-use conditions in maintenance and renovation planning. The flowchart shown in Figure 6, presents the simplified simulation process used in Article 3.

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[12] ” Optimizing the Life Cycle Costs of Building Components with Regard to Energy Renovation”. In this article the economic evaluations are carried out using only the net present value (*NPV*) method.

[13] ” The importance of life-cycle based planning in maintenance and energy renovation of multifamily buildings”

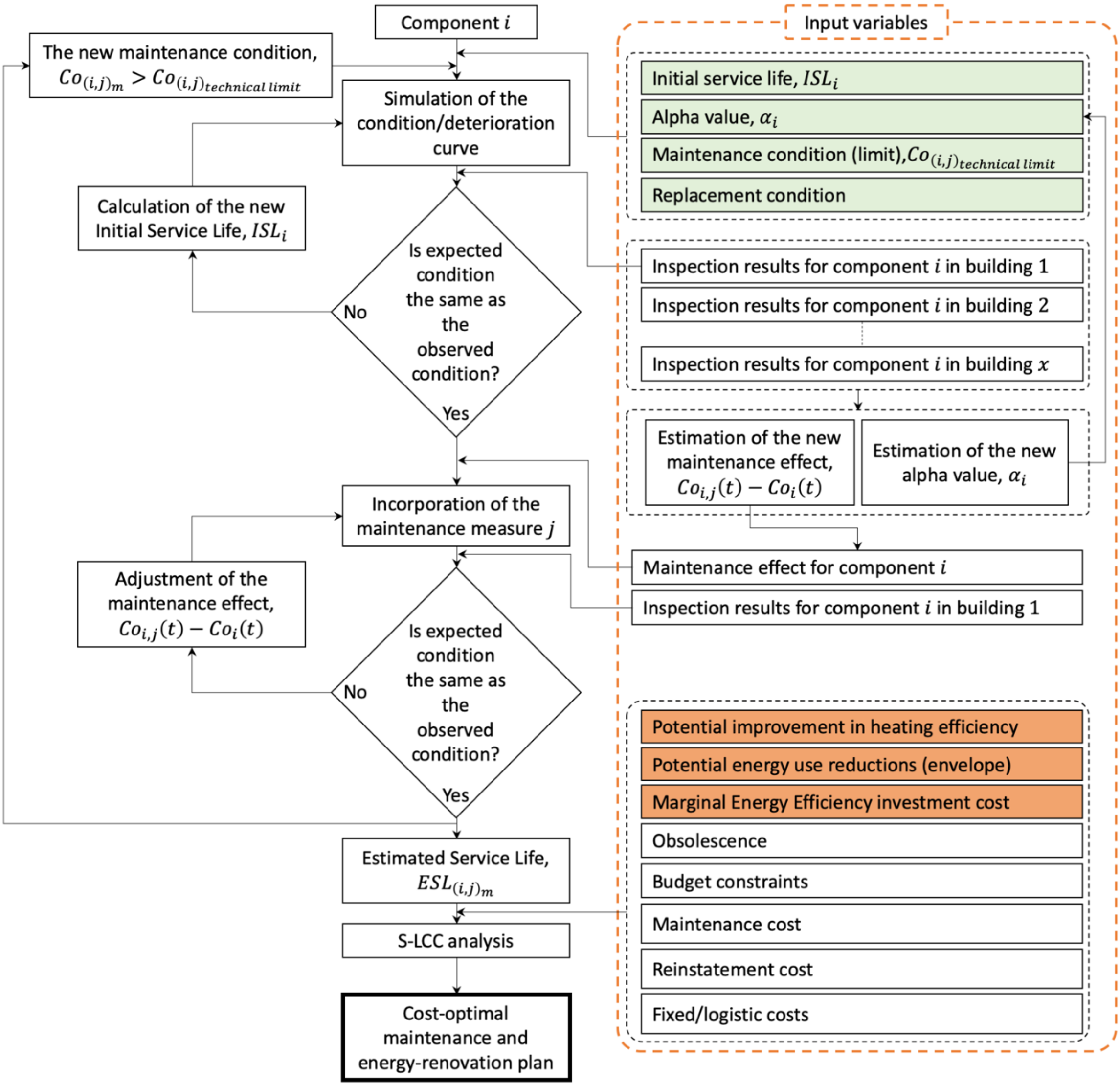

Figure 6. The implementation of energy efficiency measures in the modelling process for a single component in article 3. The green colour highlights the variables required to start the simulation. The orange colour highlights the additional input variables with regard to the implemented energy efficiency measures

2.6. Budget optimization

When planning for older buildings, there is often a need to carry out expensive maintenance/renovation measures in a short period of time. In such cases budgeting becomes problematic for housing owners who have yearly budget constraints.

In these situations, if the available financial resources are not sufficient to meet the required budget, property managers (housing owners) need to reschedule maintenance/renovation measures in the original plan (often compromising the performance level) in order to distribute the costs and respect the budget constraints.

To address the budgeting issue with the MARS method, the initial cost-optimization process is followed by the first budget optimization process (eliminating the deep-renovation optimization), as seen in Figure 7, that aims at bringing the yearly maintenance/renovation costs down to below the yearly budget requirements.

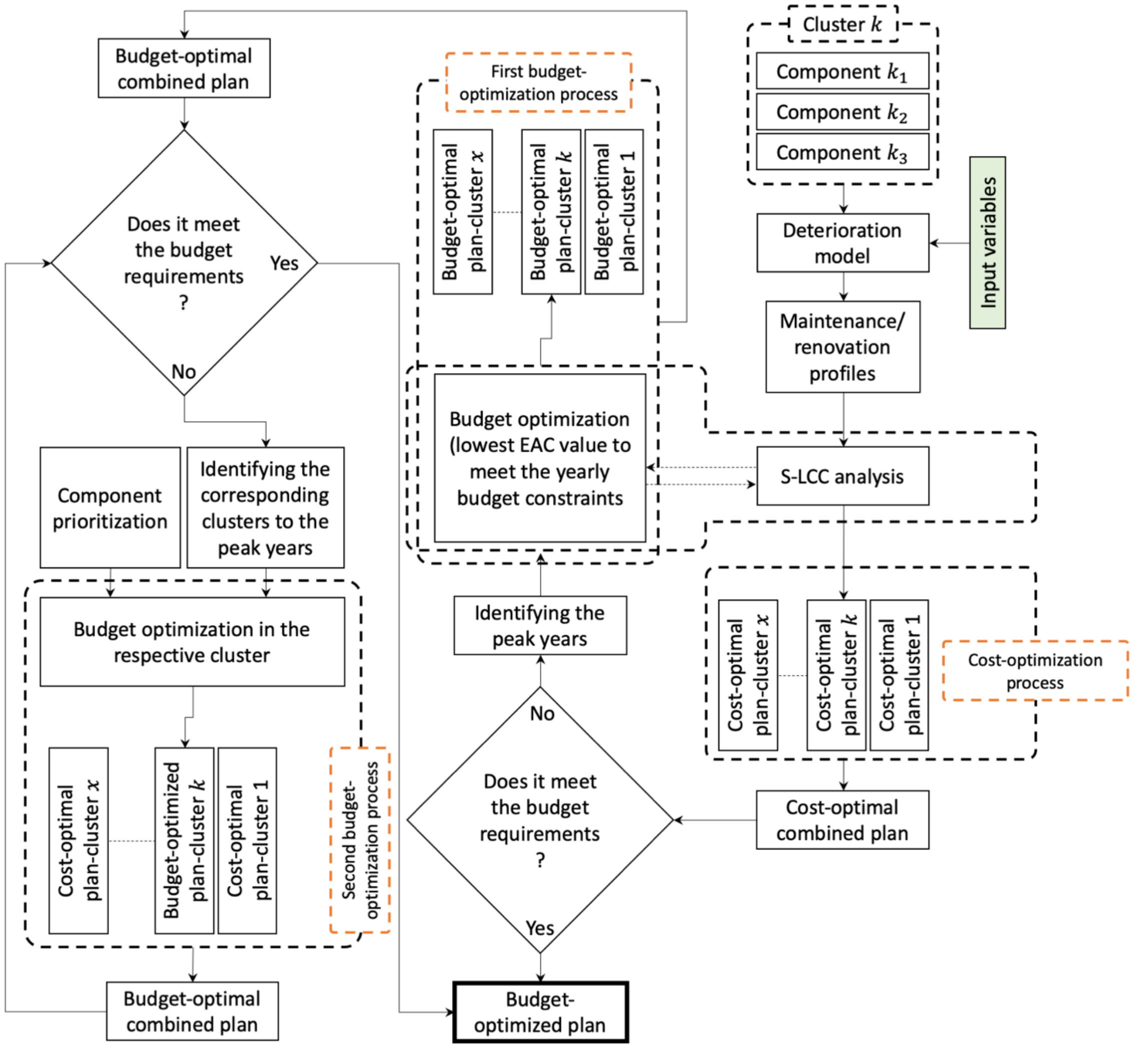

Figure 7. The budget optimisation process used in article 4. The green colour highlights the variables required to start the simulation.

In early planning, the first budget-optimization process can identify maintenance and renovation combinations that meet the yearly budget requirements, whereas in late planning, there are fewer opportunities (if any) to simultaneously reduce the costs and maintain the acceptable building performance. Nonetheless, to relax the cost profiles at designated years in planning for existing buildings (late planning), the condition technical limits $Co_{i,tech\ limit}$ are extended to enable delayed maintenance/renovation measures in the second budget-optimization process. Although postponing measures can help lower the projected costs at designated years (years at which the total maintenance and renovation costs are above the yearly budget requirements), this leaves respective components at below standard performance level. Therefore, to decrease the failure risks, if building components are not prioritized by the owners, they are first condition- and then cost-prioritized in the budget optimization process. The second budget optimization is not carried out in all clusters simultaneously but upon request to minimize the number of postponed measures. Subsequent clusters are summoned for budget optimization when the optimization in the first cluster has not lowered the total costs at designated years below the yearly budget requirements.

The budget optimization simulation process given in Figure 7 is used in Article 4[14] to demonstrate the application of the MARS method in maintenance and renovation planning under yearly budget constraints. In Article 4, using component clusters in two identical buildings (old and new), the method is also used against a conventional planning method (using local guidelines) to illustrate the economic effects of service-life cycle cost optimization in maintenance/renovation planning.

2.7. Cumulative Net Cash Flow (CNCF)

In situations where housing companies face difficulties in financing maintenance/renovation work, it is important to study the short- and long-term financial effects of the devised maintenance and renovation plan. In general, housing owners need to offset the projected costs by means of an income. The income can be in the form of a monthly rent in rental properties or a monthly fee in owner occupied properties. In either form, the minimum income should be calculated so that the sum of cash inflow can cover the sum of projected cash outflows by the end of the building's presumed service-life.

In early planning (new buildings), optimizing the service-life cycle costs of building components can potentially decrease future cash outflows hence the income required to offset the projected costs. Considering that in multifamily buildings more than 75% of the total maintenance/renovation costs are expected during the period spanning 30 to 50 years of age, (Farahani, 2017), in late planning (older buildings), if the cash inflow has not been accumulated, an initial investment fund is required to offset these projected costs.

In order to estimate these costs (both the required income in early planning and the required initial investment in late planning), the cumulative net cashflow method is used in the MARS method, equation (13). A positive value of the cumulative net cashflow indicates the capability of an asset to meet its financial obligations.

$$CNCF_t = \sum_{t=0}^{t_{build}} \left((R(1+r_r)^t - C_o) \frac{(1+r_{in})^t}{(1+r_d)^t} \right) - \sum_{t=0}^{t_{build}} \left(\frac{C_{MR,t}^{\mathrm{est}}(1+r_c)^t(1+r_{in})^t}{(1+r_d)^t} + \frac{C_{E,t}(1+r_e)^t}{(1+r_d)^t} \right) \tag{13}$$

where R is the rent; C_o is the operation costs; $C_{MR,t}^{est}$ is the total maintenance and renovation costs at year t; $C_{E,t}$ is the total cost of energy at year t, see equation (14); r_r is the rent growth rate; r_{in} is the inflation rate; r_d is the discount rate; r_c is the construction and services price growth rate; r_e is the energy price growth rate; t is time and t_{build} is the presumed building service-life.

$$C_{E,t} = \left(C_{E_{initial},t} - C_{ES,t} \right) \tag{14}$$

where $C_{E_{initial},t}$ is the initial cost of energy at year t, equation (15),and $C_{ES,t}$ is the total energy savings at year t.

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[14] "Cost-optimal maintenance and renovation planning under budget constraints"

$$C_{E_{initial},t} = \begin{cases} \left(\frac{E_h}{h_{e,initial}} . C_{e,h}. A\right) + \left(E_{el}. C_{e,el}. A\right) & , t \leq t_{h,retrofit} \\ \left(\frac{E_h}{h_{e,retrofit}} . C_{e,h}. A\right) + \left(E_{el}. C_{e,el}. A\right) & , t > t_{h,retrofit} \end{cases} \quad (15)$$

where: E_h is the heat use; $h_{e,initial}$ is the initial heating efficiency; $C_{e,h}$ is the price of heating; A is the heated floor area; E_{el} is the electricity use; $C_{e,el}$ is the price of electricity and $h_{e,retrofit}$ is the improved heating efficiency.

In Article 4, the Cumulative Net Cashflow method is further used to illustrate the effects of cost-optimal maintenance and renovation planning on both the required initial income in early planning and the initial required investment in late planning in existing buildings.

2.8. Building Stock Modelling (*BSM*)

The MARS method is also used to demonstrate its application in a bottom-up building stock modelling (*BSM*) approach. For this purpose, the budget optimization has been removed from the simulation process to facilitate cost-optimization in large scales (portfolio level). Hence, in Article 5[15], to illustrate the benefits of maintenance and retrofit (energy-renovation) cost-optimal scheduling, the MARS method is coupled with a building stock modelling method to model costs, energy and *GHG* emissions of a building portfolio. The proposed method enables the integrated long-term planning on retrofit (energy-renovation) investments and reduction of energy demand and *GHG* emissions for a portfolio of existing buildings.

2.9. Limitations

1- The required inspection input data are limited and dependent on the expert's knowledge and assessment. The default values used for initial planning can however be calibrated using collected condition sample data, (more information is provided in the section entitled 'inspection').
2- The repair costs are not included in the maintenance and renovation cost optimizations. Repair involves simple and regular measures designed to preserve the usability of a component.
3- The discount rate is fixed.
4- The profitability assessment of energy efficiency investments is outside the scope of this study.
5- Cost-optimizations are only carried out for the time at which the respective components are in service (service-life).

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[15] "A service-life cycle approach to maintenance and energy retrofit planning for building portfolios".

3. Summary of the results

This chapter discusses the main findings of the appended articles. The following results are presented to explain the research progress and how/where each article fits in the process of answering the formulated research questions and achieving the main objective of this study.

3.1. Basic cost-optimization process

In order to address the first research question, Article 1 presents an introduction to the basic deterioration function and the *S-LCC* analysis used in the MARS method.

Since maintenance is carried out to sustain an acceptable working condition (performance level) of building components, to minimize the service-life cycle costs (*S-LCC*), it is necessary to understand the relationship between the level of maintenance and the respective *S-LCC*, (Figure 3). Figure 8 illustrates this relationship for the two exemplary components, façade and windows, as presented in article 1. To create these figures, MARS method subjects the two components to different maintenance regimes with intervals ranging from t_{SW_i} (the beginning of the second phase, see equation (3)) to the initial service life identified for each component. The total service-life cycle costs for each plan is then calculated in form of an Equivalent Annual Cost (*EAC*), see equation (5). In this example, the first maintenance measures are carried out within 70% - 85% condition level corresponding to 10 - 20 years of service life (common industry standard intervals), point 1 and point 2 in Figure 8. The upper limit for the condition level is only used to decrease the calculation volume and, therefore, can also be ignored. The lower limit, however, is the lowest acceptable condition levels before which the maintenance measure has to be carried out. The lower condition limit should be selected based on either an expert's judgment on the results of a technical inspection[16] or available information e.g. manufacturer and/or local guidelines.

In Figure 8 the *EAC* value for the retroactive strategy (where maintenance includes only the reinstatement measure by the end of its service life, *ISL*) is calculated as a reference for comparison. Using the cost profile shown in Figure 8, the cost-optimal maintenance interval is selected by identifying the lowest *EAC* value within the acceptable condition levels, point 2 and point 4 for façade and windows, respectively. Here, point 2 for façade and point 3 for windows identify the industry standard maintenance intervals and their respective *EAC* values.

In case there are no conditions applied, if the *EAC* value of a proactive strategy is higher than of a retroactive strategy it is economically beneficial to carry out no maintenance and replace the component at the end of its initial service life (*ISL*). In doing so, it should be reminded that the accepted quality cannot be sustained throughout the respective component's service life.

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[16] The lower condition limit in older buildings is usually identified through inspection and includes technical, safety and aesthetic measures.

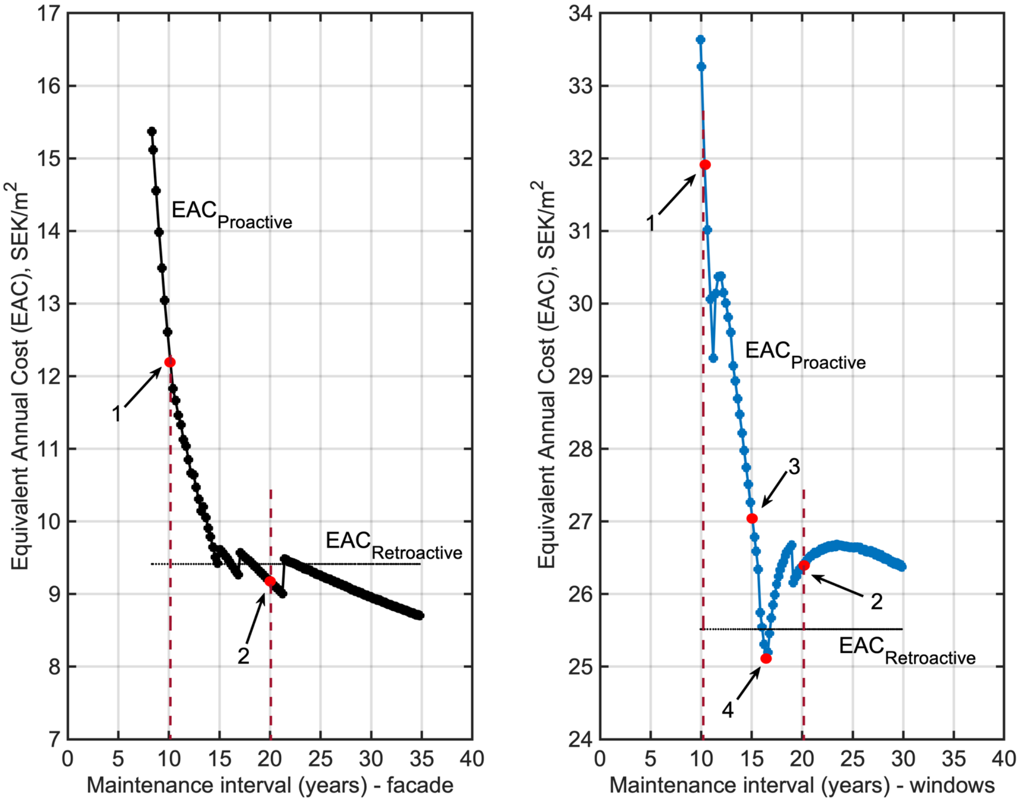

Figure 8. The relationship between the maintenance plan (maintenance intervals) and the service-life cycle costs for façade (left figure) and windows (right figure). Points 2, 3 and 4 are the same in the left figure (façade) and are represented by point 2.

To illustrate the condition/deterioration behaviour and to reveal the difference between a common industry and cost-optimal planning, both the industry and the cost-optimal maintenance renovation plans for windows are presented in Figure 9. These two plans correspond to the points 3 and 4 in Figure 8. As it is shown in the figure below, the cost-optimal interval is one year longer than the industry interval and results in 4 years shorter extended service life. The cost-optimal plan for windows in this example results in a 7,4% decrease in the total service-life cycle costs. The economic effects of combining maintenance and/or renovation measures for the two components are further discussed in Article 1.

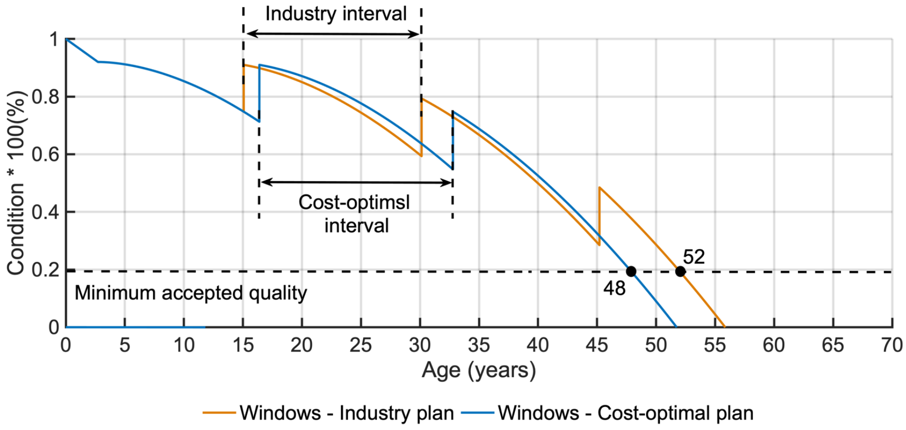

Figure 9. The condition/deterioration curves for windows under a common industry and the cost-optimal maintenance intervals

3.2. Energy renovation

Complementing the *S-LCC* analysis offered in Article 1 by implementing the costs and benefits of energy performance improvements in the *S-LCC* analysis in Article 2, it is possible to study the economic effects of an opportunistic approach in renovation with regard to energy efficiency. For this purpose, three scenarios are studied targeting both a common planning approaches in the industry (scenario 1 and 2) and the proposed approach in this study (scenario 3).

In the reference scenario, scenario 1, it is assumed that “façade” is planned for renovation by the end of its extended service life (*ESL*), at 60 years of age, as seen in Figure 10. The energy efficiency measure is to be applied during renovation and is expected to improve the energy performance of the building by 25%.

In scenario 2, it is assumed that due to the failure in other envelope components (e.g. windows and roof) an opportunity has shown up to combine all envelope components and benefit from the sharing fixed/logistic costs. And so, façade is planned for renovation together with the rest of envelope components at year 51.

As mentioned earlier, the problem with the opportunistic approach is that there is loss of value in premature renovation of building components. this loss of value is most often neglected in the economic evaluation of these projects. Therefore, In scenario 3, to avoid the premature renovation of façade and the consequent loss of value, a maintenance plan is devised so that the end of service life for façade would be 51 years of age without loss of value, as seen in Figure 10.

Costs and benefits of the energy efficiency measure are added to the total maintenance and renovation costs to calculate the total costs in each scenario, see Article 2.

The results show that the *S-LCC* (service-life cycle costs) in the opportunistic renovation approach in scenario 2, (at 1155 SEK/m^2 and 1200 SEK/m^2 with and without including the savings through energy use reductions) is higher than the *S-LCC* of the reference scenario at 1140 SEK/m^2. This outcome indicates the importance of a service-life cycle approach in the economic evaluation of renovation projects. Here, the opportunistic approach (scenario 2) could only be economically justified if the benefits gained from combining the envelope components would result in higher savings than the loss of value due to premature renovation of the façade.

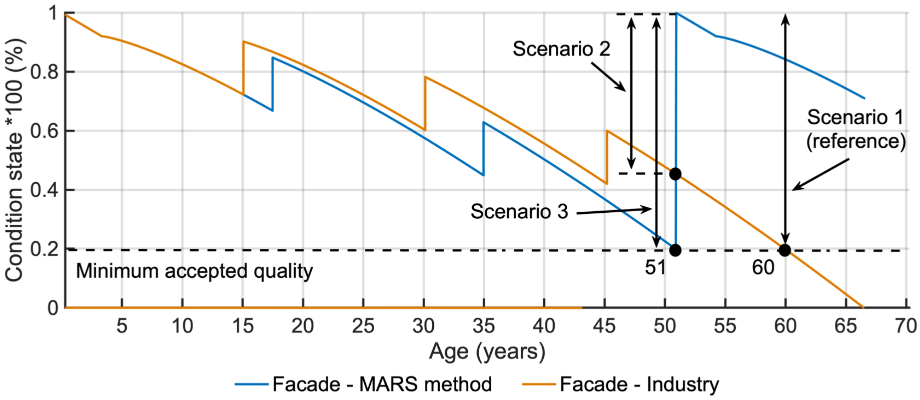

Figure 10. The condition/deterioration curves for façade in three different energy renovation scenarios

In scenario 3, the resulting *S-LCC*, at 1122 SEK/m^2, is lower than the *S-LCC* of scenario 1 and 2. The 33 SEK/m^2 difference between the *S-LCC* of scenario 2 and scenario 3 is equal to 12% of marginal investment costs of the façade's energy efficiency measure.

It is to be mentioned that the maintenance and renovation plan in scenario 3 is not the cost-optimal plan but only a plan that results in 51 years of life expectancy. The cost-optimal plan and more discussion on the economic effects of including the costs and benefits of energy efficiency measures in the *S-LCC* analysis in maintenance and renovation planning can be found in article 2.

Building upon the knowledge presented in article 2, the proposed cost optimization process, as seen in Figure 6, is used for energy-renovation planning for the envelope cluster (windows, façade and roof) in Article 3. The cost-optimization process enables the property managers (housing owners) to take advantage of deep-renovation benefits while avoiding the loss of value in premature renovation. The cost-optimization process in this article, not only minimizes the service-life cycle costs (*S-LCC*) of the combined maintenance and energy-renovation plans, equation (11) and (12), but also identifies the cost-optimal schedule for implementing the selected energy efficiency measures.

The condition/deterioration curves, in this article for the simplification purposes, are replaced and presented by planning figures where only maintenance and renovation years are marked, as seen in Figure 11.

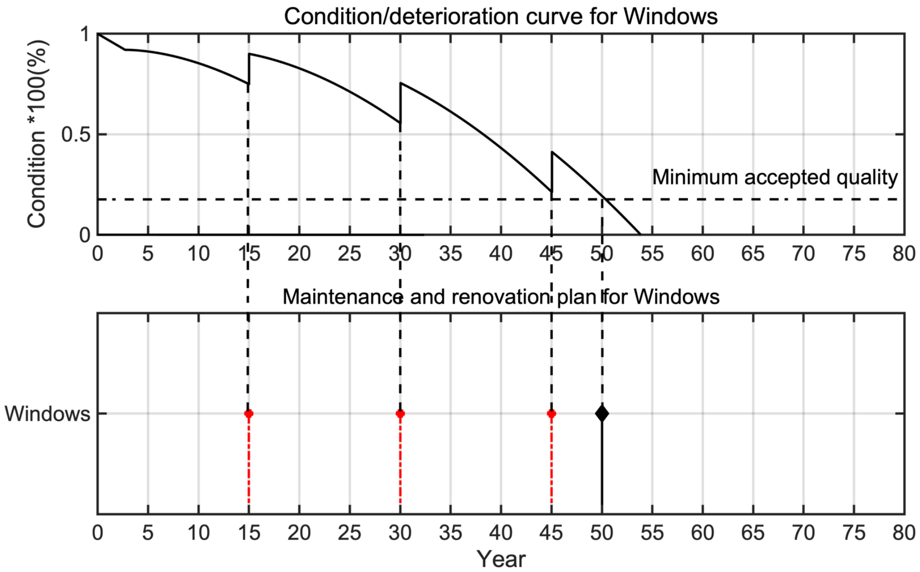

Figure 11. The condition/deterioration curve (on the top) and the corresponding maintenance and renovation plan (in the bottom)

In planning for maintenance and energy-renovation three scenarios are discussed in Article 3. The first two scenarios study both a deep-renovation and a gradual renovation approach to maintenance and energy-renovation planning. Whereas, in the third scenario, the economic effects of a worsening in-use condition in maintenance and energy-renovation planning is discussed. Here, a summary of the first two scenarios are presented. Information regarding the third scenario can be found in detail in Article 3.

In the first scenario, a conventional (*BAU*) approach is taken toward planning using both gradual- and deep-renovation strategies. The devised plans for the two strategies in scenario 1 are given in Figure 12 and Figure 13.

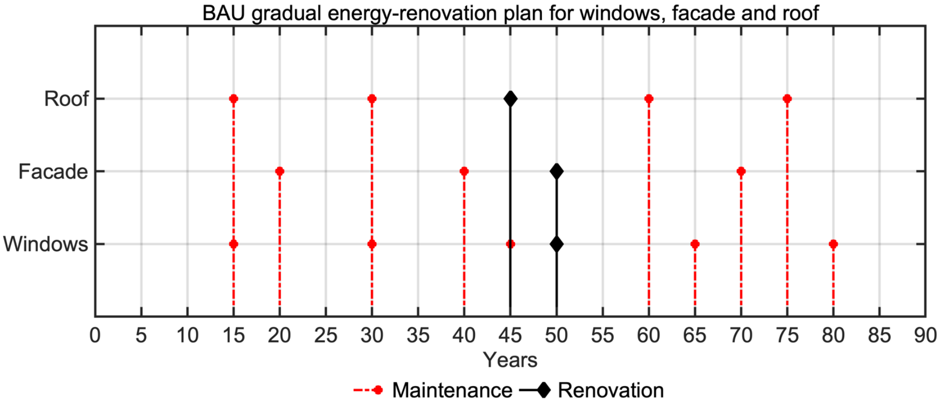

Figure 12. The BAU gradual energy-renovation plan

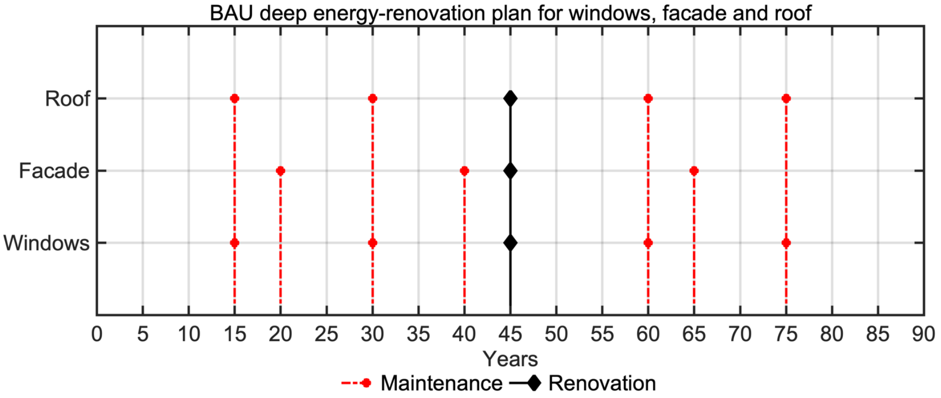

Figure 13. The BAU deep energy-renovation plan

The maintenance and renovation intervals in the first scenario are taken directly from the local guidelines, (SABO, 2013). For the gradual-renovation strategy, the total *S-LCC* is calculated using the *EAC* method at 104 SEK/m^2. Whereas the *S-LCC* for the deep-renovation strategy results in the *EAC* value of 103,5 SEK/m^2, indicating almost no financial gains in combining renovation measures as opposed to the gradual-renovation plan. Here, the presumed cost reductions (fixed/logistic costs as well as savings through energy use reduction) are offset by the loss of value in premature renovation of façade and windows, as seen in Figure 13. In order to demonstrate the importance of long-term planning with a life-cycle perspective, the cost-optimization process in the MARS method is used in the second scenario to find the cost-optimal maintenance and renovation plan for the combination of the three components, as seen in Figure 14.

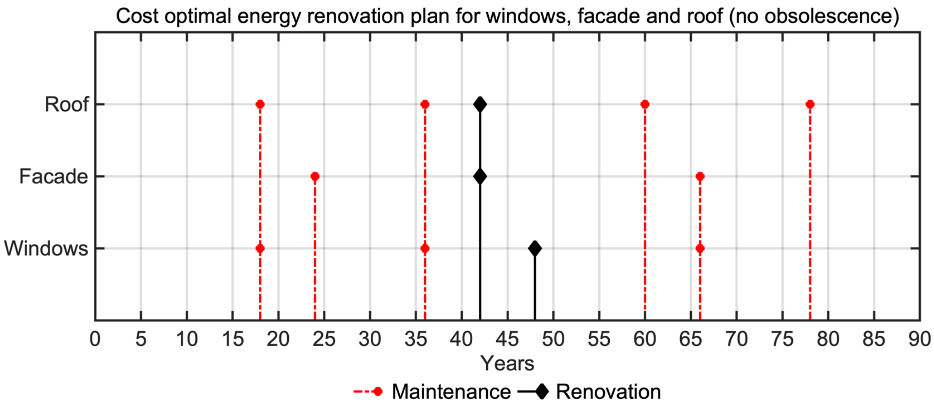

Figure 14. The cost-optimal energy-renovation plan

The total *EAC* value calculated for the cost-optimal plan at 95.5 SEK/m2, stands 8% lower than the *EAC* of the *BAU* deep-renovation plan. The 8% reduction is equal to 73% of the total marginal investment costs of the respective energy efficiency measures. The cost-optimal plan suggests earlier renovation year for all three components compared to the *BAU* gradual-renovation plan. The cost-optimal plan results in lower total fixed-costs and higher savings through energy use reduction.

Article 2 and Article 3 present the results from the second development phase of the MARS method (implementing the costs and benefits of energy efficiency improvements in *S-LCC* analysis of the MARS method) to address the second research question in this study. These results illustrate the economic benefits of a service-life cycle approach in maintenance and energy-renovation planning.

3.3. Planning under budget constraints

To address the third research question, the MARS method is used in Article 4 in building level for planning under yearly budget restrictions. The method is used on two identical buildings of different age to also demonstrate the economic effects of late maintenance and renovation planning. The resulting plans are compared to the plans devised by the managing company. Here in this section, only the results from the budget optimization process in the MARS method (given in Article 4) are presented and briefly discussed. The complete evaluation study can be found in the appended articles, Article 4.

Here the studied building is 44 years old and the maintenance and renovation plan is devised for 9 building components. Figure 15 shows the *BAU* plan devised by the managing company, SUSTEND. The initial plan is devised using the inspection results and then extended using a standard maintenance and renovation intervals (SUSTEND's own database) to produce the complete long-term plan shown in Figure 15. The corresponding budget plan is also given in Figure 16. The calculated total *EAC* value for this plan is 616 040 SEK.

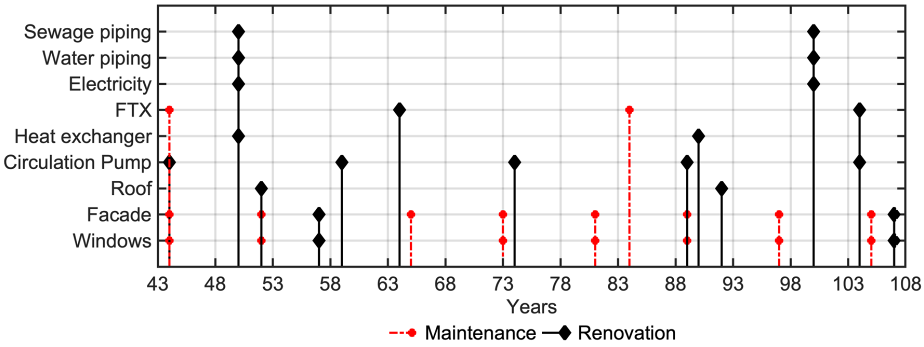

Figure 15. The maintenance and renovation plan devised by the managing company (SUSTEND) for the 44 years old building (BAU)

In this study it is assumed that the housing owners have an expenditure cap of 2 million SEK per year. The budget plan devised by the managing company shows that the budget needed for maintenance/renovation measures at years 50, 52 and 57 are above the owner's expenditure limit of 2 million SEK per year, (see figure below).

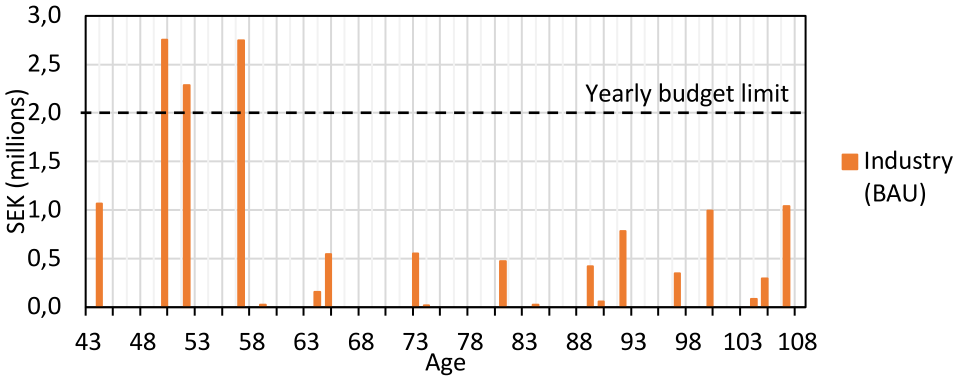

Figure 16. The maintenance and renovation budget plan devised by the managing company (SUSTEND) for the 44 years old building (BAU)

In general, to meet the yearly budget restrictions, short-term plans (3-5 years) are devised by the housing companies and the costs are broken down by distributing the required maintenance/renovation measures. Applying the same approach to the given plan in figure 15, results in a more relaxed cost profile that is shown in Figure 17. The corresponding budget plan for the updated maintenance and renovation plan is also given in Figure 19.

As it is shown, the total costs at years 50, 52 and 57 are now lower than the owner's expenditure limit of 2 million SEK per year. The calculated corresponding *EAC* value of the new plan is however 9% higher than the *EAC* of the original *BAU* plan, as seen in Figure 15. The higher *EAC* value once again indicates the importance of a service-life cycle perspective in economic evaluation of maintenance and renovation planning. The results show that the more evenly distributed costs do not necessarily translate into lower total costs and, therefore, more attention must be paid in the economic evaluations especially in short term cost distributions. Moreover, since maintenance and renovation measures are postponed (distributed) to lower the projected yearly costs, condition requirements in the respective components are disregarded.

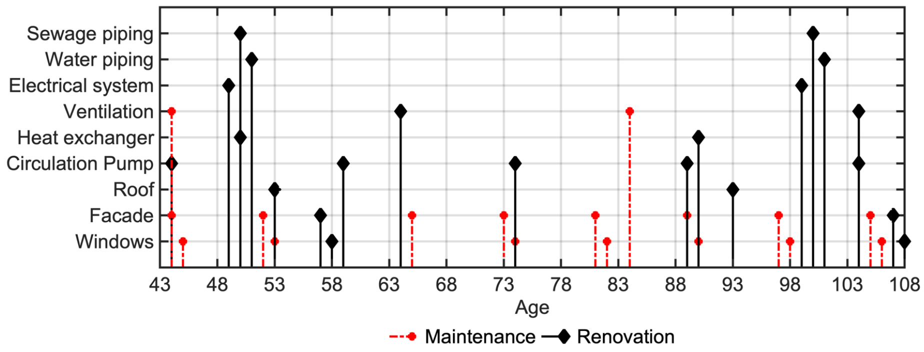

Figure 17. The BAU maintenance and renovation plan for 44 years old building with 2 million SEK yearly budget limit

To address these issues, the budget optimization process in the MARS method is used to create a plan that not only meets the presumed owner's budget requirements but also minimizes the corresponding service-life cycle costs. The resulting maintenance and renovation plan as well as the corresponding budget plan are shown in Figure 18 and Figure 19, respectively.

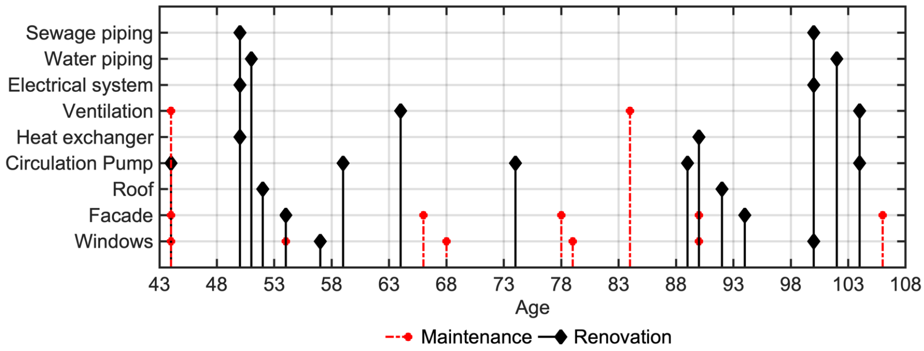

Figure 18. The cost-optimal maintenance and renovation plan for 44 years old building with 2 million SEK yearly budget limit

The projected costs are once again (this time using the MARS method) lower than the owner's expenditure limit of 2 million SEK per year. The resulting *EAC* value is however 9,5% lower than the industry budget plan shown in Figure 17. Here, it is important to note that the *EAC* value for the budget-optimized plan generated by the MARS method is even slightly lower than the *EAC* value of the original industry (*BAU*) plan with no budget limit (see Figure 15).

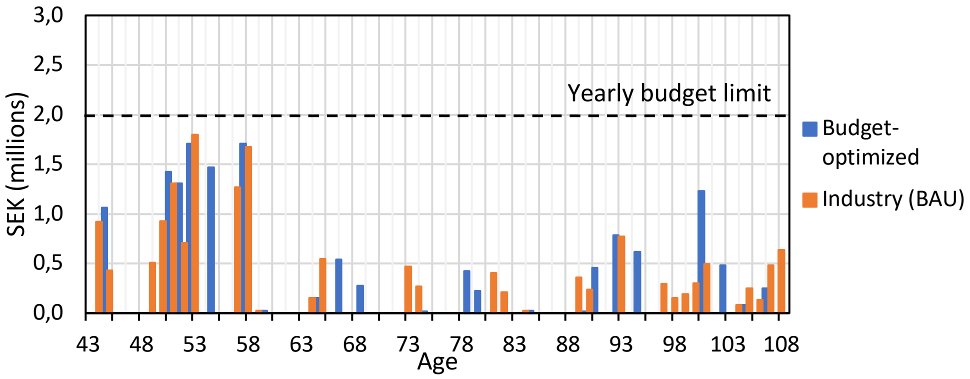

Figure 19. The BAU and the cost-optimal maintenance and renovation budget plan for 44 years old building with 2 million SEK yearly budget limit

The budget-optimized maintenance and renovation plan (the MARS method) not only meets the presumed owner's budget requirements but also lowers the corresponding service-life cycle costs. Considering that the budget optimization process in the MARS method is condition-prioritized, maintenance/ renovation measures are postponed only if necessary. In this case, the renovation measure in only one component (water piping) is postponed by one year compared to the three components (water piping, roof and windows) with postponed maintenance/renovation in the *BAU* budget plan. The result from Article 4 illustrate the negative effects of conventional planning under budget restrictions on both the economy of the plan and the condition of the building components. The results further show that with the use of the MARS method the condition requirements are still difficult to meet under budget restrictions.

3.4. Maintenance and renovation planning in portfolio level

In Article 5, the MARS method is used to demonstrate the application of cost-optimal maintenance and renovation planning in a bottom-up building stock modelling approach. The results from this article are meant to address the fourth research question in this study. In this article, a building stock modelling (*BSM*) approach is used to model costs, energy use and greenhouse gas (*GHG*) emissions of a building portfolio. The *BSM* approach is combined with the MARS method to forecast and optimize the timing of maintenance and energy-renovation measures on a portfolio level. The method is applied to more than 1800 multifamily buildings of the municipal housing company of Gothenburg to study the effects of implementing an ambitious energy-renovation package on the projected energy use, *GHG* emissions and the service-life cycle costs of the portfolio.

The development of the energy demand intensities in the portfolio in the industry plan as well as in the optimized plan for the energy-renovation scenario are shown in Figure 20. As it is shown in the figure, the projected energy use in both scenarios shows steady developments in the first 15 years with the share of low-performance buildings (using more than 100 kWh/m^2 year) gradually decreasing. The development pace increases after the year 2030 in both scenarios. In the retrofit scenario (Industry plan) there is an increase in the number of buildings (56.7% of the portfolio) using less than 75 kWh/m^2 year by the year 2050. Due to the optimized maintenance and retrofit planning this share is larger in the optimized scenario, with 64.3% of the buildings using less than 75 kWh/m^2 year by the year 2050. This observation indicates that retrofit measures are carried out earlier (i.e. components reaching the *ESL*) in the optimized scenario. Earlier retrofit measures also result in more retrofit measures being implemented until the year 2050. The optimization results in a reduction of the total energy use of 340.6 GWh/year (-46.1%) by the year 2050 compared to the total energy use of 320.7 GWh/year (-43.3%) in the retrofit scenario (Industry).

The more interesting outcome of the optimization is that the lower total energy use in the optimized scenario is achieved at 5% lower annual costs (*EAC*) across the portfolio compared to the retrofit scenario (Industry).

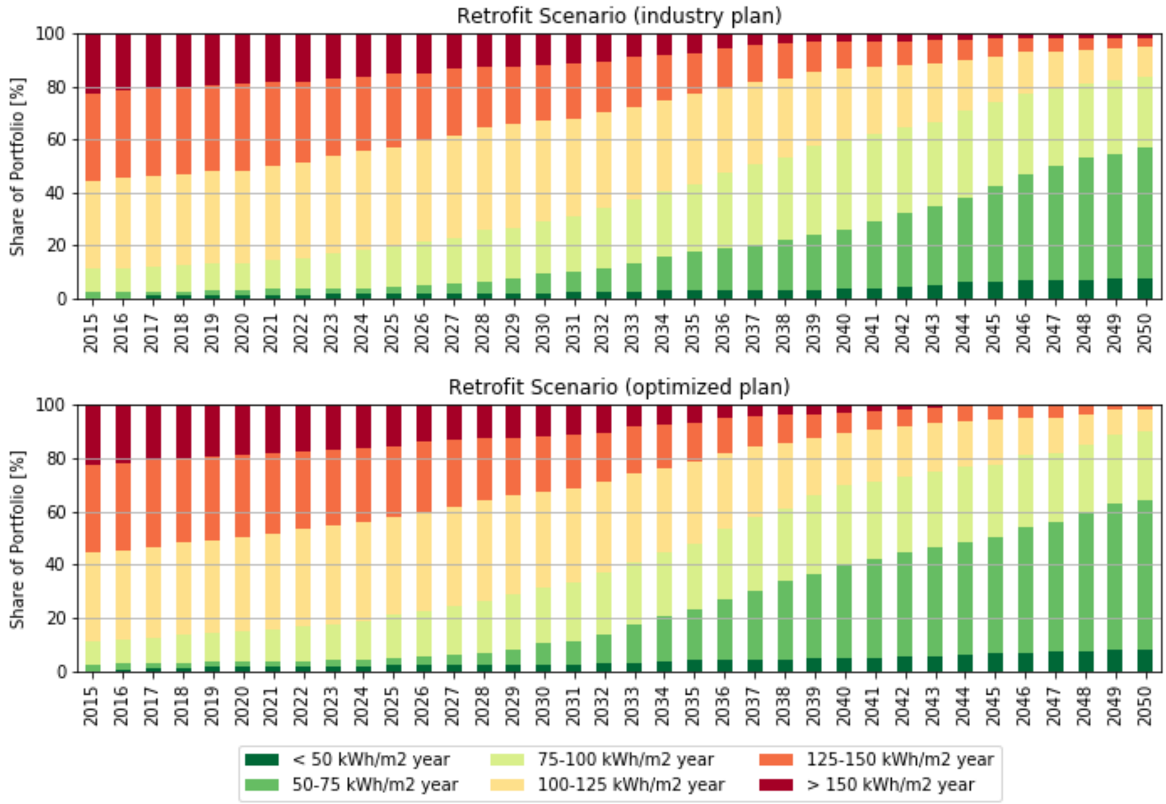

Figure 20. Development of the energy demand intensity distribution in the portfolio for the retrofit scenario based on the industry plan and the retrofit scenario based on the optimized plan

The results of this study indicate that by optimizing building-specific maintenance and energy-renovation plans, ambitious energy efficiency measures can be introduced in the majority of the buildings with a positive effect on the service-life cycle costs (*S-LCC*) of the buildings. This share could be further improved by tailoring retrofit measures in building level e.g. by lowering the ambition or excluding components that already have a good energy efficiency standard.

4. Discussion and conclusions

4.1. Revisited background

The Swedish real estate sector is often identified by its ambitious public housing program during the record years (1960-1974). The million homes program was at the time the largest housing program per capita in the world where more than a million apartments were built in a nation with a population of 8 million. These apartments once being the pride of a nation, today are facing a lot of problems, ranging from vacancy and unacceptable physical condition to poor energy performance.

Approaching the end of the service life, these buildings are in need of extensive maintenance and renovation measures. Considering the technological development today, the problem with maintenance and renovation remains to be of a financial nature. These financial difficulties are the result of both internal (property management) and external (market variants) system deficiencies.

Regulatory issues are usually found to have roles in the development of such financial difficulties. For example, the rent negotiation procedure in the Swedish rent-controlled housing market, the limitation on maintenance provisions for municipal housing companies or despite the positive effects of the component depreciation approach, the limitation in the use of different depreciation methods can impose financial burden specially in smaller housing companies.

Still and all, on top of these externally imposed limitations, there are internal system deficiencies within housing companies which further limit the progress of renovation and energy efficiency in the Swedish housing market. These deficiencies exist both in the economic evaluation of renovation and energy efficiency investments and in the choice of maintenance/renovation strategies.

For example, maintenance measures in many cases are neglected or postponed and deep-renovation is still favoured by many organizations. Besides, maintenance and renovation plans are short-term and economic evaluation of renovation projects are not carried out in a service-life cycle perspective. The existing methods are complex and/or incapable of multi-objective planning which makes decision making a difficult task under restricting conditions.

To address these problems and the complexity involved, this study proposes a systematic approach to strategic maintenance and renovation planning through which life cycle costs can be minimized and market/owners' requirements can be met.

To achieve this, the condition-deterioration function of the commonly accepted method Schroeder is modified to separately take into account the effects of maintenance on the life expectancy of building components. Combined with a complete service-life cycle cost analysis (including costs and benefits of energy performance improvements), the economic effects of timing are evaluated under different maintenance regimes. The resulting maintenance and renovation scheduling (MARS) method allows for maintenance and renovation cost optimization under condition, time and/or budget constraints.

Moreover, in the MARS method, the effects of the remaining in-use conditions are collectively implemented in the deterioration function by means of time increments. This enables a simple incorporation of the inspection results which in return improves the reliability and accuracy of the resulting maintenance and renovation plans.

4.2. Research questions

The formulated research questions in this study are addressed through the development of the MARS method and the detailed findings are presented in the appended articles. The first article addresses the first research question by presenting an introduction to the deterioration function and the service-life cycle cost analysis used in the MARS method. This article demonstrates how the MARS method can be used to minimize service-life cycle costs of building components under condition (time-performance) and time constraints. It further illustrates the economic effects of maintenance and/or renovation groupings in a service-life cycle perspective.

The second and the third articles address the second research question in this study. Article 2 demonstrates how the costs and benefits of energy efficiency measures are implemented in the *S-LCC* analysis of the MARS method. The third article then shows a developed cost-optimization process with regard to energy efficiency upon the updated *S-LCC* analysis presented in the second article. The results from these articles illustrate the economic benefits of a service-life cycle approach in maintenance and energy-renovation planning. The results also show that the cost-optimal planning often result in shorter extended service life of building components than in the industry planning which leads to higher total energy savings. Moreover, considering the insensitivity of the MARS method toward changes in the calculated energy savings, the method does not require accurate estimation of the energy use reductions and so can be used with rough estimation of the initial energy saving potential.

In the fourth article, the complete maintenance and renovation scheduling (MARS) method is introduced. To address the third research question in this study, the presented MARS method incorporates building clusters to enable energy performance improvements and cost-optimizations in building/portfolio level. Furthermore, it adds a budget optimization process that enables cost-optimizations under yearly budget constraints. The results from this study illustrate the negative effects of conventional maintenance and renovation planning under yearly budget constraints on both the economy of the devised plans and the condition of building components. Although the total service-life cycle costs are minimized with the use of the MARS method for budget-optimized planning, the condition requirements are not always met.

Finally, in the fifth article, to address the fourth research question, the application of the MARS method is demonstrated in a portfolio level. in this article, a building stock modelling approach is combined with the MARS method to forecast the maintenance and renovation costs, the energy use and the *GHG* emission reductions in a building portfolio. The results show the potential for improved energy and *GHG* emission reductions at lower costs in an optimized scenario compared to an industry scenario in a building portfolio of the municipal housing company of Gothenburg. The results indicate that by optimizing building-specific maintenance and renovation plans, ambitious energy efficiency measures can be introduced in the majority of the buildings with a positive effect on the life-cycle costs of the buildings.

4.3. Sensitivity and uncertainty of the MARS method

Considering that deterioration is uncertain in nature, service life estimations can never be precise. The MARS method, similar to any other planning method, is bound to contain uncertainties. These uncertainties are however much less pronounced in short-term condition predictions. That is why inspections play an undeniably important role in the reliability and accuracy of maintenance and renovation plans. So, to improve the results of the MARS method, inspection results are directly implemented in the deterioration function and are further used for calibration of the component specific deterioration behaviour. As discussed in Article 1, the planning results are relatively insensitive toward reasonable changes in the deterioration variables, for example alpha value and maintenance effect. Nonetheless, these values, as mentioned earlier, can be calibrated using available time-performance data.

As for the sensitivity in the economic evaluations, in general there are certain cost variables that play an important role in the long-term economic evaluation of maintenance and renovation planning, for example the discount rate, the energy price growth rate, etc. Changes in these variables can affect the resulting cost estimates. However, as the sensitivity analysis in Article 1 shows, the planning results from the MARS method are once again fairly insensitive toward reasonable changes in these cost variables. Similar results are also observed with the implementation of energy efficiency measures. Considering the large difference between the marginal costs of energy efficiency measures and the costs of the total energy saved, cost-optimal planning results are fairly insensitive towards changes in the calculated energy use reductions.

Long-term budgeting plans, regardless of the method used, must be taken into account and used cautiously. Long-term plans are mainly useful for budget allocation and the efficient distribution of resources.

4.4. Future development

In general, the MARS method is meant to provide support for property managers (building owners) in form of techno-economic assessment of potential maintenance and renovation scenarios. When planning for maintenance and renovation, apart from the techno-economic issues there are other important factors that need to be considered carefully. For example, in article 3 and article 4 it is discussed how the use of a systematic planning approach can be beneficial to the tenants specially in less-attractive markets. Moreover, buildings with heritage value present specialised maintenance and renovation problems, which require further investigation.

The MARS method has so far been developed based on common industry standard inspection and maintenance/renovation planning procedures. It has further been applied on example building components in co-operation with a company that offers maintenance planning and contracting solutions (SUSTEND, Article 4). Furthermore, the building portfolio data used in Article 5 is developed in previous and parallel research projects.

The next step is to apply the MARS method in real maintenance and renovation cases in close cooperation with building owners. In order to do so the MARS method has already been implemented in another environment with a user-friendly interface that can be demonstrated for and used by building owners and other actors that show interest in the development. It is further anticipated that the future development will comprise new research and development projects within Sweden, as well as the EU.

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