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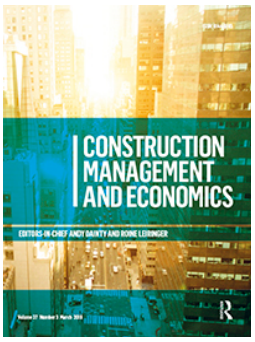

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Optimized maintenance and renovation scheduling in multifamily buildings – a systematic approach based on condition state and life cycle cost of building components

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ABSTRACT

Proactive maintenance strategies in principle are devised to control degradation and sustain optimal performance of building components. While realizing the technical necessities, they also serve as an instrument towards multiple and often conflicting objectives during financial constraints. An optimal proactive maintenance strategy therefore should comprise a multiannual maintenance action plan optimized on different criteria corresponding to owners' objectives under existing constraints. This study offers a systematic approach based on a condition-deterioration model to address the complexity involved in decision making regarding optimized maintenance and renovation planning. Life-cycle cost analysis in form of Equivalent Annual Cost (EAC) is used for the economic assessment of maintenance/renovation scenarios. In this paper, the model is used to compare the economy of different maintenance/renovation plans in a chosen scenario in order to determine the optimal maintenance interval for a single and a combination of building components. Two façade elements, windows and façade rendering, are used to illustrate the application of the proposed method. This method is intended to help decision makers at both design and post-construction phases in the choice of both building components and maintenance/renovation strategies.

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Proactive maintenance; renovation; residential buildings; service life; life cycle cost

Introduction

The residential building stock in Europe is rather old. With more than 40% of the stock built before 1960 (Artola *et al*. 2016), the majority have reached or are approaching the extent of their service life. Buildings in less attractive markets, due to budget constraints, have been left with little care. Even in more attractive markets, maintenance planning has not been approached systematically. As a result, buildings grew old in poor conditions, providing below standard service quality, and low energy performance. With the ever-growing housing demand, today, there is an urgent need to attend the current housing situation and meet current standards and requirements. That is why maintenance and renovation (the definition will follow in chapter 2) has gained a lot of attention and became quite important to the building sector in recent years.

Property managers of larger housing portfolios are responsible for planning maintenance and renovation work. In real estate, a common practice to lower costs in asset management is to reduce or postpone maintenance activities when there are financial constraints, (Caccavelli and Genre 2000). These constraints come in form of temporary budget and/or market induced limitations, i.e. a rent-control housing market where maintenance measures do not qualify for rent adjustments. Decisions regarding maintenance and renovation are based on internal requirements and market conditions. Besides, there is very little knowledge amongst property managers regarding the effects of timing on the service-life cycle costs of building components. The ability to predict the forthcoming maintenance and renovation expenditures would enable the property managers to efficiently utilize resources to maintain an acceptable building performance and lower the budgetary pressure. A key parameter required for a proper life-cycle cost analysis is the life expectancy of building components under different maintenance strategies.

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Basically, any method used for budgeting maintenance and renovation, relies on the prediction of the life expectancy. And, the prediction of the life expectancy can be a complex and time-consuming process. Respective studies are very limited and relevant useful information is rare. On the other hand, the deterioration process is uncertain in nature and is affected by different in-use conditions (ISO15686–3 2016). i.e. the prediction of service life expectancy is never an exact science (Hovde and Moser 2004).

In general, there are two approaches to predict the life expectancy of building components; the deterministic approach and the probabilistic approach (Kumar *et al.* 2010). The deterministic approach requires expert input whereas the probabilistic approach requires statistical data and mathematical models. The former gives a robust estimation of the expected service life (ESL) and is widely used in real estate and construction industry, whereas the latter approach considers deterioration as a stochastic process and requires detailed input in form of probabilities.

The deterministic approach estimates the ESL using a reference service life (RSL) and the effects of in-use conditions in terms of coefficients, which have individually been assigned to each variable by experts (ISO15686–3 2016). The RSL in return has ideally been provided by a full deterioration model using a probabilistic approach (Hovde and Moser 2004). The RSL for different building components can be obtained from manufacturers, e.g. through environmental performance declarations (EPDs), statistics, certain publications or local building codes and standards (ISO15686–3 2016).

Considering its simplicity and robustness, the deterministic approach is widely used in the real estate and construction industry. Since its outcome is dependent on the experts' input, the effects of different in-use conditions have been studied in number of studies to examine the applicability of the deterministic approach. Age, occupancy and type of environment were studied in number of healthcare facilities to determine a facility coefficient to be used to better estimate the maintenance expenditure required for each facility (Lavy and Shohet 2007). In another study, a hybrid deterministic condition-based approach was proposed to predict the service life of façade elements in failure condition for maintenance purposes (Shohet *et al.* 2002). Nonetheless, studies on the application of the deterministic approach highlight the uncertainty of the estimations, given that the outcome is a single value for the service life (Bourke and Davies 1997, Strand and Hovde 1999, Marteinsson 2003, Hovde and Moser 2004). To obtain more representative service life values, it has been suggested that the effects of in-use conditions and the reference service life (RSL) value should be given as probability density functions rather than single values, to obtain the ESL in form of a probability distribution (Engineering approach (Lounis and Lacasse 1998)). The main problem with probabilistic approaches, however, is that they are inherently complex.

Although, there also has been a number of studies using the probabilistic approach for the estimation of building components life expectancy (Cinlar *et al.* 1977, Bon 1988, Frangopol *et al.* 2004, Lawless and Crowder 2004, Nicolai and Budai 2004, Nicolai *et al.* 2007, van Noortwijk 2009), these methods are often too complicated to be used by property managers.

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 were designed to assist building owners in budgeting and planning for maintenance and renovation. EPIQR (Brandt and Wittchen 1999) is a method based on previous methodology (MERIP, (PI-BAT 1993)) for diagnosis and analysis of maintenance and refurbishment plans for residential buildings which includes sustainability criteria. It describes the deterioration state of building components in form of probability distributions (MEDIC method (Flourentzou *et al.* 2000)). INVESTIMMO (Balaras *et al.* 2005) was developed based on EPIQR's methodology to further investigate the effects of external factors on the deterioration and life expectancy of building components. To assess the condition of commercial buildings and elaborate refurbishment scenarios, TOBUS (Caccavelli and Gugerli 2002) was developed that is also based on EPIQR methodology. TOBUS is an analytical method that requires a quality assessment of building components. In another attempt, PABI was developed to facilitate maintenance and refurbishment budgeting without on-site assessment (Bahr and Lennerts 2010)). Another widely used method for budgeting of maintenance and renovation has been the method Schroeder (Schröder 1989; Christen *et al.* 2014). The method is based on condition-deterioration behaviour of different building components used to determine the value and condition of the respective component in function of time. The condition behaviour function proposed by Schroeder was validated in a research program later in 1995 (IP BAU 1995).

Although these methods offer an estimation for future maintenance and renovation costs and facilitate quick analysis of buildings condition, they fail to address the problem complexity under budget and time constraints.

Either, the purpose is to plan and budget maintenance work in new construction or to carry out major renovation work, the timing for each individual action to achieve a cost-optimal long-term plan is of crucial importance. To be able to address timing, knowledge of the actual condition of building components and their respective remaining service life is often decisive. In existing methods, the effects of maintenance on the condition state and subsequently the life expectancy of building components are taken into account only by considering the quality and extent of maintenance measures carried out. Neglecting timing can result in the loss of potential value. For example, it is important to be able to evaluate whether a component should be replaced prematurely or by the end of its service life. Or if there are benefits in over maintaining (shorter maintenance intervals) an individual component knowing that it will be cost inefficient. One reason behind the inability to deal with timing in existing methods is the difficulty in the assessment of the effect of maintenance on the condition state and subsequently the life expectancy of the building components.

Scope of study

The theoretical methodology presented in this paper proposes a systematic approach to optimized maintenance planning regarding condition state and life cycle economy of building components. This study attempts to address the gap by modifying the condition-deterioration function of the commonly accepted Schroeder method in order to estimate the effects of maintenance (timing as well as quality) on the life expectancy of building components. The systematic approach proposed in this study is meant to provide support for building management in forms of technical and economic evaluation of possible maintenance and renovation scenarios (definitions will follow in section 2). The property managers can decide on the component/building/portfolio level, the objective of the evaluation and the level and type of restrictions.

Definition and modelling assumptions

Considering the existing inconsistency in 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 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 replacement of building components. Whereas, proactive measures, in addition to the replacement, include actions carried out to sustain a proper working condition and/or prolong the service life of building components. In both proactive and retroactive strategies, a building component is replaced with a new identical part. And the term 'renovation', is used only for the replacement of a building component with a better/higher quality component (increased utility-value).

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

- Building components are mutually independent. A maintenance measure only affects the respective component. Such effects however are not neglected in this study. These effects are considered and implemented in the model using building inspection results, (more details are given in the next chapter).
- Considering the long service life of costly building components (the two components in this study have 30–50 years of service life), the effects of changes made in the deterioration are considered to not greatly affect the service-life of the respective components in a period shorter than one year. Therefore, the duration of proactive maintenance measures become negligible and the maintenance effect can be applied to the condition state at the time of maintenance.
- Deterioration process include the effects of aging, wear and other cumulative damages and is the only cause of system failure.
- In-use conditions have no effect on the deterioration path of building components. Deterioration is regarded as component characteristic.
- Except for maintenance, the effects of in-use conditions are integrated directly in to the size of time increments and subsequently estimation of the life expectancy.
- Maintenance does not affect the deterioration path but restores the condition state of the respective component to a new state.

Deterioration model

The key complication in maintenance and renovation planning comes from the difficulty and uncertainty in

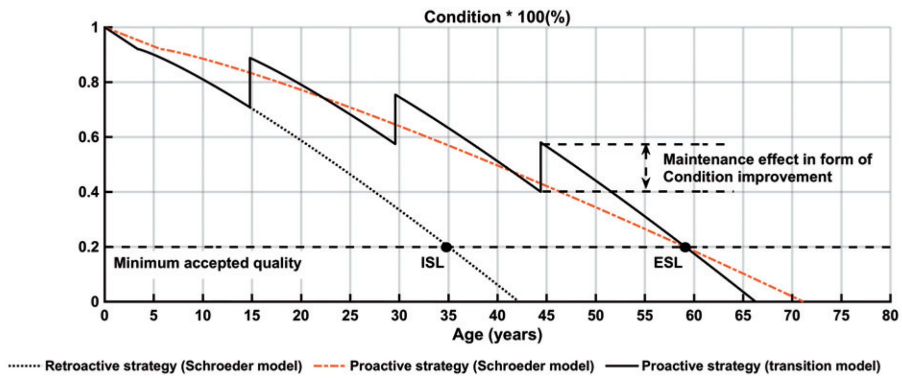

Figure 1. Exemplary condition curves for both retroactive and proactive strategies.

the estimation of the time to failure (service life) and/or the deterioration behaviour. A number of empirical studies (Cinlar *et al.* 1977, Ellingwood and Mori 1993, Hoffmans and Pilarczyk 1995, van Noortwijk and Klatter 1999) have shown that the deterioration can be expressed by the power law; that is, the expected deterioration can be written as:

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

Where $X(t)$ denotes the deterioration at time 't' for physical constants $a > 0$ and $b > 0$ at time t, (van Noortwijk 2009). Similar to these studies, Schroeder (Schröder 1989) explained building components' deterioration behaviour in form of a simplified condition/deterioration curve using Equation (1). Schroeder's equations describe deterioration in two phases, both of which are expressed by the power law. Phase one describes the initial irreversible degradation process and the second phase outlines the degradation process during which the condition of building components is retrievable by means of maintenance. Considering the creditability (Christen *et al.* 2014) and simplicity of the Schroeder method its approach to deterioration is used in this study as the basic deterioration/condition function.

In order to estimate the effects of in-use conditions on the life expectancy of building components, Schroeder's deterioration function is modified using the main property of a discrete-time Markov chain process (deterioration); i.e. the condition of a system in the future depends on the current condition state of the system (Gagniuc 2017). This allows for the incorporation of the condition-improving maintenance measures. Maintenance increases components' performance by improving the condition state. This effect, is considered to be a non-repeating modification of the deterioration behaviour (Frangopol *et al.* 2004; van Noortwijk and Frangopol 2004) meaning that the deterioration rate after maintenance is equal to the deterioration rate at the corresponding new condition state.

Considering a building with 'n' non-identical components, it is assumed that component condition state can be characterized by a physical variable 'Co_i' with $i = \{1, 2, \ldots, n\}$. For each component, one minimum accepted quality (condition) and $j = \{1, 2, \ldots, m\}$ maintenance operations are considered. Assuming $Co_i(0) = 100\%$ (new component), the deterioration model predicts the future condition state '$Co_i(t)$' of a component at time 't' based on its current condition. A threshold minimum accepted condition '$Co_{i,min}$' is identified for each component to determine the end of corresponding estimated service life (ESL). When the condition state reaches $Co_{i,min}$, the component 'i' is assumed unusable (failed), (Figure 1).

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

where: t_{sw_i} – time when phase 1 ends and phase 2 begins (years); α_i – exponent defining the shape of the condition/deterioration curve during each phase and; $Co_i(t_{sw_i})$ – condition in percentage at t_{sw_i}.

Incorporating the effect of maintenance, the corresponding added service life, $\delta t_{i,j,}$ is calculated using Equation (3):

$$\delta t_{i,j} = \begin{cases} t - t_{sw_i}\left(\frac{1 - Co_{i,j}(t)}{t_{sw_i}}\right)^{(1/\alpha_{i,\ 1})}, & \text{for } Co_{i,j}(t) \geq Co_i(t_{sw_i}) \\ t - t_{sw_i} - Co_i(t_{sw_i})\left(1 - \left(\frac{Co_{i,j}(t)}{Co_i(t_{sw_i})}\right)\right)^{(1/\alpha_{i,2})}, & \text{for } Co_{i,j}(t) < Co_i(t_{sw_i}) \end{cases} \tag{3}$$

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

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, and be specified for each component (Moser 1999). For example, the service life value can be defined by aesthetic requirements before the component reaches minimum condition level regarding safety or functionality. In this context, it is therefore necessary to provide the requirements that must be accomplished and the respective measures that must be carried out in order to sustain the expected performance during the service life for each building component.

In Figure 1, deterioration behaviour is illustrated for an exemplary building component using the condition/deterioration curves. The points denoted as ISL (initial service life) and ESL (estimated service life), mark the end of service life in retroactive and proactive strategies, respectively. Moreover, the condition improvement represents the effect of a maintenance measure (or a combination of measures carried out together) on the condition state of the building component and marks the shift from a retroactive to proactive strategy.

The ISL values to be used in the deterioration model can be taken from available datasets given by manufacturers, statistics, local standards/guidelines, etc. In this study, the ISL values are taken from one of the local guidelines, namely "*Nyckeltal för underhåll av bostäder*" (SABO 2013).

In general, the condition/deterioration curve, is the best fit to the available time-performance (overall condition of a component at the given time) data of the respective component. The shape of the condition/deterioration curves in this study are defined by the 'α_i' value. The 'α_i' value can be estimated using the maximum likelihood method when there are time-performance data available for the respective components. Considering that such information in real estate is sparse, the default values for 'α_i' in Equation (2), to start the optimization with, are taken directly from the IP BAU report (IP BAU 1995). Since the majority of the rather costly building components have long service lives (20–50 years (SABO 2013)), the default values can be corrected/calibrated using inspection prior to the designated first maintenance intervals.

Inspection provides time-performance data which is used to both improve the accuracy of the chosen 'α_i' value (using the maximum likelihood method) and incorporate the effects of in-use conditions in service-life expectancy of building components. Considering that the deterioration behaviour is a characteristic of a component alone and not time (discrete-time Markov chain process), a simple approach is used in this study through which, the effects of in-use conditions (inspection results) are calculated in the deterioration function and reflected in the size of time increments in condition/deterioration curves. The changes in the time increments are proportional to the time difference between the inspection time and the time on the simulated condition/deterioration curve at which the observed condition state given by the inspection results is equal to the expected condition state at the time of inspection. Figure 2 illustrates the basic modelling process used in this study. The input variables (α_i, ISL_i and $(Co_{i,j}(t) - Co_{i,j}(t))$) are estimated and then calibrated using inspection results. This not only allows for a better, more accurate ESL estimation but also improves the accuracy of the input values for the next simulation process.

An exemplary result of the modelling process has been shown in Figure 1. In that figure, the dashed orange line follows the same deterioration behaviour as the dotted black line except that it includes the maintenance effect (one of the in-use conditions) in form of longer time increments. These curves both were generated using the original method by Schroeder. The black line in this figure however, is generated using the model in this study, illustrating the same maintenance effect as in the dashed orange line in form of condition improvements.

Using the deterioration behaviour given by the condition/deterioration curves, the ESL can be calculated for the time when the condition level falls below the minimum accepted quality. For example, in Figure 1, with no maintenance measure carried out (the retroactive strategy), the ISL is set at its predefined value (35 years) where the ESL, given the condition improvement in a proactive strategy, is calculated at 58 years of age. In this example, the maintenance condition is set at 70% corresponding to the maintenance interval of 15 years. Once the first maintenance is scheduled, a periodic plan is devised using the respective maintenance interval.

Service-Life cycle cost (S-LCC) model

The S-LCC analysis considers the entire service life of a component and is used for the economic evaluation of each maintenance strategy in order to minimize maintenance costs. The total cost for each strategy

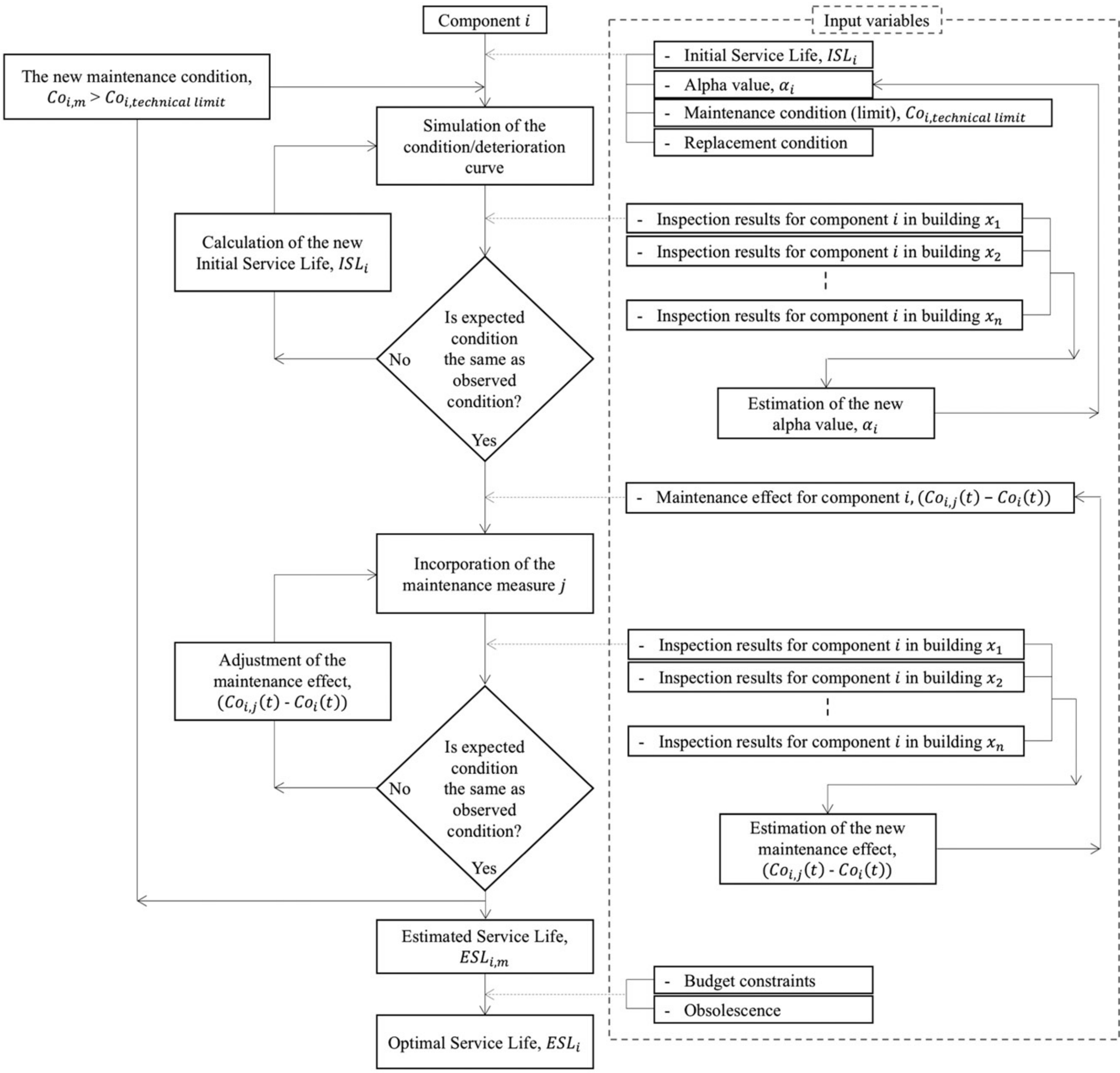

Figure 2. The basic modelling processes.

includes inspection, all maintenance measures and reinstatement costs. Since different maintenance intervals in a given strategy result in unequal ESLs, the equivalent annual cost method (EAC) (Flanagan 1989), which combines all the costs into a single annual cost, is used for a better S-LCC evaluation. The maintenance interval, which yields the lowest EAC is then considered as the optimal maintenance interval for the respective component.

$$EAC_i = \frac{1}{A_{ESL_i,r_d}} \sum_{t=0}^{ESL_i} \frac{C_t^{est_i}(1+r_e)^t}{(1+r_d)^t} \tag{4}$$

where: A_{ESL_i,r_d} – is the present value of annuity factor for plan i; $C_t^{est_i}$ – is the estimated cost for plan i in year t; ESL_i – is the service life for plan i; r_e and r_d – are the price differential rate (in costs of services and materials) and the discount rate, respectively. The present value of annuity factor is used in order to simplify the evaluation of the total cost in different maintenance plans and is equal to

$$A_{ESL_i,r_d} = \frac{1-(1+r_d)^{-ESL_i}}{r_d} \tag{5}$$

The cost function $C_t^{est_i}$ includes all the costs identified for the maintenance and replacement of each building component. For example, for the heating system, life cycle maintenance can include: proper controls (flue gas, etc.); cleaning; venting of the

Table 1. Maintenance operations, costs and maintenance intervals for façade and windows, (IP BAU 1995; SABO 2013).

Component	Alpha value	Switch condition	Maintenance and replacement operation		Cost, SEK/m^2	Time intervals (years)
Cementous facade	1.3	0.92	Repainting	Scaffolding + weather protection High pressure cleaning Decolouring + repainting	220	10–20
			Replacement	Scaffolding + weather protection Replacement + painting	1040	35
Wooden windows	1.8	0.92	Part 2 – Adjustment	Windows adjustment Handles and hinges fixation Mounting new sealing	1315	15–20
			Part 1 – Repainting outside	Repainting the outside frame Repainting the windows sash Skylift	1266	10–15
			Part 2 – Repainting inside	Repainting the middle sash Repainting the inner frame Repainting the inner sash	914	15–20
			Replacement	Demounting New windows Handles, fittings and lock chains Inner casing and sealings Outer sealings including windowsill	12 879	30

distribution system and the radiators; general repairs; replacing radiator valves; dismantling and cleaning radiators; replacing the burner; replacing pumps and valves.

$$C_t^{est_i} = C_{insp} + \sum C_{pro} + C_{rest} \tag{6}$$

where: C_{insp} - is the inspection cost; C_{pro} – is the proactive maintenance cost (of different types) and C_{rest} – is the restoring cost. The estimation of the costs for each maintenance measure is based on market average values. Costs for each maintenance scenario are calculated in Swedish Krona (SEK), 1 SEK = 0.1 Euros. The discount rate of 4% and the price differential rate of 0% have been considered for this study. These values can be set by the user based on the given market conditions. Furthermore, the effects of changes in the discount rate and the maintenance costs in this demonstration are discussed in the sensitivity analysis section.

It is important to mention that the maintenance cost in this paper is fixed and considered to be the cost of maintenance at the limited technical condition level. Since in this method building components are kept at acceptable working condition, maintenance negligence and/or delays are excluded from the results. Otherwise, the cost of maintenance should be increased as further deterioration after the technical limit not only increases the costs of maintenance but potentially affects the performance of other building components.

Considering the calculation procedure and the volume of the data to be processed, a Matlab code was written and used to run all the simulations. The following results were all generated using the aforementioned code.

Optimal maintenance planning

The unique feature of the proposed methodology is the ability to optimize maintenance and renovation with regard to external limitations and constraints. In the following illustrations, a technical and economic analysis has been performed in order to find the optimal maintenance scenario for the respective components. In this analysis, theoretical concepts and deterioration models are based on empirical studies and international research.

The characterization of condition-deterioration models depends on the identification of current degradation mechanisms. For the two components considered in this study, namely the cementitious plaster (façade) and the double-glazed wooden windows (windows), degradation state and required maintenance actions were based on the evaluation of the physical and visual degradation of the respective components. The two chosen components and their corresponding maintenance and renovation costs are amongst the more expensive measures in residential buildings for which maintenance optimization makes economic sense. Besides, the two components share on certain fixed costs related to maintenance and renovation (i.e. scaffolding) and have effects on building energy performance. The model assumptions and maintenance measures considered for each of the components including different operations, maintenance interval and respective costs are given in Table 1. Moreover, the minimum accepted quality $Co_{i,min}$ was chosen at 20% condition level for both components (IP BAU 1995).

It is important to mention that late maintenance (negligence/postponing) is not considered in the

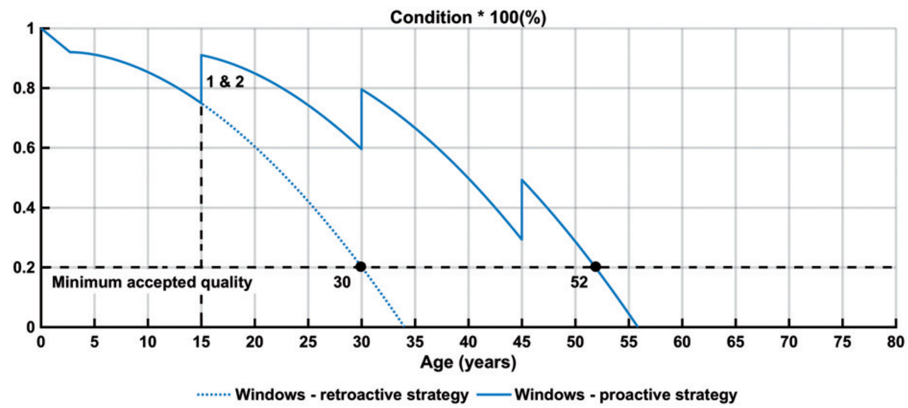

Figure 3. First maintenance scenario for wooden windows in Sweden.

simulations, therefore the extra costs of maintenance and damages due to negligence is avoided in the results. The maintenance intervals for the two components given in Table 1, were defined for the deterioration state before/during which a proactive measure should be carried out in order to sustain an acceptable performance of the respective component. In general, the upper limit has no effect in simulation results as the model only uses the lowest condition state before which maintenance should be carried out as the end point for the simulation of maintenance scenarios.

The choice of maintenance strategy

The first step in construction management is to devise a proper maintenance strategy for each building component. In order to meet the requirements based on local standards and guidelines, the choice of a proper maintenance strategy can be crucial. The method proposed in this study can be used to evaluate the S-LCC of different proactive maintenance scenarios for a single component. For example, there are two common maintenance scenarios for wooden frame windows in Sweden (SABO 2013; INCIT 2017), Figures 3 and 4. In scenario 1, both maintenance parts, 1 (repainting outside) and 2 (repainting inside and adjustments to the frame) specified in Table 1, are carried out at the same condition level, 75%, (same interval) resulting in 52 years of ESL, Figure 3. Whereas in the second scenario, part 1 of the maintenance (repainting outside) is carried out at 85% condition level (10 years of service life) and part 2 (repainting inside and adjustments to the frame) at 70% condition level (20 years of service life) resulting in 50 years of ESL, Figure 4. Both simulated ESL values are in line with the respective guidelines. For the calculation of the given scenarios, maintenance effects of 4% and 16% were applied to part 1 and part 2, respectively. The calculated EAC (Equivalent Annual Cost) values for the two scenarios are 27 and 28 SEK/m^2, year. Considering the small difference between the LCC of the two scenarios, the choice of maintenance strategy relies on the owner's preferences and objectives. In this case, since there are advantages in carrying out part 1 and part 2 of the maintenance measures at the same time, both logistically and financially (reduced fixed costs), the first scenario is chosen as the better scenario and is used in the rest of this study.

The maintenance effect can either be calculated using the Matlab code, given the availability of the required data, i.e. the maintenance plan and the respective life expectancy, or be estimated using experts input. In both cases, a probability distribution can be calculated for more sensible outcome, however, generating probability distribution for each simulated maintenance interval increases the computer power demand exponentially. For that reason, the accuracy of the calculated/estimated maintenance effect is improved using the inspection input as shown in Figure 2. To achieve this, the maintenance effect is adjusted to compensate for the time difference between the inspection time and the time on the simulated condition/deterioration curve at which the observed condition state given by the inspection results is equal to the expected condition state at the time of inspection. The given values in this study have been calculated using the information available in local guidelines (SABO 2013; INCIT 2017). As for the windows, the maintenance scenario 2 (discussed above) was used to calculate the maintenance effects of the maintenance parts 1 and 2 at 4% and 16%, respectively. The calculated maintenance effects are then applied to the second scenario to estimate the expected service life for the windows. The same approach is used to calculate the maintenance effect on the façade rendering.

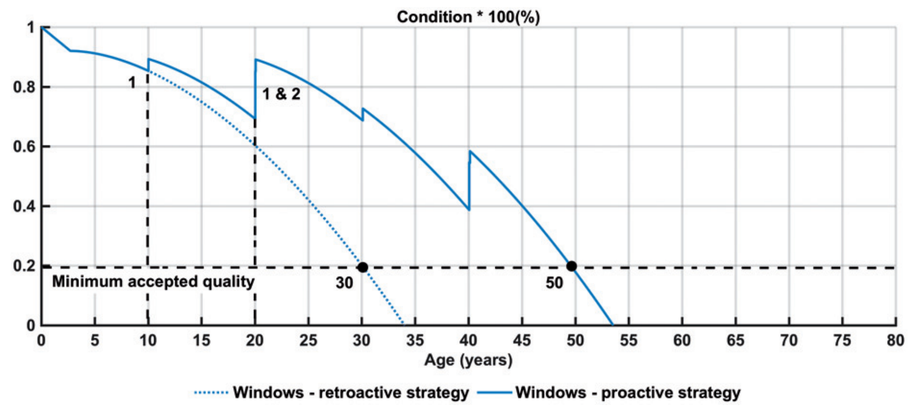

Figure 4. Second maintenance scenarios for wooden windows in Sweden.

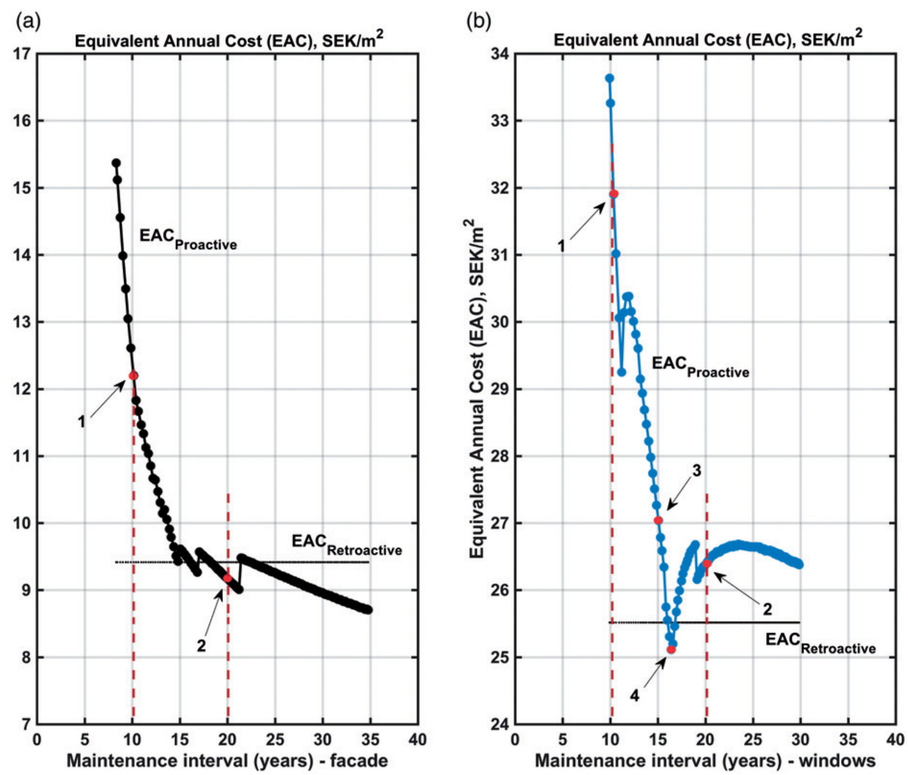

Figure 5. Cost profile for the two components.

Once the optimal scenario is chosen, to obtain the optimal maintenance interval, a series of plans for each component using different maintenance intervals are simulated, which results in a cost profile for each component over its respective service life (Figure 5). Every point on these profiles represents the service-life cycle economy of the respective component for each given maintenance interval in form of an equivalent annual cost (EAC). Taking into account the range of intervals given in Table 1, for both components, it is decided that the first maintenance measures should be carried out within 70%–85% condition level corresponding to 10–20 years of service life, point 1 to point 2 in Figure 5. These values are decided for, using experts' knowledge and technical inspection of the components. The chosen limit identifies the condition restriction applied to the following examples. The condition limit is usually identified through inspection and includes technical, safety and aesthetic measures. The life cycle economy of the retroactive strategy for each component is also given as a reference for the purpose of a fair comparison. 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

Table 2. Summary of the maintenance scenarios.

	Plan 1		Plan 2		Plan 3		Plan 4	
Component	Windows	Façade	Windows	Façade	Windows	Façade	Windows	Facade
ISL (years)	30	35	30	35	30	35	30	35
EAC retroactive individual (SEK/m^2)	25.51	9.41	25.51	9.41	25.51	9.41	25.51	9.41
EAC retroactive combined (SEK/m^2)	34.92		34.92		34.92		34.92	
Maintenance interval (years)	15	20	16	20	16	16	13	17
ESL (years)	51.84	49.61	47.76	49.61	47.76	58.06	57.82	57.60
EAC proactive individual (SEK/m^2)	27.04	9.17	25.11	9.17	25.11	9.36	29.81	9.26
EAC proactive combined – including savings (SEK/m^2)	36.21		34.28		30.68		38.14	

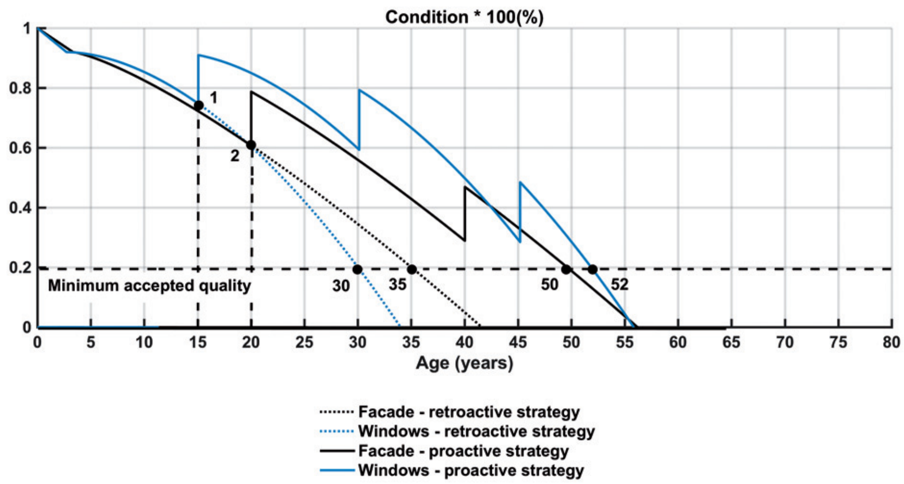

Figure 6. Industry standard individual maintenance plans for the two components.

accepted quality cannot be sustained throughout the respective component's service life.

Plan 1: industry standard maintenance plan

In plan 1, the first maintenance interventions are carried out according to Table 2. The maintenance effects of 20% and 18% are applied to windows and façade, respectively. In Figure 6, the condition states and deterioration behaviour of the two components under plan 1 are shown. In this plan, for each component the age at given maintenance condition, point 1 and 2 corresponding to 15 and 20 years of service life, is taken as the maintenance intervals and applied to the respective remaining service life (uniform intervals). The resulting ESLs are calculated at 52 and 50 years, respectively. The corresponding EAC values for each component are marked as point 2 in Figure 5(a) and point 3 in Figure 5(b). It is shown that the EAC value for the windows maintenance plan is calculated at 27.04 SEK/m^2, year, 1.53 SEK/m^2, year higher than the EAC value of the retroactive strategy at 25.51 SEK/m^2, year. As for the façade, the EAC value is calculated at 9.17 SEK/m^2, year, 0.24 SEK/m^2, year below the respective value of the retroactive strategy at 9.41 SEK/m^2, year. The costs of retroactive strategies are given only as a reference for the results of optimization in the given demonstrations. The model selects the optimal plan depending on the given optimization criteria and no comparison is made against the costs of retroactive strategy.

Plan 2: cost-optimal individual maintenance plan

In plan 2, the maintenance plan which resulted in the lowest EAC value, Figure 5, is chosen as the cost-optimal plan for each component. The corresponding condition states and deterioration behaviours for the respective plans are given in Figure 7. The estimated service life values (ESL) in this plan are calculated at 48 and 50 years for windows and façade, respectively.

Considering the cost profile of maintenance interventions for windows, the lowest EAC value of 25.11 SEK/m^2, year is achieved at the maintenance interval of 16 years, 1 year longer than the presumed industry standard, point 4 in Figure 5(b). While changes in the interval had little effect on the ESL value comparing to plan 1, the reason behind the lower EAC value in this

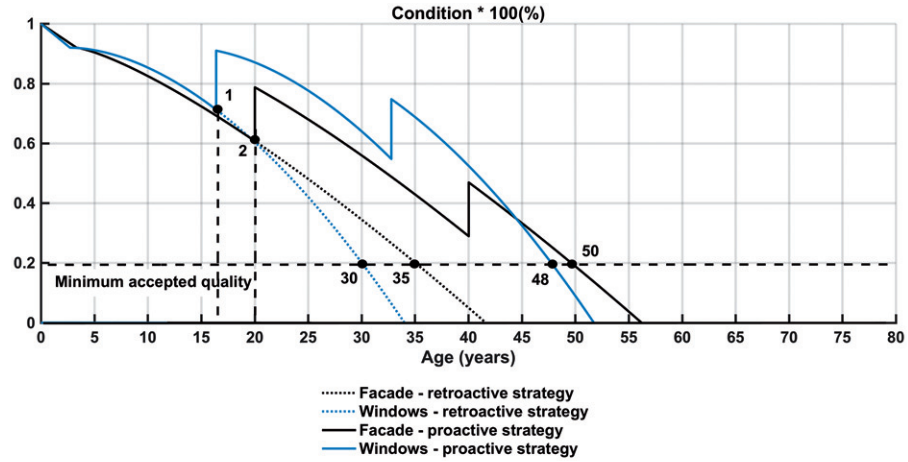

Figure 7. Cost-optimal individual maintenance plans for the two components.

plan is that the third maintenance intervention is changed by the replacement of the part. As for the facade, the cost profile indicates that the industry standard plan (point 2 in Figure5(a)) was already the cost-optimal plan within the given technical restriction.

With a simple adjustment, while keeping the components in proper working condition, it is shown that the total maintenance cost can be lowered from 36.21 SEK/m^2, year to 34.28 SEK/m^2, year, standing below the total cost of 34.92 SEK/m^2, year for the retroactive strategy. Facing difficulties in optimizing maintenance plans, housing owners tend to postpone maintenance in order to lower costs and meet budget constraints. One of the main reasons why housing owners postpone maintenance is to combine maintenance/renovation measures so that they can save on logistic and fixed costs. Such planning however is often opportunistic meaning that once a failure has reached in one or more of the costly building components, maintenance/renovation for other components is brought forward to combine the work, which results in loss of value. In this study, to foresee such opportunities in maintenance planning while avoiding the loss of value, maintenance and replacement years are added to the selection criteria, where all possible combinations of maintenance scenarios for the two building components are assessed in a multi objective selection process.

Plan 3: Cost-optimal combined maintenance plan – same maintenance interval

In this scenario, all the possible maintenance plans for the two components are put together to find those combinations which result in at least one shared maintenance year. It is assumed that when maintenance for the two components is carried out at the same time, 80 SEK/m^2, year can be saved from logistic and fixed costs. The selected plans are then limited by minimum accepted condition states from which the combination with the lowest EAC value is chosen as the cost-optimal maintenance plan for the two components. The condition states and deterioration behaviours for the two components in this scenario are presented in Figure 8.

The selected combination results in the EAC value of 30.68 SEK/m^2, year with the maintenance interval of 16 years comparing to the total retroactive EAC value of 34.92 SEK/m^2, year. It is shown in the figure that in this plan there are two intervention years with 16-years interval when the shared fixed costs can be deducted from one of the maintenance plans (in this case, it is deducted from the total maintenance costs for windows). It should be noted that, for economic evaluation of a complete maintenance plan which includes all building components, the action plan for the end of each individual component should be clearly defined. In this study, it was assumed that both components are replaced by identical components by the end of the service life. In either case, whether building components are replaced with exact same type or better alternatives, the shared fixed costs can be deducted from either component. In plan 3, the costs of individual maintenance plans for windows and façade are calculated at, 25.11 SEK/m^2, year and 9.36 SEK/m^2, year respectively.

Plan 4: Cost-optimal combined maintenance plan – same ESL

In some cases, there are benefits in carrying out replacement/renovation measures at the same time.

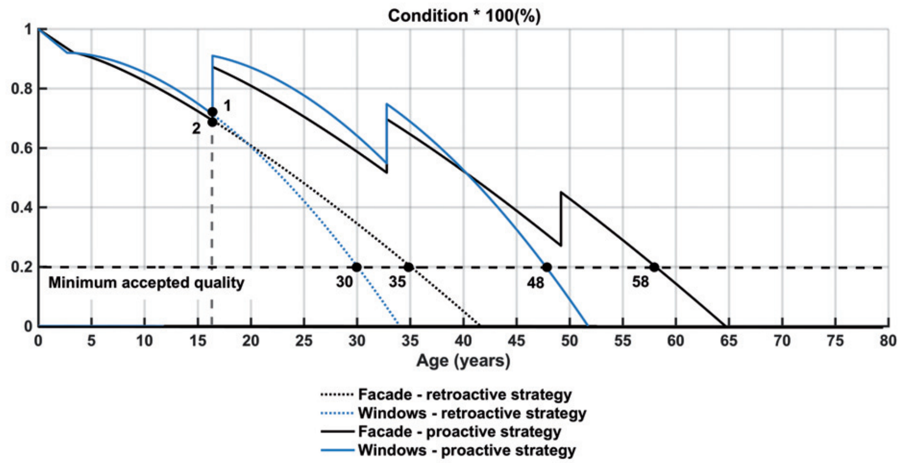

Figure 8. Cost-optimal combined maintenance plans with the same maintenance interval.

For example, there are benefits in terms of energy efficiency; economy and comfort when both windows and façade are renovated at the same time. Replacement of windows with more energy efficient alternatives without renovation of façade or vice versa, does improve the indoor condition but creates a mismatch both in terms of comfort and technical difficulties. Besides, the full energy efficiency potential is not utilized. In some situations, renovation measures require relocation of tenants which is time- and cost-intensive and is often avoided unless necessary. Having replacement/renovation measures combined can lower these expenditures while providing better comfort for tenants.

In plan 4, individual maintenance plans resulted in the same ESL value are selected from all possible scenarios. Thereafter, the combination, within the acceptable condition states (technical limits), with the lowest EAC value is chosen as the cost-optimal maintenance plan for the two components. It is assumed that when replacement of the two components is carried out at the same time 200 SEK/m^2 can be saved from logistic and fixed costs.

The optimal maintenance/renovation plan results in 58 years of service life (ESL) and the EAC value of 38.14 SEK/m^2, year with the maintenance intervals of 17 and 13 years for façade and windows, respectively. The condition states and deterioration behaviours for the two components in this scenario are presented in Figure 9.

Discussion

Table 2 summarizes the four different maintenance plans discussed above. For the first two plans maintenance scenarios are individually evaluated to demonstrate the effects of individual maintenance optimization. It is shown that for windows the total cost could be decreased in plan 2 by around 2 SEK/m^2, year comparing to plan 1, a 7% decrease through a simple adjustment to the maintenance interval and frequency. The individual optimization does not change the total cost for façade as the optimal plan within the technical limit is found to be the same as the industry standard plan.

For the last two plans, the combination of maintenance/renovation work between the two components is also taken into account in the optimization process. In plan 3, maintenance intervals are coupled and the shared fixed costs are deducted from the total costs to study if the financial benefits gained in combining maintenance measures outweigh the potential extra costs of respective individual maintenance plans. The simulation results shows that the maintenance interval of 16 years for both façade and windows reduces the total costs by around 6 SEK/m^2, year from the industry standard plan, plan 1, marking a noticeable 15% decrease.

In plan 4 on the other hand, the aim is to couple replacement/renovation year (ESL) and deduct the presumed shared fixed costs from the total costs to find the cost-optimal plan. The results show that the lowest service-life cycle cost is achieved for 13 and 17 years maintenance intervals for windows and façade, respectively. The estimated life expectancy for the given plan is 58 years and the total cost is calculated at 38 SEK/m^2, year, a 2 SEK/m^2, year increase from the total cost in industry standard plan, plan 1. Therefore, to apply plan 4, the user should be able to justify the extra cost through savings made in either the actual

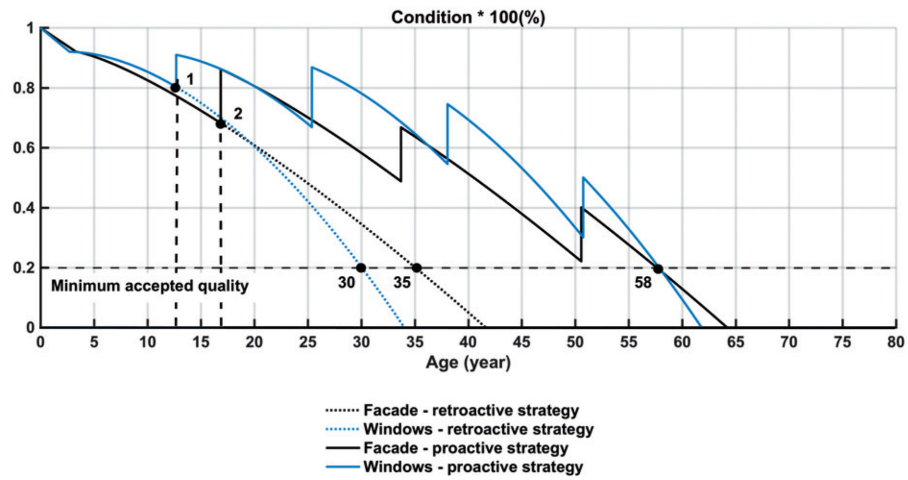

Figure 9. Cost-optimal combined maintenance plans with the same ESL.

replacement/renovation work or the logistics and side activities. It should be reminded that the original savings considered in plan 4, 200 SEK/m^2, is a rough estimation of savings made only through the reduction of the fixed costs.

The results illustrate the saving potential through service-life cycle analysis of maintenance/renovation plans. It should be reminded that the given numbers are produced for only two components. When put together in building or portfolio level, savings are expected to increase. It is also shown that more expensive individual maintenance plans can benefit housing owners in terms of techno-economics as the sum of the costs of individual maintenance for the last two plans was higher than the sum of the costs of the combined plan.

In the end, it is important to mention that the addition of obsolescence to the optimization process ensures that the model does not produce results for which the estimated service life (ESL) is longer than the estimated obsolescence for the respective components. Obsolescence is to be added as an optimization criterion in the future development of the proposed method.

Sensitivity analysis

One of the unique features of this study is that it provides information regarding the effects of components' characteristics and calculation variables on timing and the economy of different maintenance alternatives. In this regard, the variation in number of influencing factors has been studied to analyse the sensitivity of the proposed model. The results are presented below in Figure 10.

Alpha value

The alpha value defines the deterioration rate of a component over time. The deterioration rate during a component's service life is often a good measure of its durability, (Kesik and Saleff 2005). Higher alpha values identify highly durable components that are expected to remain in function in a good condition for longer time. In order to understand the effect of durability on maintenance planning, Figure 5 is regenerated for three different alpha values. The results are given in Figure 10. As depicted in this figure, with increase in durability, late maintenance interventions becomes more difficult to financially justify. This can be explained by higher deterioration rate during latter years in highly durable components (sewage/water piping) which makes maintenance measures more difficult and less cost effective. Overall, the calculated EAC values varies around 4% or less than 1 SEK/m^2, year toward suggested alteration of the alpha value. On the other hand, the cost-optimal maintenance interval falls in the range of 15 to 18 years for windows whereas for façade, the cost-optimal interval in technical limit range remains unchanged at 20 years.

Maintenance effect

The effectiveness of a maintenance intervention depends on different factors: the quality of workmanship; condition of the component; materials used and so on. Considering the uncertainty of a deterioration process itself this value is either calculated (mentioned earlier in the section "Service-Life cycle cost (S-LCC) model") or estimated using experts' input. On the analysis of the influence of maintenance effect on the

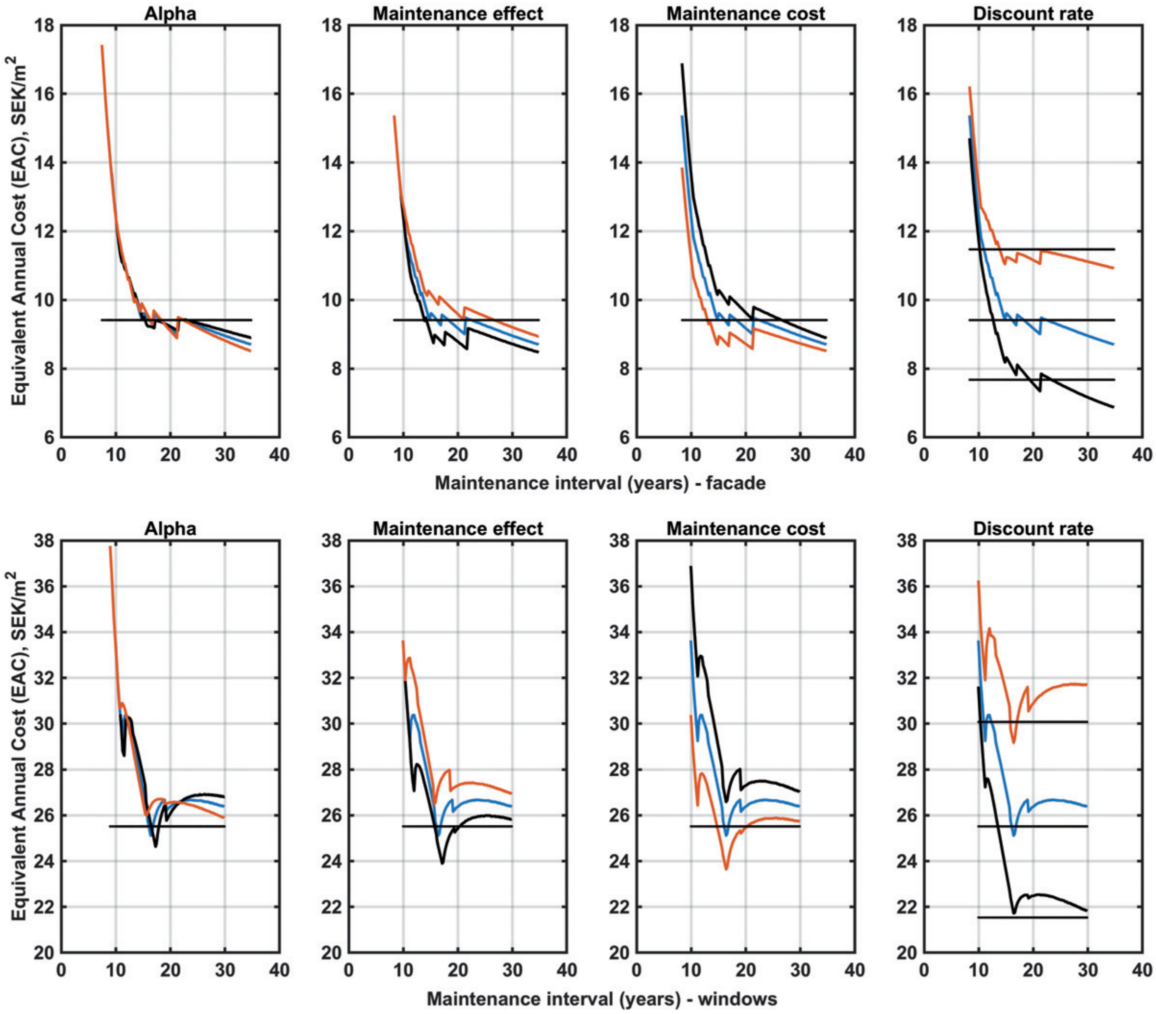

Figure 10. Sensitivity analysis – orange is 10% lower; blue is the original value; black is 10% higher.

calculated EAC value (Figure 10), it is shown that higher maintenance effect, as expected, results in better life cycle economy of the simulated maintenance plans. The point on point maximum difference in the EAC value is calculated at 5%. As for the cost-optimal maintenance interval, 15 to 18 years for windows and no noticeable change for façade is observed.

Maintenance and replacement costs

To devise a cost-optimal maintenance plan, the maintenance and replacement costs are key factors. These two costs in general have opposite effect on the EAC value of the respective scenario. Therefore, to keep the EAC value of the retroactive plan unchanged, changes have only been applied to the maintenance costs (includes both the costs of labour and materials) and the maintenance effects are kept unchanged. As shown in Figure 10, it is concluded that the higher maintenance cost for a component in respect to its required replacement expenditures, assuming constant effect, results in better EAC value. On the other hand, changes in the maintenance costs have very little effect on the cost-optimal maintenance interval for both components.

Discount rate

The discount rate not only takes into account the time value of money, but also the risks involved in the future cash flow of the current investment. The perception of these risk profiles varies from one company to another and depends on different factors. Evaluating the effects of discount rate on the EAC value of different maintenance plans for the two components in this study (Figure 10), it is observed that higher discount rates have noticeable effect on maintenance plans with shorter intervals making early maintenance measures less cost-effective. On the contrary, lower discount rates make shorter maintenance intervals more cost-effective. Whereas for late maintenance measures, higher discount rates increases the profitability justifying the extended service life with regard to the costs of late maintenance interventions. Studying the effect of discount rate on the cost-optimal maintenance interval, there is no noticeable change in either of the components.

Summary

The variation of the input values as expected changed the magnitude of the total costs in the simulation results however very subtle change was imposed to the shape and extent of the cost profile figures. Meaning that, despite the changes in the absolute value of the expenditure required for each maintenance/renovation plan, the cost-optimal plan has very little variation in the time interval and frequency of its maintenance measures. This is very clear for the façade where almost no change to the cost-optimal plan is observed with the variation of the input values. As for the windows, the cost-optimal maintenance interval varied between 15 and 18 years. This finding shows that the proposed approach can be reliably used to produce a preliminary optimized maintenance/renovation plan for the given components. The preliminary plan can then be improved with the correction of both the alpha value (α_i) and the maintenance effect $(Co_{i,j}(t) - Co_{i,j}(t))$ using the results from the first inspection round.

Conclusion

The key information required for a technically and financially coherent renovation decision is the life expectancy of building components. In proper estimation of life expectancy, it is important that the effects of in-use conditions are taken into account. Existing methods take these effects into account collectively which limits their ability to optimize renovation economy by adjusting the effects of an individual in-use condition, (maintenance in this case). Amongst these methods, SPECTUS and STRATUS allow for adjustments in the quality and extent of maintenance in the evaluation of the remaining service life. The option gives users with budget constraints, the ability to plan renovation accordingly. This advantage however is offered at the expense of performance quality (lower building condition).

To avoid the low performance quality and to address the complexity involved in decision making under budget and time constraints, this study proposes a method that incorporates the effects of maintenance timing in the evaluation of life expectancy. In this method, a hybrid condition-deterioration model is coupled with a complete service-life cost analysis for a multi-objective optimization of maintenance/renovation planning.

Considering the complexity of the probabilistic approaches (used in EPIQR and INVESTIMMO), the hybrid condition/deterioration model used in this study takes on a more efficient and simpler deterministic approach in estimating the life expectancy. The use of the hybrid model allows for a simple implementation of in-use conditions which in return improves the reliability of the results.

This paper presents a systematic approach that opens an interesting prospect in building maintenance planning by methodizing edecision-making process with regard to user-defined sets of objectives and limitations. The acquired knowledge through simulation of possible maintenance scenarios, can be used in optimization of maintenance and renovation plans both in the design and the application phase. In design, components can be selected so that the initial cost of investment can be optimally balanced against the expected maintenance costs. In the application phase on the other hand, the cost of proactive maintenance plans can be optimally balanced against the cost of current industry standard or respective retroactive strategies.

Four different plans are studied to demonstrate the application of the model for the given two building components having both acceptable condition and an expenditure cap as limitations in decision criteria. It is possible to add other decision criteria such as, energy efficiency and heritage value in terms of benefits/limitations. It is shown that for the two building components, windows and façade, the total maintenance and renovation costs can be decreased by up to 15% which indicates the considerable saving potential in maintenance optimization. Considering that the model can be used in building and/or portfolio level, the potential savings are expected to increase.

This study carries out a partial dynamic modelling of the changes in the costs of services and materials and the effects of innovation, technological development and the socio-economic issues . Future analysis will include both the obsolescence and the dynamic cost-condition modelling (where data is available) and will evaluate the effects of innovation, technological development and socio-economic issues in form of utility value in the proposed method.

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