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A service-life cycle approach to maintenance and energy retrofit planning for building portfolios

Claudio Nägeli*, Abolfazl Farahani, Magnus Österbring, Jan-Olof Dalenbäck, Holger Wallbaum

Chalmers University of Technology, Sustainable Building Group, Gothenburg, Sweden

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ABSTRACT

Residential buildings account for almost a quarter of the total energy use in Sweden and building owners are, therefore, under pressure from policy makers to improve the energy performance of their buildings. Building portfolio owners (BPOs) generally face multiple barriers in energy efficiency investments such as financial constraints and lack of knowledge of the current state when planning energy efficiency measures.

This paper presents a method for cost-optimal scheduling of maintenance and retrofit measures on a portfolio level by drawing on research on building stock modeling and maintenance retrofit planning. The method uses a building stock modeling approach to model costs, energy and greenhouse gas emissions (GHG)of a building portfolio and combines this with a method for optimal maintenance and retrofit scheduling in order to forecast and optimize the timing of measures on a building portfolio level. This enables the integrated long-term planning on retrofit investments and reduction of energy demand and GHG emissions for a portfolio of existing buildings.

The application to the building portfolio of the municipal housing company of Gothenburg showed that by optimizing the maintenance and retrofit plans, ambitious retrofit measures can be introduced in the majority of the buildings with a positive effect on the service-life cycle costs. Moreover, the method is easily transferable to other building portfolios in Sweden as it builds up on nationally available data sets but is ideally complemented and verified using inspection data and existing maintenance plans of the BPOs in future applications.

1. Introduction

Residential buildings account for almost a quarter of the total energy use in Sweden [1] and the European Union [2]. This sector, therefore, plays an important part in achieving the 2050 energy and climate objectives both in Sweden and Europe. Although, the historical development in Sweden has driven the building sector's territorial carbon emissions beyond the average EU performance level [3], the energy performance of the existing buildings does not reach new construction standards. Therefore, considering the low rate of new construction, the existing building stock offers the biggest potential for energy savings.

The economic boom and rapid growth of the construction rate in Sweden during 60s and 70s resulted in the rise of more than a million apartment units around the country. The characteristics of the Swedish rent-controlled housing market [4] together with the financial difficulties and lack of knowledge and skills, however, resulted in the management deficiency within housing companies that has left many buildings from this period with minimum care. Today, a large share of this stock is old and in need of extensive maintenance and renovation measures. This presents a unique opportunity for implementation of energy efficiency measures at marginal costs.

Building portfolio owners (BPOs) in Sweden generally face multiple barriers in energy efficiency investments to make use of this potential. Most often, financial constraints and lack of knowledge of the current state of their buildings are crucial hindrances. Consequently, the increased investment risks due to lack of information have stagnated the energy renovation (retrofit) progress [5].

Therefore, providing necessary knowledge to the BPOs and reducing the investment risks can push the energy performance improvement in the retrofit market forward. In this regard, an assessment of the current state of the buildings and the effect of energy performance improvement on a portfolio level, can help address the issue of retrofit planning from a more strategic point.

Bottom-up building stock models (BSMs) are designed to project energy demand and GHG emissions of large building stocks from urban to national scale [6,7]. They typically forecast the development of a building-stock in terms of new construction, demolition and retrofit on the total energy demand and GHG emissions [6–8]. As such they are usually used for policy advice at different levels or to support urban

* Corresponding author. Chalmers University of Technology, SE-41296, Gothenburg, Sweden.
E-mail address: claudio.naegeli@chalmers.se (C. Nägeli).

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energy planning [8–10]. However, a BSM approach yet has not been used to support BPOs in the planning of investment in energy efficiency and GHG emission reduction. This is probably mainly due to the use of average data in BSM, which makes the results less relevant to BPOs, who are in need of building specific information. However, as building specific energy data comes more readily available, several BSMs have been developed using building specific information [9,11,12], making it possible to apply BSM methods for strategic planning of retrofit for building portfolios.

However, while the existing bottom-up BSM models are capable in projection of energy demand and GHG emissions by introducing different energy efficiency measures and packages, they are not tailored to BPOs needs. As such they do not offer alternative scheduling solutions for maintenance and retrofit with a service-life cycle perspective. In order to adjust and optimize retrofit timing to produce alternative scheduling solutions, the knowledge concerning the right timing and sequencing of actions is of crucial importance. Although important, the economic effects of timing are most often missing in the economic assessments of retrofit projects.

To address the timing issue, knowledge regarding the condition of building components and the respective remaining service life is essential. For this purpose, the maintenance and renovation scheduling (MARS) method [13,14] is used. It combines the deterioration function of building components with a service-life cycle cost (S-LCC) analysis to find the cost-optimal time for maintenance and retrofit measures.

The aim of this paper is to enable the cost-optimal planning and scheduling of maintenance and retrofit measures from a life-cycle perspective on a portfolio level by combining a BSM approach with the MARS method. The method presented in this paper uses a building stock modeling approach to model the costs, energy and GHG emissions of a building portfolio and combines this with the MARS method for maintenance and retrofit scheduling in order to project and optimize the timing of measures on a building portfolio level. Using this combined approach, the method projects costs of maintenance and retrofit measures and their effect on energy demand and GHG emissions of a building portfolio over time. It, thereby, enables the integrated long-term planning on retrofit investments and reduction of energy demand and GHG emissions for a portfolio of existing buildings. The methodology is implemented and applied to the multifamily housing stock of the municipal property owner for the city of Gothenburg, Sweden.

2. Methodology

The following section describes the methodology for an integrated energy and retrofit planning method/tool on a portfolio level by combing building stock modeling with a building maintenance and retrofit planning approach (see Fig. 1). The method uses data on the existing state of the building portfolio as well as techno-economic data on maintenance, reinstatement and retrofit measures including their costs and technological properties. Based on that input data the method optimizes the maintenance and retrofit plan through an integrated cost, energy and GHG emission assessment for a given retrofit/reinstatement scenario. The result is a portfolio level optimized maintenance and retrofit plan considering the impact in terms of costs, energy demand and GHG emissions.

2.1. Definitions

Maintenance is considered as actions carried out to sustain and restore the original function of a managed component (e.g. painting or cleaning façade). Reinstatement is the replacement of building components by the end of the service life (e.g. re-plastering the façade) whereas retrofit (or energy-renovation) is used when an energy efficiency measure is carried out together with the reinstatement work (e.g. addition of insulation to the façade). Costs are given in Swedish crowns (SEK), 10 SEK corresponds to 0.93 EUR or 1.04 USD.

2.2. Input data and initial processing

2.2.1. Building portfolio data

Data is collected to characterize the multifamily housing stock of the municipal property owner for the city of Gothenburg. The building stock data is taken from previously developed research for describing the multifamily building stock of the city of Gothenburg [12,15,16] {FormattingCitation}. For these papers, data have been gathered from national board of building housing and planning as well as the Swedish mapping, cadastral and land registration authority. The national board of building, housing and planning supplied energy performance certificates (EPC) for all buildings in the City of Gothenburg. The Swedish EPC contain information on heating and ventilation systems, number of apartments, building height as well as measured energy use data. The Swedish mapping, cadastral and land registration authority provided access to parts of the property register. This contains information on year of construction, year of renovation, owner and mid-point coordinates for each building. These datasets were combined using a common unique identifier and spatially linked to a 2D-map of Gothenburg provided by the city planning office. The 2D footprints were then extruded based on building heights in the EPC to derive surface areas for energy calculations. From the complete dataset the buildings belonging to the municipal housing company are extracted, which

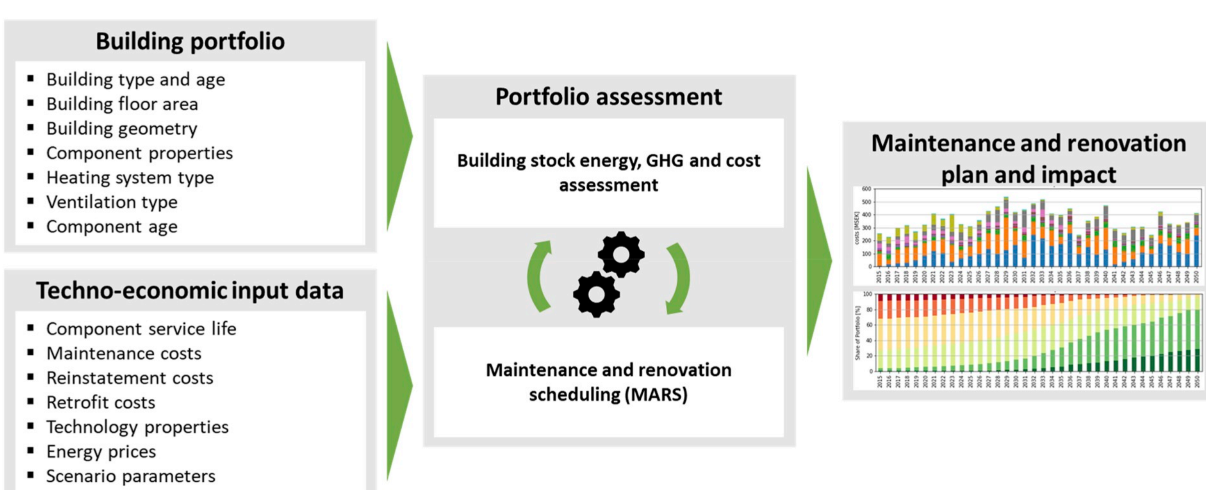

Fig. 1. Overview over the integrated approach to building portfolio maintenance and renovation planning.

results in a building portfolio of 1802 buildings or 6.13 million m^2 of heated floor area.

The buildings were then further characterized and calibrated based on the method originally developed in Nägeli et al. [17] as described in Ref. [15] in order to be able to run building energy demand calculations. The method characterizes the initial state of the buildings in terms of U-value, heating system efficiency, etc. based on building typology and architecture history, historic building regulations and surveys as described in Ref. [12], but also accounts for already implemented retrofit measures. Previous measures are accounted for by simulating already carried out retrofit and replacement cycles based on an estimated service life according to data based on [18,19](see section 2.2.2 below). Based on the estimated year of the last intervention, the current state in terms of the component's U-value or efficiency is updated to account according to the efficiency standard of that year. Based on this procedure, the initial state is calibrated based on the energy use data from the EPC as outlined in Ref. [15]. Additionally, in this study it is assumed that buildings in the portfolio have been maintained using an industry standard maintenance regime according to Ref. [20]. This allows the MARS model to determine the initial condition of the components using only the age of the components.

2.2.2. Techno-economic input data

Cost data for the individual maintenance, reinstatement and retrofit measures are based on [20–22]. The cost factors include both material and labour costs as well as direct and indirect overhead costs. Costs from the side of the BPO as well as VAT are not included. Both reinstatement and retrofit cost factors of the different envelope components depend on the construction type of the component and can, therefore, vary for the same component. Moreover, the cost factors for heating and ventilation systems take into account diminishing marginal costs depend on the size of the system (i.e. installed heating power for heating systems and number of serviced dwellings for ventilation systems). Additionally, fixed costs are only included for the use of scaffolding and relate to the measures on the building envelope (windows, façade and roof).

The initial service life (ISL) of components are modeled using data from Refs. [18,19]. Based on this data, a Weibull distribution for each component is fitted in order to estimate the initial lifetime of the component. For each component different distributions are fitted depending on the construction type or system type (for heating and ventilation) of the component. The ISL data is used to estimate the initial service life (see above) as well as in MARS model for the calculation of the estimated service life (ESL) under different maintenance regimes.

The initial energy prices are based on [23] for oil and electricity and [24,25] for district heating and gas to reflect the local prices. The emission factors of the different energy carriers are based on [26–29]. Both energy prices and emission factors according to energy carrier are shown in Table 1.

2.3. Portfolio assessment method

2.3.1. Energy and GHG emissions assessment

The energy demand of buildings before and after implementation of a retrofit measure is calculate using a bottom-up engineering model originally developed for [17]. It calculates the monthly energy demand of each building in terms of space heating, hot water, appliance use, lighting and auxiliary electricity use (ventilation, pumps, etc.). The energy demand for space heating is calculated based on the monthly steady state method according to the ISO EN 52016-1 standard [30]. Energy demand in this paper is only assessed for the building related energy services (space heating, hot water and auxiliary electricity use), excluding household electricity demand for appliances and lighting. Based on the energy demand, the resulting GHG emissions are calculated using GHG-emission factors (see Table 1).

Table 1
Energy prices and emission factors according to energy carrier based on [23–29].

Energy Carrier	Energy Price [SEK/kWh]	Emission factor [gCO2-eq/kWh]
Oil	1.20	299
Gas	0.81	238
Electricity	1.30	131
District Heat	0.84	56

The different retrofit measures change the energy demand and the related GHG-emissions in different ways. Retrofit measures on the building envelope result in a lower U-value based on the amount of added insulation or the U-value and g-value of the new component in case of windows. Heating system exchanges result in an increased efficiency of the system based on the technological improvements in the technologies. The exchange of ventilation systems results in better or added heat recovery either through a heat recovery unit in central supply and exhaust systems or through the addition of an exhaust air heat pump.

2.3.2. Cost assessment

The building stock assessment model calculates the reinstatement and retrofit costs of each component based on the cost factors in the input data. The marginal retrofit costs are then calculated based on difference between the reinstatement and retrofit costs. In the case of envelope components, the retrofit cost factor of component depends on the construction type of the component as well as the applied insulation thickness (or the u-value in case of windows). For heating and ventilation systems cost factors depend on the size of the system (see above). For these systems the marginal retrofit costs are calculated from the difference between replacement of current system with the same (reinstatement) and the costs of the new system. The marginal retrofit costs are, therefore, zero if retrofit option is the same as reinstatement. Some components (such as the water and sewage piping) do not have a retrofit option at all as these components do not have a relevant effect on the energy demand of the building.

The change in energy costs is calculated based on the change in energy demand according to energy carriers (typically district heating for space heating and hot water and electricity for ventilation and general building services) and their energy prices. While building envelope measures affect only the space heating energy demand, changes to the ventilation system may decrease heating but increase electricity demand (e.g. addition of exhaust air heat pump). A change in the heating system affects the heating demand through a change of the efficiency of the system but may also affect the energy price in case there is a change in energy carrier (e.g. due to switch from gas to a heat pump).

The cost function used in the MARS method includes both the aforementioned costs (maintenance, reinstatement and retrofit) and the operational costs (energy use) to calculate the total EAC (equivalent annual cost) value EAC_{total} in different scenarios.

$$EAC_{total} = EAC_{maintenance} + EAC_{reinstatement} + EAC_{retrofit} + EAC_{Energy}$$

The EAC value for reinstatement measure includes only $EAC_{maintenance}$ and $EAC_{reinstatement}$, while the EAC value of a retrofit measure additionally includes both the $EAC_{retrofit}$ and EAC_{Energy}. $EAC_{retrofit}$ is calculated using the net present value (NPV) annuity factor for the service life of the respective component whereas for the EAC_{Energy}, the NPV annuity factor for each component is calculated for the longest estimated service life (as reference) amongst all components in the respective building. This allows for a fair comparison of the total EAC value in cost optimization of maintenance and retrofit scheduling.

2.3.3. MARS optimization

In order to estimate the life expectancy of building components, the effects of in-use conditions [31] need to be taken into account. Since the deterioration is regarded as a component characteristic, in the deterioration function these effects are incorporated in forms of condition improvements and/or changes in time increments. These in-use conditions include: inherent performance level; design level; work execution level; indoor environment; outdoor environment; usage condition and maintenance level. With no changes in these conditions, the estimated/extended service life (ESL) is equal to the initial service life (ISL). In this study all in-use conditions except for maintenance are assumed to remain unchanged.

Using the MARS method, the condition/deterioration behaviour of building components are simulated to calculate the life expectancy of the respective components under different maintenance regimes. The estimated service-life is then used for a complete service-life cycle cost analysis to determine the cost-optimal time for maintenance and retrofit for the respective components [13], Fig. 2.

For the simulations, the shortest and longest maintenance intervals are set to t_{SW_i} (the shortest possible date [13]) and $t_{tech\ limit}$ (latest time[1] at which a measure is to be carried out to sustain acceptable performance level) respectively. Within these constraints, the maintenance interval, its subsequent estimated service life and the resulting maintenance and retrofit plan that results in the lowest total EAC value is chosen as the cost-optimal plan for that respective component.

In the calculation of the operational costs (energy costs), the longest estimated service life (ESL) is chosen as the reference year and energy use reductions in the simulated retrofit plans are calculated against the reference year. To be able to use the energy use reduction for the estimation of the cost-optimal maintenance and retrofit year, the EAC value of the operation cost (i.e. EAC_{Energy}) is always calculated for the reference year and added to the EAC of the respective maintenance and retrofit plan [14].

In order to realize the deep-renovation benefits and avoid the loss of value, components which share fixed/logistic costs (e.g. façade and windows) are grouped in clusters where the simulated individual plans for given components are coupled to find possible cost reductions during the ESL. This is done for all the possible maintenance/retrofit combinations within each cluster. The resulting combined plan with the lowest EAC value is selected as the cost-optimal plan for the respective building. To keep building components at acceptable working condition, maintenance negligence and/or delays are excluded from the results.

In the simulation of the condition/deterioration behaviour, the default values for the selected components, apart from the initial service life, are taken from the a techno-economic input data [20–22]. Fig. 3 illustrates the simplified optimization process used in MARS method.

2.3.4. Scenarios

The portfolio is assessed for two main scenarios. The first scenario includes only reinstatement measures and only considers minimal energy efficiency improvements due to direct replacement of components (e.g. due to exchange of the heating system with a newer, more efficient version of the same type). The second scenario is an ambitious retrofit scenario including energy efficiency measures for all the major components with a high level of ambition in the energy efficiency gains. The exact measures per component included in both scenarios are described in Table 2. For each of the scenarios two maintenance and retrofit plans are generated, a common industry standard plan with fixed maintenance and renovation intervals for each component based on [20] as well as an cost-optimized plan generated using the MARS method (see section 2.3.3). The maintenance and retrofit plans are generated for a period of 35 years starting from 2015 until the year 2050. This allows for an evaluation of the energy retrofit results against the 2050 EU/national energy and climate goals.

Here, the envelope measures as well as the ventilation systems undergo maintenance measures depending on the type and age of the measure. The implemented maintenance measures are taken directly from the available datasets used for the industry standard maintenance and retrofit planning, [20–22].

Economic frame parameters such as energy price development, discount rate, etc. are kept the same for all scenarios. The discount rate is assumed to be 4%, energy prices are assumed to increase with a fixed rate of 2%, construction costs (i.e. material, labour and overhead costs) are assumed to be increased by 1% and the inflation rate is set at 0%. The in-use conditions for the deterioration of the components are assumed to be unchanged (excluding maintenance) during the analysis period. The effects of maintenance on the deterioration of building components are separately taken into account in MARS method (see section 2.3.3).

The assumptions and model specifications used in MARS method are as follows:

- Building components are mutually independent. A maintenance measure only affects the respective component.
- The time it takes to implement a measure is considered to have no effect on the deterioration and so the life expectancy of building components.
- Deterioration process include the effects of aging, wear and other cumulative damages and is the only cause of system failure.
- The maintenance and renovation plans are optimized in a service-life cycle perspective. The results therefore are calculated for the service life but only presented for the 35 years assessment period.

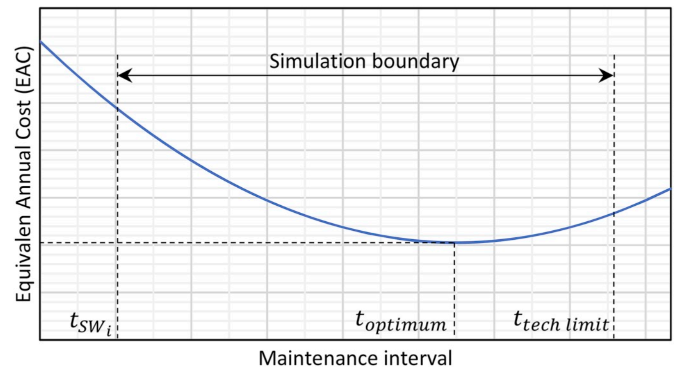

Fig. 2. Exemplary maintenance interval – S-LCC relationship.

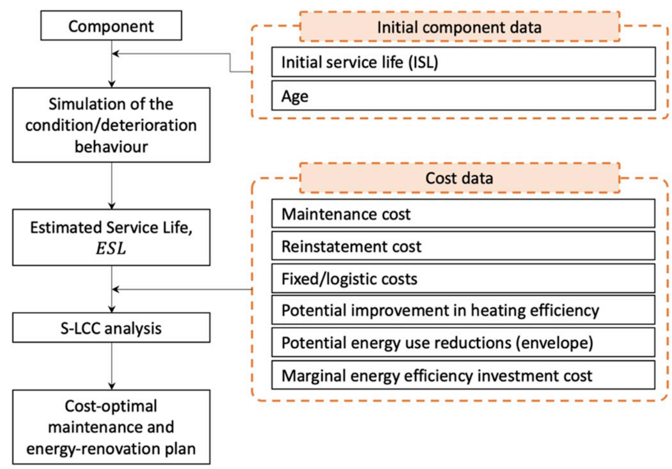

Fig. 3. Simplified simulation process.

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

Table 2
Measures included in the reinstatement and retrofit scenario respectively.

Component	Reinstatement scenario	Retrofit scenario
Facade	Reinstatement of façade material	Reinstatement with addition of 200 mm insulation (λ = 0.035 W/Km)
Roof	Reinstatement of roofing	Reinstatement with addition of 400 mm insulation (λ = 0.035 W/Km)
Windows	Exchange of window with same U-value as before or a minimum of U-value of 1.5 W/m^2 K	Triple glazed window with U-value of 0.8 W/m^2 K
Floor	Reinstatement of floor plastering	Reinstatement with addition of 100 mm insulation (λ = 0.035 W/Km)
Heating (supply) system	Replacement of current system with a system of the same type	District heating remains with same system, all other heating systems are replaced with a ground/water heat pump (SCOP = 3.3)
Ventilation system	Replacement of current system with a system of the same type	Central exhaust and supply systems are replaced with a central system with heat recovery (HRR = 75%), exhaust only systems and naturally ventilated buildings are equipped with an exhaust system with an exhaust air heat pump (SCOP = 2.5)
Water piping	Reinstatement of pipes	Reinstatement of pipes
Sewage piping	Reinstatement of pipes	Reinstatement of pipes
Electrical system	Reinstatement of electrical system	Reinstatement of electrical system

3. Results

3.1. Status quo of the portfolio

An overview over the current state of the portfolio in terms of size, age, energy demand and GHG emission intensity is shown in Fig. 4. While the majority of the portfolio includes smaller multifamily buildings with up to 5000 m^2 of heated floor area, less than 5 floors and less than 40 dwellings, there is a significant share of larger buildings, even building with a total heated floor area of over 10′000 m^2. Because of the post-WWII construction boom, the majority of the existing buildings in Sweden were built before 1975. As it is shown in Fig. 4, similarly in the studied portfolio the majority of the buildings are from this period. However, the portfolio also includes a significant share (24%) of buildings built before 1945. Since the first (significant) energy regulation was introduced in 1977, the energy performance of the majority of the buildings compared to new Swedish construction standards is poor. More than 88% of the buildings in this portfolio use more than 100 kWh/m^2 year (see Fig. 4). Since 97% of the buildings are connected to a district heating network, which has a low emission

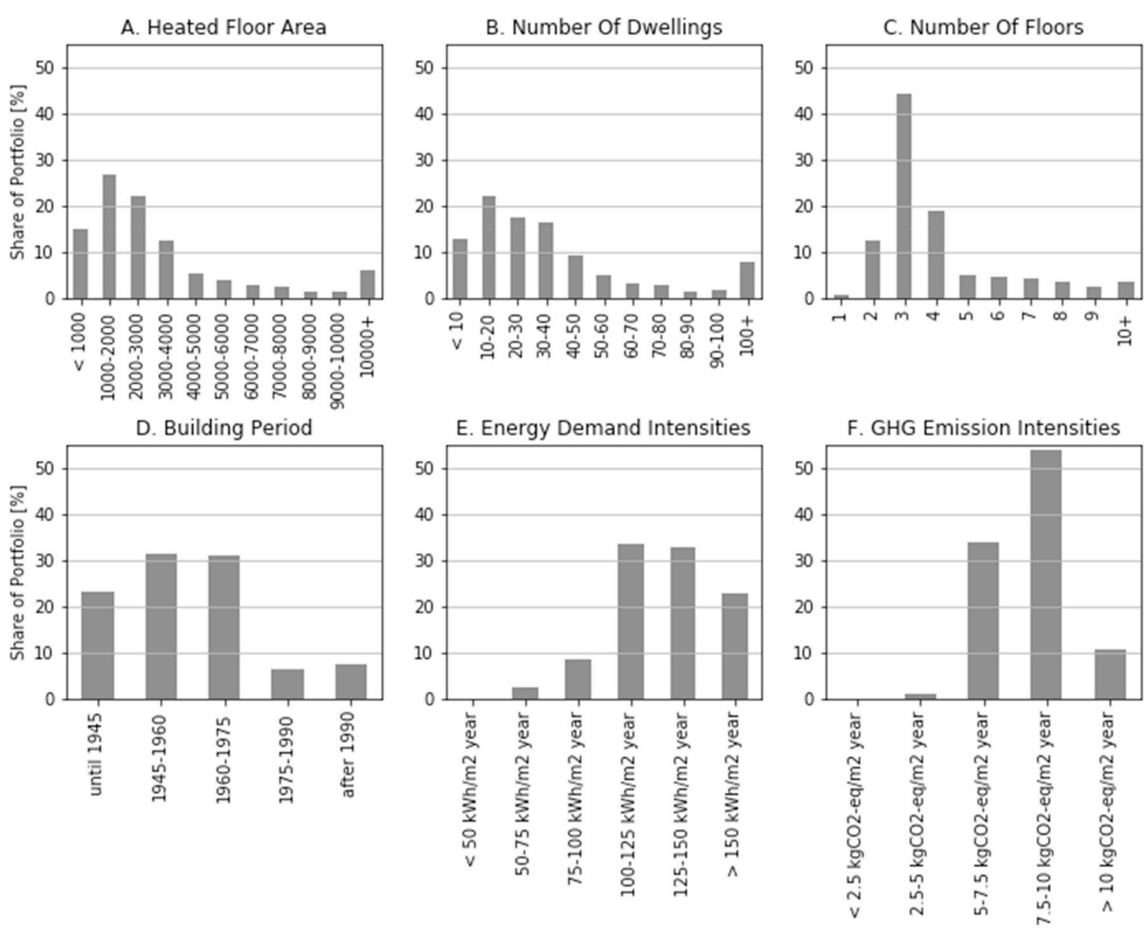

Fig. 4. Overview of the distribution of buildings in the portfolio in terms of size, age, energy demand and GHG emissions.

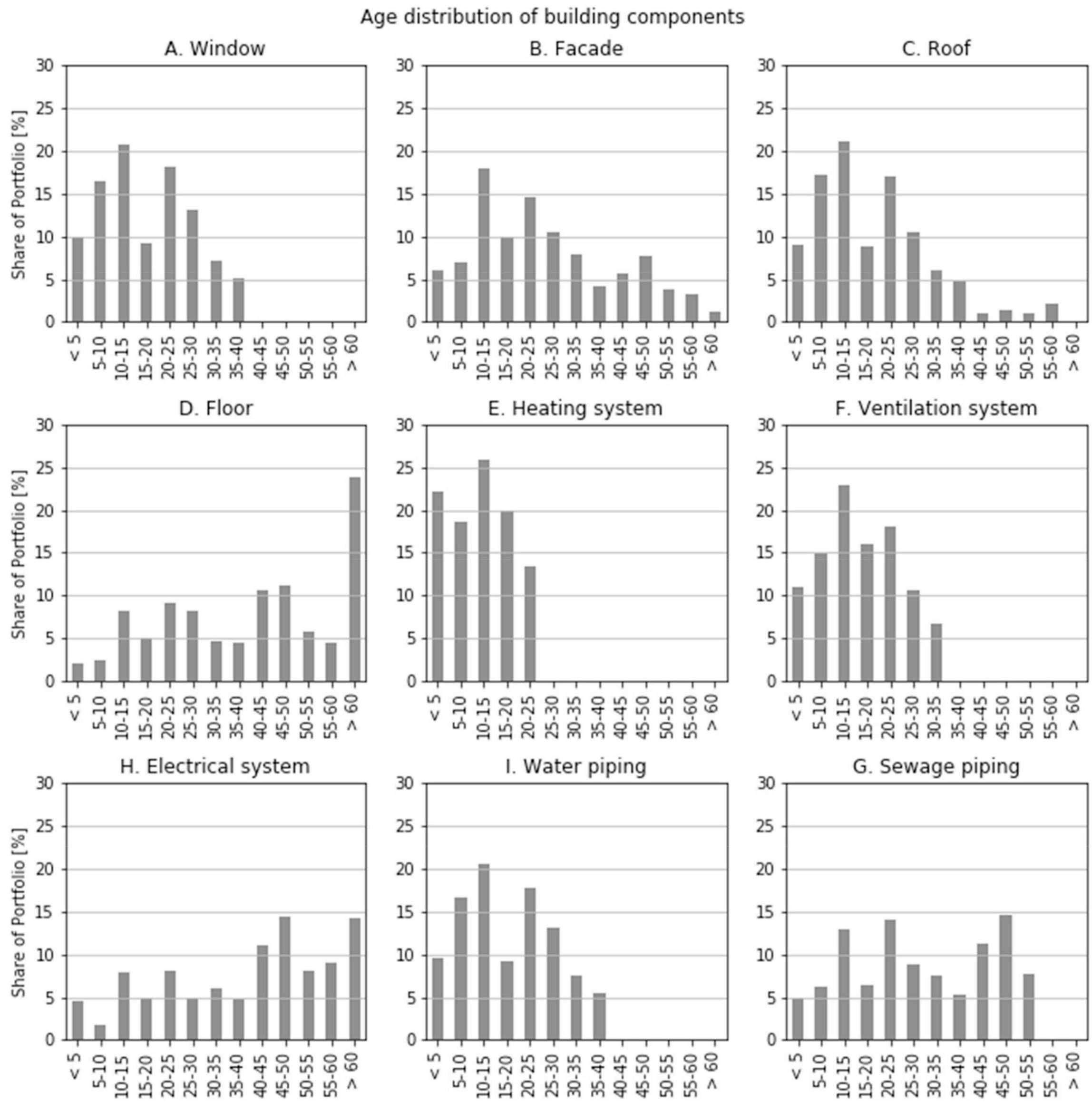

Fig. 5. Initial distribution of the age of different components in the portfolio.

factor (see Table 1), despite the relatively poor energy performance the GHG emission intensity levels are considerably lower than the average EU level.

The age distribution of different building components in the portfolio are shown in Fig. 5. The different age distributions are a result of the initialization procedure described in section 2.2.1. The age reflects the (assumed) timespan between the reference year (2015) and either the building construction year or the last reinstatement/retrofit year. Building components with a relatively short life span (e.g. ventilation and heating system) show an age distribution spanning only a couple of decades back. Building components with a longer lifespan are more distributed, and so a significant share of buildings has components that are older than 40 years (e.g. electrical systems and sewage piping).

3.2. Scenario results

The development of the energy demand intensities in the portfolio according to two scenarios according to the industry plan as well as according to the optimized plan for the retrofit scenario (the optimized plan for the reinstatement scenario is excluded as it closely resembles the industry plan) is shown in Fig. 6. The projected energy use in the reinstatement scenario (industry plan) shows only slight improvements in the portfolio that is due to the improvements in the energy performance of buildings through reinstatement measures (e.g. exchange of windows, improvements in efficiency of the heating system). The energy use development in this scenario leads to a decrease of the average energy demand from 120.8 kWh/m^2 year to 112.6 kWh/m^2 year until 2050 leading to annual energy savings of only 50.5 GWh/year (−6.8%) across the portfolio.

In the retrofit scenario, using the same industry plan, the efficiency gains show a steady development in the first 15 years, with the share of buildings with the lowest performance (consuming more than 125 kWh/m^2 year) gradually decreasing. The development pace increases after the year 2030 resulting in an increase in the number of buildings (56.7% of the portfolio) consuming less than 75 kWh/m^2 year by the year 2050. This indicates that more retrofit measures are carried

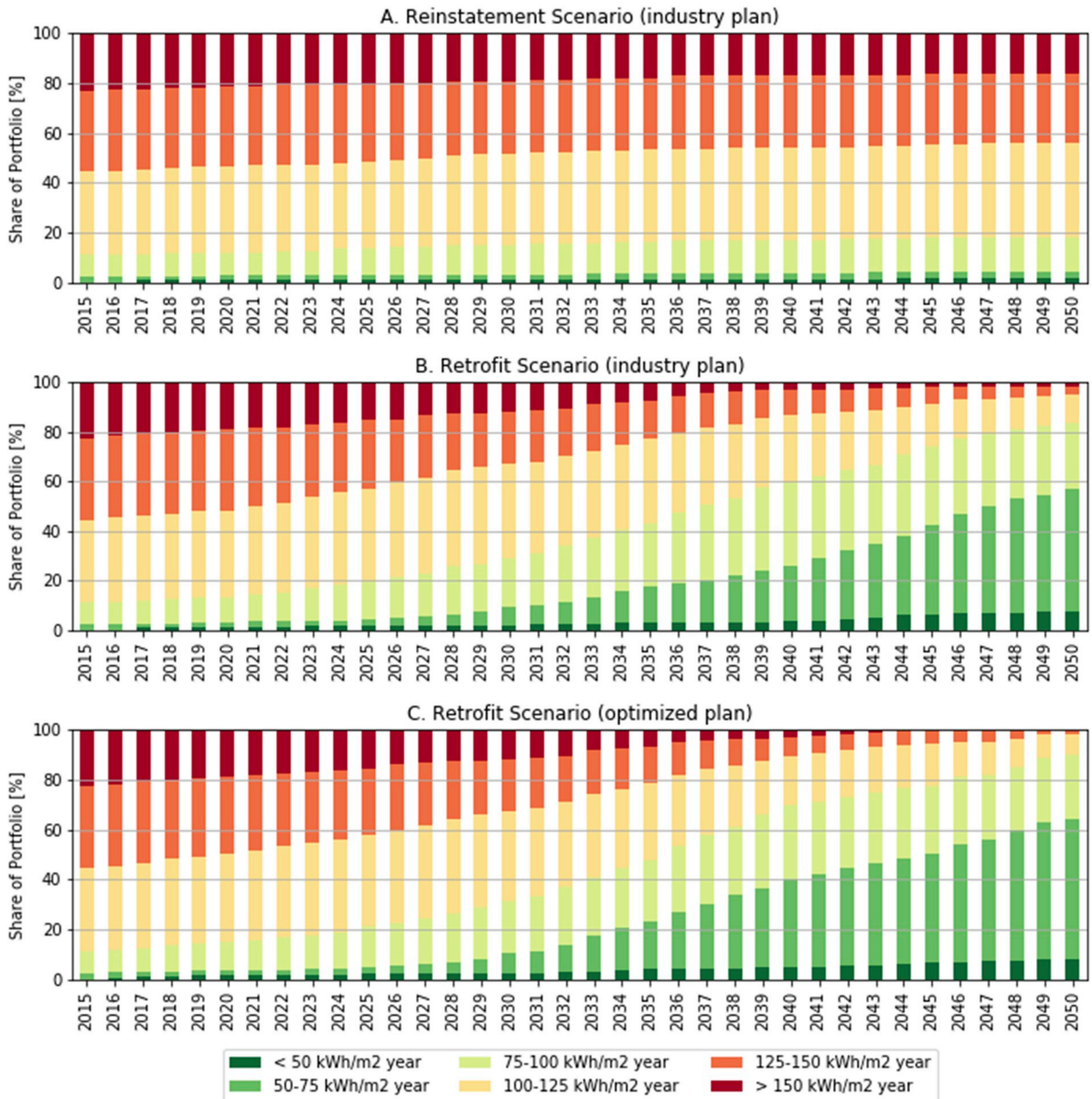

Fig. 6. Development of the energy demand intensity distribution in the portfolio for the reinstatement scenario (A), the retrofit scenario based on the industry plan (B) and the retrofit scenario based on the optimized plan (C).

out in this period (i.e. components reaching the ESL) as well as multiple retrofit measures in a building adding up. This development leads to the decrease of the average energy demand from 120.8 kWh/m^2 year to 68.4 kWh/m^2 year resulting in a reduction of the total annual energy use by 320.7 GWh/year (−43.3%) by the year 2050.

In the retrofit scenario, using an optimized plan, retrofit measures are carried out earlier compared to the industry plan, which results in better energy performance mainly after 2030 compared to the industry plan due to the optimized maintenance and retrofit planning. The fact that retrofit measures are carried out earlier, also leads to more retrofit measures being implemented until 2050, resulting in a larger share of buildings with less than 75 kWh/m^2 year energy use 64.3% compared to the 56.7% share in the industry plan. The optimization results in a decrease of the average energy demand from 120.8 kWh/m^2 year to 65.0 kWh/m^2 year resulting in a reduction of the total energy use of 340.6 GWh/year (−46.1%) by the year 2050. The lower total energy use in the optimized scenario is achieved at 5% lower annual costs (EAC) across the portfolio compared to the industry retrofit scenario and 15% lower annual costs compared to the industry reinstatement scenario.

The projections of the development of the GHG emission intensities in the portfolio follow a similar trend as the energy demand intensities shown in Fig. 6. This is because the type of heating system does not change in both retrofit and reinstatement scenarios except for the 3% share of the portfolio that are not connected to the district heating network. The GHG emission intensity projection results are given in Fig. 10 in the appendix. In summary, until the year 2050, the results show GHG emission savings of 3.7 ktCO_2-eq/year (−8%) for the

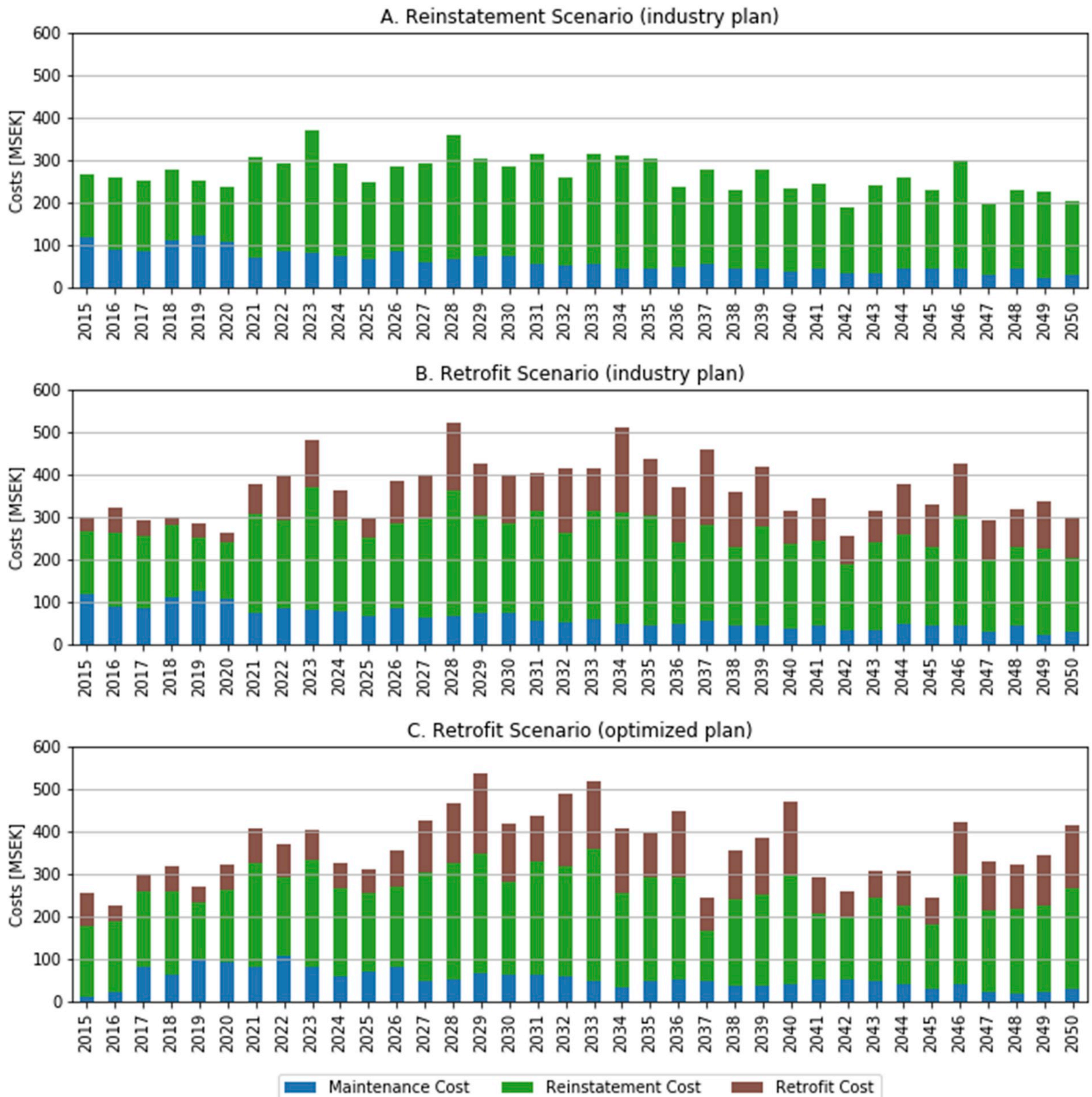

Fig. 7. Discounted maintenance, reinstatement and retrofit costs for the reinstatement scenario (A), the retrofit scenario based on the industry plan (B) and the retrofit scenario based on the optimized plan (C).

reinstatement scenario, 18.5 ktCO_2-eq/year (−39.9%) for the industry retrofit scenario and 19.6 ktCO_2-eq/year (−42.3%) for the optimized retrofit scenario.

The (discounted) investment volume for the different scenarios according to maintenance, reinstatement and retrofit costs is shown in Fig. 7. The difference between the reinstatement and industry retrofit scenario, shows the additional costs of retrofit measures. The results show relatively low levels of retrofit activity in the reinstatement scenario for the first 10 years, with larger investments being made later on.

In the optimized retrofit scenario, the optimization process reduces the number of maintenance measures (especially at the beginning of the period) resulting in lower ESL of the affected components and thus an earlier implementation of the respective retrofit measures. Therefore, the optimized planning of retrofit measures not only increases the energy savings in the studied period but also results in lower costs than the total costs in the industry retrofit scenario.

The cost breakdown according to building component is shown in Fig. 8. A more detailed cost breakdown per component and according to maintenance, reinstatement and retrofit costs for the different scenarios and plans are given in Figs. 11–14 in the appendix. Across all scenarios, the major costs come from façade and window measures, with sewage and water piping being additional large cost factors. The other components such as roof, floor, heating and ventilation system have minor contribution to the total costs. Furthermore, Fig. 8 shows that there are more retrofit costs associated with both windows and façade between 2025 and 2035 in the optimized scenario than in the other two scenarios (industry plans). As mentioned earlier in the optimization process, the maintenance measures are reduced in the early years resulting in shorter ESL thus earlier expected retrofit dates. Since these two components have considerable contribution to the total energy savings,

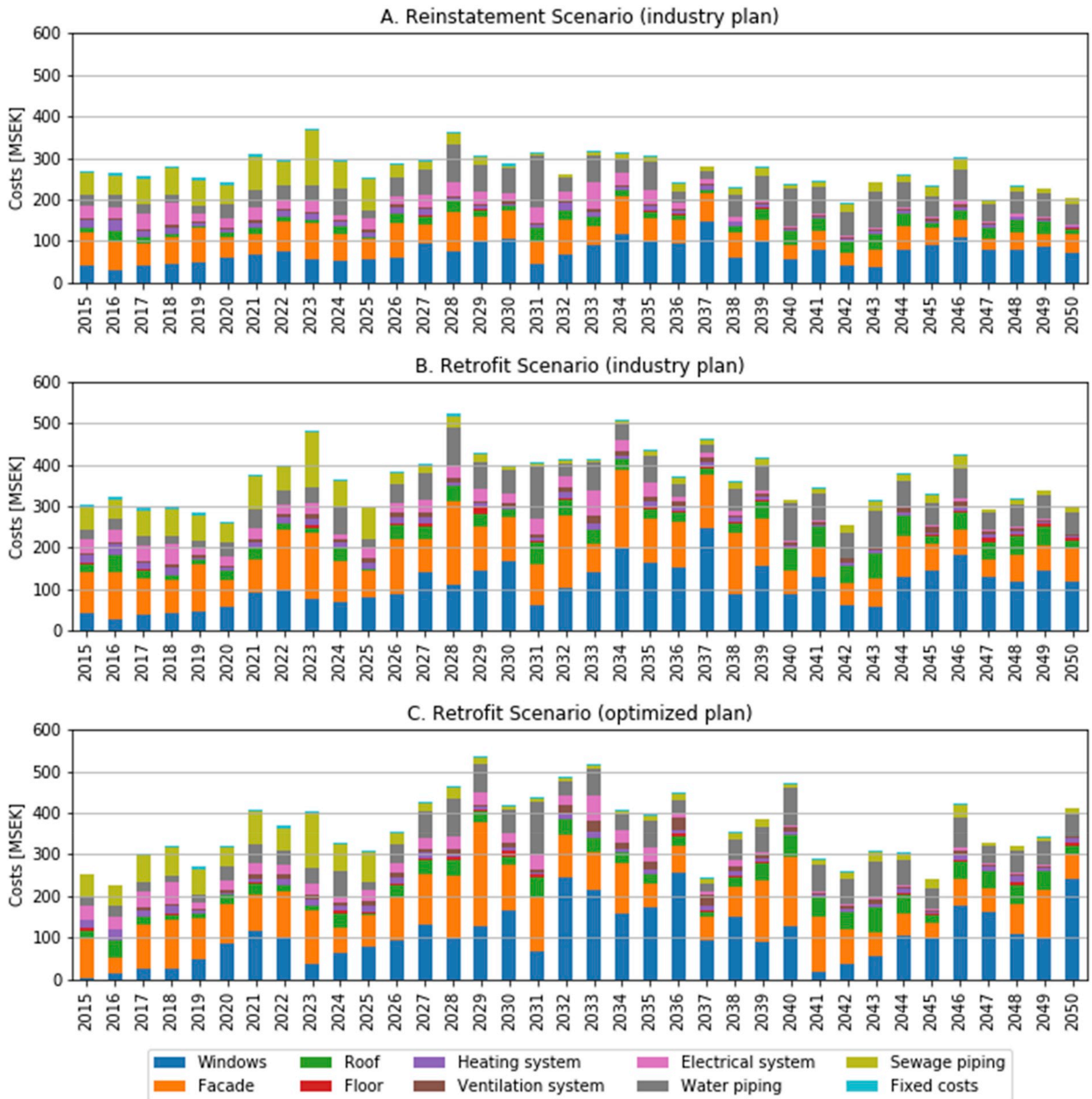

Fig. 8. Discounted total costs according to building components for the reinstatement scenario (A), the retrofit scenario based on the industry plan (B) and the retrofit scenario based on the optimized plan (C).

the energy efficiency gains during and after this period is higher in the optimized scenario than in the industry retrofit scenario, Fig. 6.

Fig. 9 shows the relative difference between the calculated total EAC (equivalent annual cost) on a building level in the retrofit scenario compared to the reinstatement scenario for both the industry plan (upper left) and the optimized plan (upper right) as well as according to the industry and the optimized plans for the reinstatement scenario (lower left) and the retrofit scenario (lower right). A positive difference in EAC means that the addition of retrofit measures leads to a decrease in the total annual costs of the respective building. The comparison between the retrofit and the reinstatement scenario for the two plans shows a reduction in the EAC for 71% of the buildings (green area in Fig. 9) in the industry plan and 71.9% of the buildings in the optimized plan. Moreover, the average difference in the EAC is increased from 8.1% to 9.8%. This highlights how the optimization process reduces service-life cycle costs and thereby makes the retrofit scenario economically feasible in a larger number of buildings.

The comparison between the industry and the optimized plan for the two scenarios shows that for the reinstatement scenario, in almost 40% of buildings, there is only a 0–2% difference between the industry schedule and the optimized schedule. In 9.5% of buildings there is even zero difference, meaning that the industry plan already yields optimal service-life cycle costs. This happens in older buildings where reinstatement/retrofit measures are due shortly. Late planning inevitably lowers optimization opportunities. For the rest of the buildings, optimizing the maintenance and renovation plan lowers the EAC up to 10%, excluding a few outliers. On average the EAC can be decreased by 2.8%. In contrast, in the retrofit scenario, the optimization yields on average a 5.1% lower EAC, with cost reductions going up to 20–30%. This shows that adding retrofit measures to the maintenance and reinstatement

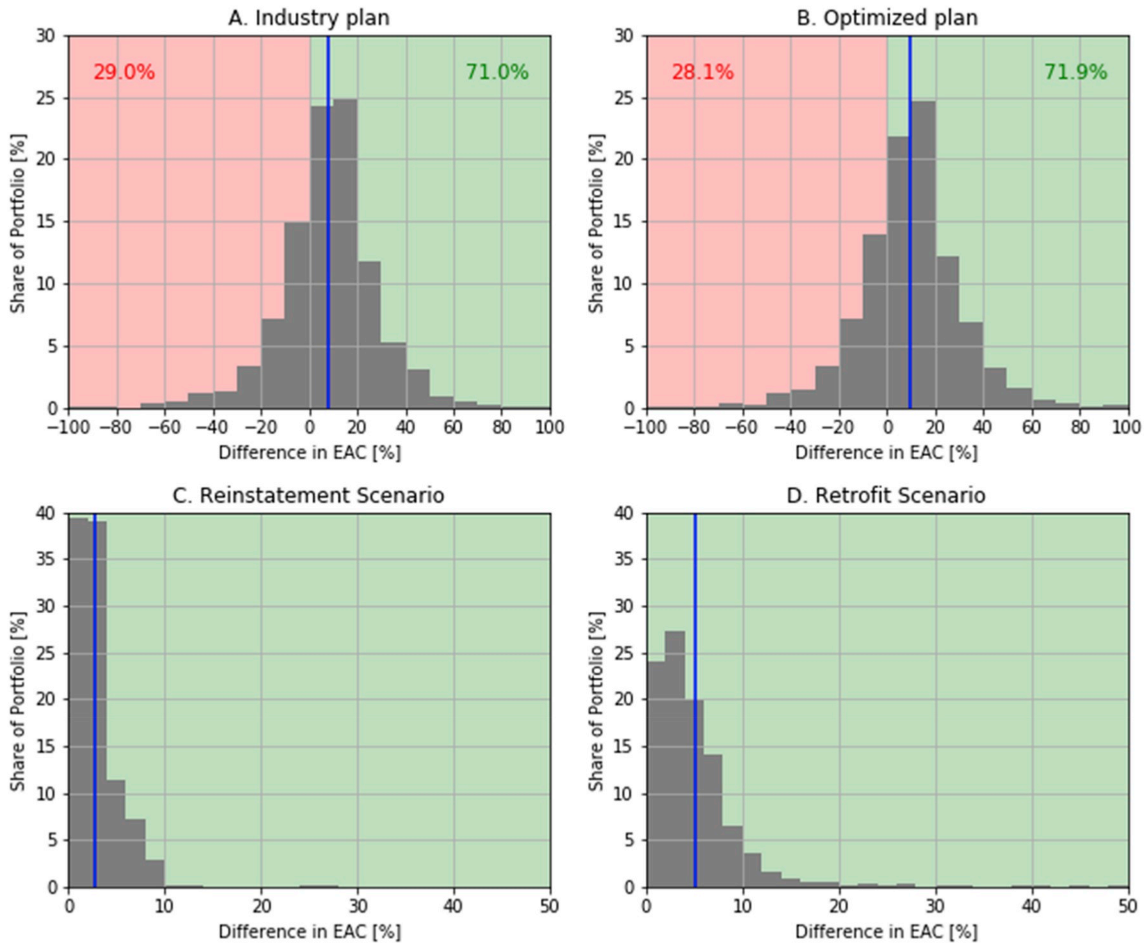

Fig. 9. Difference in the total equivalent annual cost (EAC) between the reinstatement scenario and the retrofit scenario for the industry (A) and optimized scenario (B) as well as the difference between the industry and optimized scenario for the reinstatement scenario (C) and the retrofit scenario (D). Red area: negative difference in EAC, green area: difference in EAC equal and larger zero, blue line: mean value.

plans increases the effect of the optimization as it gives more options to optimize the service-life cycle performance.

Comparing the industry reinstatement scenario and the optimized retrofit scenario up to 77% of the buildings show better economic performance in optimized retrofit planning compared to the industry reinstatement planning. Meaning, that these buildings can be retrofitted according to the measures specified in the retrofit scenario at lower life-cycle costs. On average, the optimized retrofit scenario leads to a reduction of the EAC by 12% compared to the reinstatement scenario.

4. Discussion

In this paper we demonstrate the effect of taking a service-life cycle perspective to the planning and scheduling of maintenance and retrofit measures on a portfolio level by combing the MARS method with a BSM approach. The method was applied to the portfolio of the municipal property owner for the City of Gothenburg. The results are calculated for two different scenarios: a reinstatement only as well as a retrofit scenario. Results are calculated for maintenance and retrofit planning based on an industry standard approach as well as an optimized approach according to the MARS method. The generated modeling framework provide an integrated tool for portfolio owners to assess and plan the effect and costs of retrofit measures from a portfolio perspective.

The results for the municipal housing stock of Gothenburg show that by applying the specified retrofit measures (Table 2) to the complete building portfolio, the annual energy demand of the buildings can be lowered by 43–46% until 2050 depending on the timing of the retrofit measures. By applying these retrofit measures, the average energy demand can be lowered from 120.8 to about 68.4 kWh/m^2 year when applied based on the industry plan and 65.0 kWh/m^2 year in the optimized scenario. This highlights the substantial potential for energy efficiency in the stock.

The MARS method optimizes the scheduling of the maintenance and retrofit measures to reduce overall life-cycle costs. Through optimization, the total EAC of the retrofit scenario can be lowered by 5% compared to the total EAC of the industry retrofit scenario, and by 15% compared to the industry reinstatement scenario. These results not only illustrate the economic benefits of building retrofits but also benefits gained from a service-life cycle perspective in maintenance and retrofit planning, which amplifies the effect of the retrofit measures.

While over the complete building portfolio the optimized retrofit scenario yields lower life cycle costs compared to a reinstatement scenario, a comparison of the EAC levels on the building level shows that for about 30% of buildings (depending on the plan), the retrofit scenario yields higher EAC than the reinstatement scenario. This is not surprising, as the specified retrofit scenario is rather ambitious and, therefore, may not be feasible for all buildings. Moreover, about 20% of the portfolio was built after the implementation of the SBN 75 in Sweden in 1977. Besides, there are some buildings which have already been retrofitted previously to some degree and, therefore, already have an improved energy efficiency standard. For these buildings such an ambitious retrofit scenario, therefore, will not be feasible. This could be addressed by adapting the retrofit measures more to the initial state of the buildings instead of using predefined measures.

The results are built upon general data sources from the city of Gothenburg and national sources (see section 2.2.1), which makes the model transferable and easy to set up for other cases in Sweden. However, the use of general data over more portfolio specific data sources also limits the model results. The initial state of the building is not known in terms of what measures have already been implemented and when. Even though the initial dataset is calibrated based on the energy demand of the EPC, a considerable uncertainty remains on the state of the buildings, especially when it comes to the initial age distribution of components in the building. Moreover, the merging of datasets from different sources may introduce some error to the results (e.g. single building footprint in 2D map may include several buildings in the property registry and EPC database). Österbring et al. [12] shows these uncertainties in greater detail. Such errors may lead to an over- or underestimation of the achievable energy savings and the related costs, which may lead to outliers in the results of the portfolio assessment (e.g. overestimation of façade area leads to overestimation of retrofit costs for this component). This may be addressed by verifying the input data with data from the BPO. The uncertainties in cost-optimal planning related to the over-underestimation of the potential energy savings are, however, minimal (see Ref. [14] for a detailed assessment). The main contributor to the planning uncertainties is the ratio of the reinstatement/retrofit costs to the maintenance costs. Uncertainties in the cost data used may introduce error to the planning results. The use of building specific cost data instead of a more generic cost data used in this study could address the resulting errors. Moreover, cost-optimal maintenance/retrofit planning is fairly insensitive towards reasonable variations in cost variables such as the discount rate and the energy price growth rate (see Refs. [13,14] for the detailed sensitivity analysis). In this regard, the extent of planning variation depends specially on the ratio of the reinstatement/retrofit costs to the maintenance costs. The reliability and accuracy of the individually tailored maintenance and retrofit plans can be improved by means of building inspections. In the MARS method, inspection results are directly implemented in the deterioration function and are further used for the calibration of component-specific deterioration behaviour, (see Ref. [13]).

Nevertheless, long-term budgeting plans, must be taken into account and used carefully. Long-term plans are useful for budget allocations and efficient distribution of resources. As the results of this study suggest, an introduction of a systematic and harmonized approach to maintenance and retrofit planning can be an effective instrument toward achieving the national energy and climate goals.

The results have some limitations due to the assumptions on the initial condition of building components, assuming that they have been properly maintained. This is an optimistic assumption since there are probably buildings in the portfolio that due to financial constraints have been left with minimum or reduced maintenance. This assumption may address the 10 years gap in the beginning of the studied period before projected major retrofit costs. This could be remedied using inspection results of the building portfolio in order to check the initial conditions. However, as the data used in this model was built up on general data from the city of Gothenburg and national sources, such specific data was not available.

In the MARS method, the cost-optimal maintenance and retrofit plans are optimized for component clusters to take into account the potential financial benefits of combining measures for components with sharing fixed/logistic costs. Therefore, retrofit measures that bring financial/logistic benefits to the owners when carried out simultaneously, are grouped together in the resulting maintenance and retrofit plans.

Considering that the MARS method incorporates a service-life cycle costing approach in planning optimizations, a deep-renovation (major retrofit work) scenario is very unlikely to become the cost-optimal planning result. In such scenarios where a major retrofit work is the cost-optimal planning result, the associated costs with the relocation of tenants (if required), are not included in the fixed/logistic costs which can have practical implications.

5. Conclusion

The aim of this paper was to enable building-specific cost-optimal maintenance and retrofit scheduling on a portfolio level in order to project future costs, energy and GHG emissions of the municipal housing company of Gothenburg. For this purpose, a bottom-up BSM approach was combined with the MARS method to project and optimize the timing of retrofit measures on a building portfolio level. This approach enables the integrated long-term planning on retrofit investments and reduction of energy demand and GHG emissions for the respective portfolio.

The results of the application of the method to the building portfolio of the municipal housing company of Gothenburg, shows the potential for energy and GHG emission reductions in the stock. The results indicate that by optimizing building-specific maintenance and retrofit plans, ambitious retrofit measures can be introduced in the majority of the buildings with a positive effect on the life-cycle costs of the buildings. This share could even be improved by individually tailoring retrofit measures in building level e.g. by lowering the ambition or leaving out components that already have a good energy efficiency standard.

The method is easily transferable to other building portfolios in Sweden as it builds up on national available data sets. The downside of this, is that the initial condition of the building components in the building portfolio is unknown and has to be assumed by the model applied in this paper. The general data should, therefore, be complemented and verified through inspection data and existing maintenance plans of the BPO when operationalizing the proposed method for a building portfolio. While the method itself would also be applicable for portfolio's outside Sweden, more extensive work is needed to collect the input data that is needed to apply this method; as both the portfolio data and the economic data that are currently applied are based on Swedish data sources.

In the future, the optimization approach to retrofit and maintenance planning in building portfolios could be further developed in different ways. As BPOs often operate under budget constraints, these could be included in the optimization approach as boundary conditions. Moreover, the portfolio approach to planning could be further strengthened, e.g. by combining neighboring buildings in the planning to cut down on logistics cost and make use of the economies of scale.

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Appendix

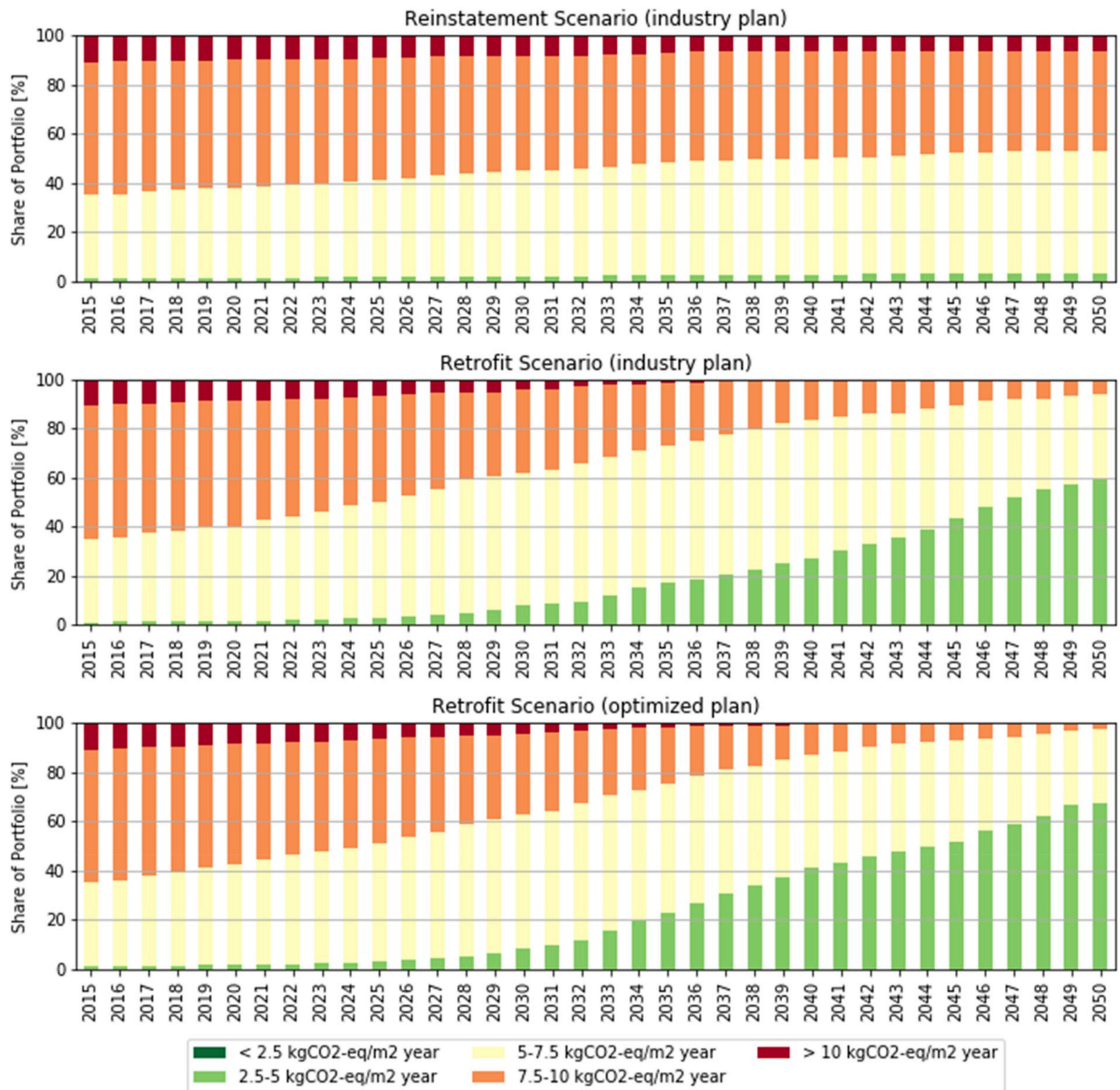

Fig. 10. Development of the GHG emission intensity distribution in the portfolio for the reinstatement scenario, the retrofit scenario based on industry plan and the optimized plan for the retrofit scenario.

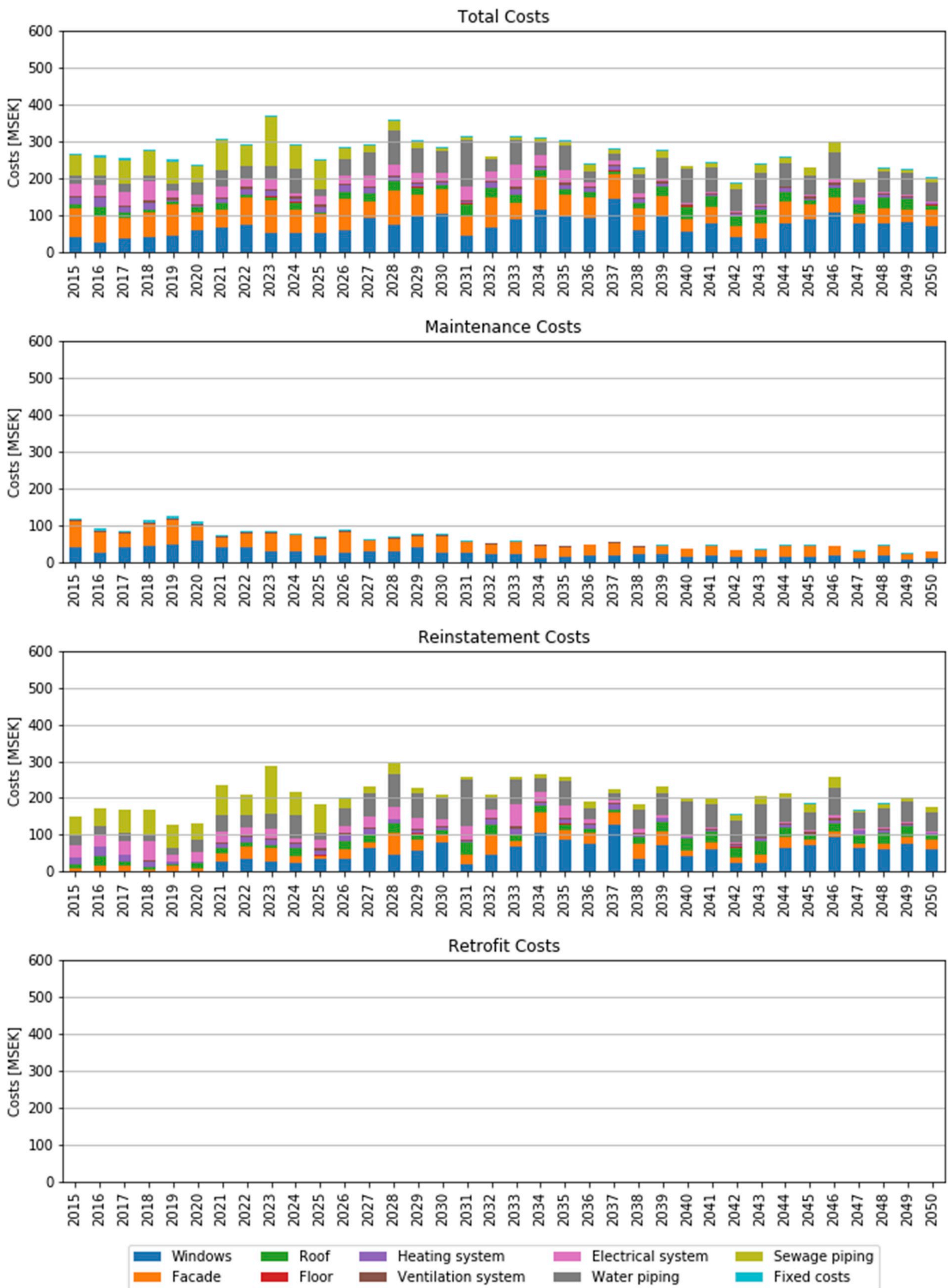

Fig. 11. Total, maintenance, reinstatement and retrofit costs according to building component for the reinstatement scenario (industry plan).

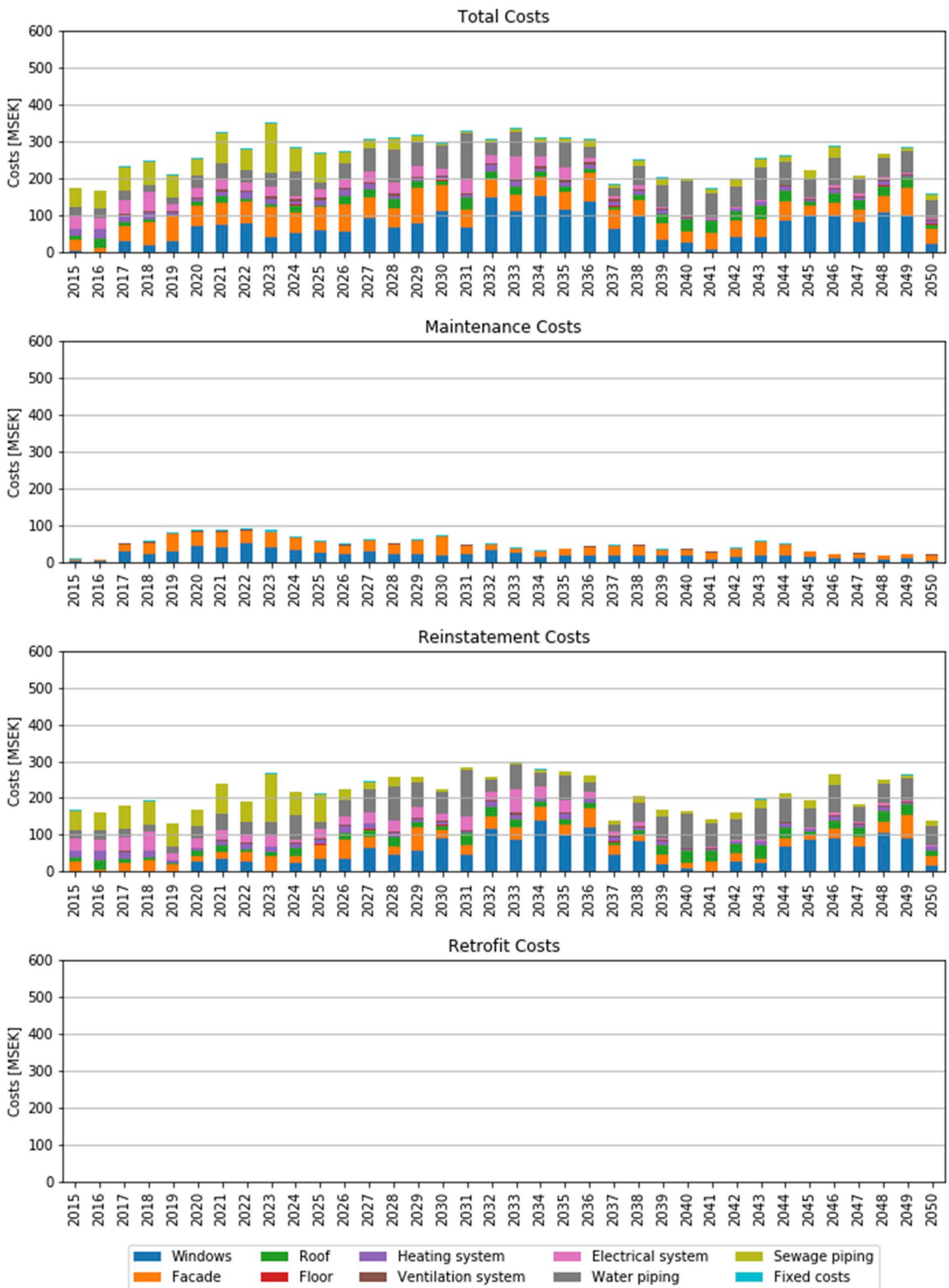

Fig. 12. Total, maintenance, reinstatement and retrofit costs according to building component for the reinstatement scenario (optimized plan).

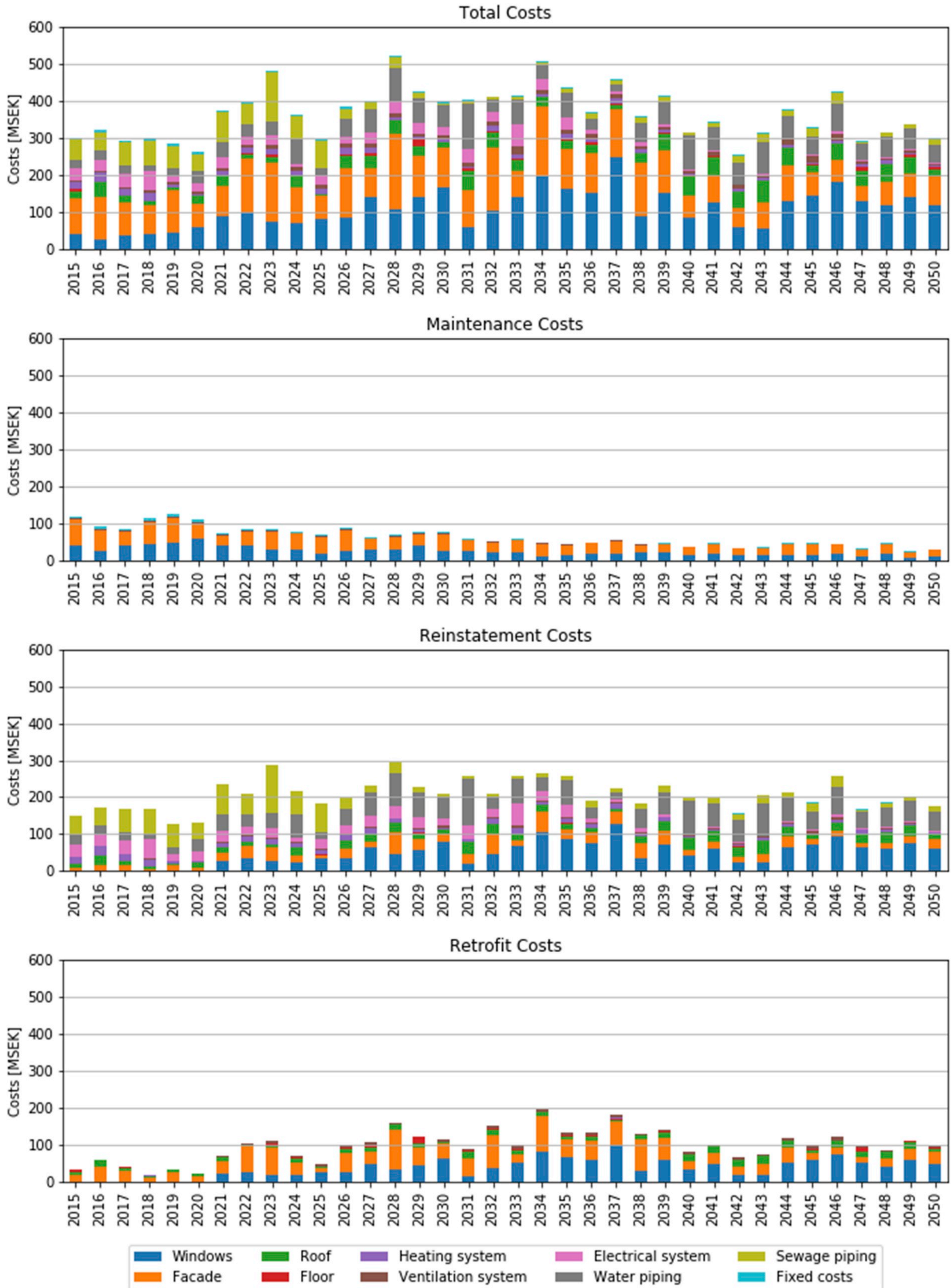

Fig. 13. Total, maintenance, reinstatement and retrofit costs according to building component for the retrofit scenario (industry plan).

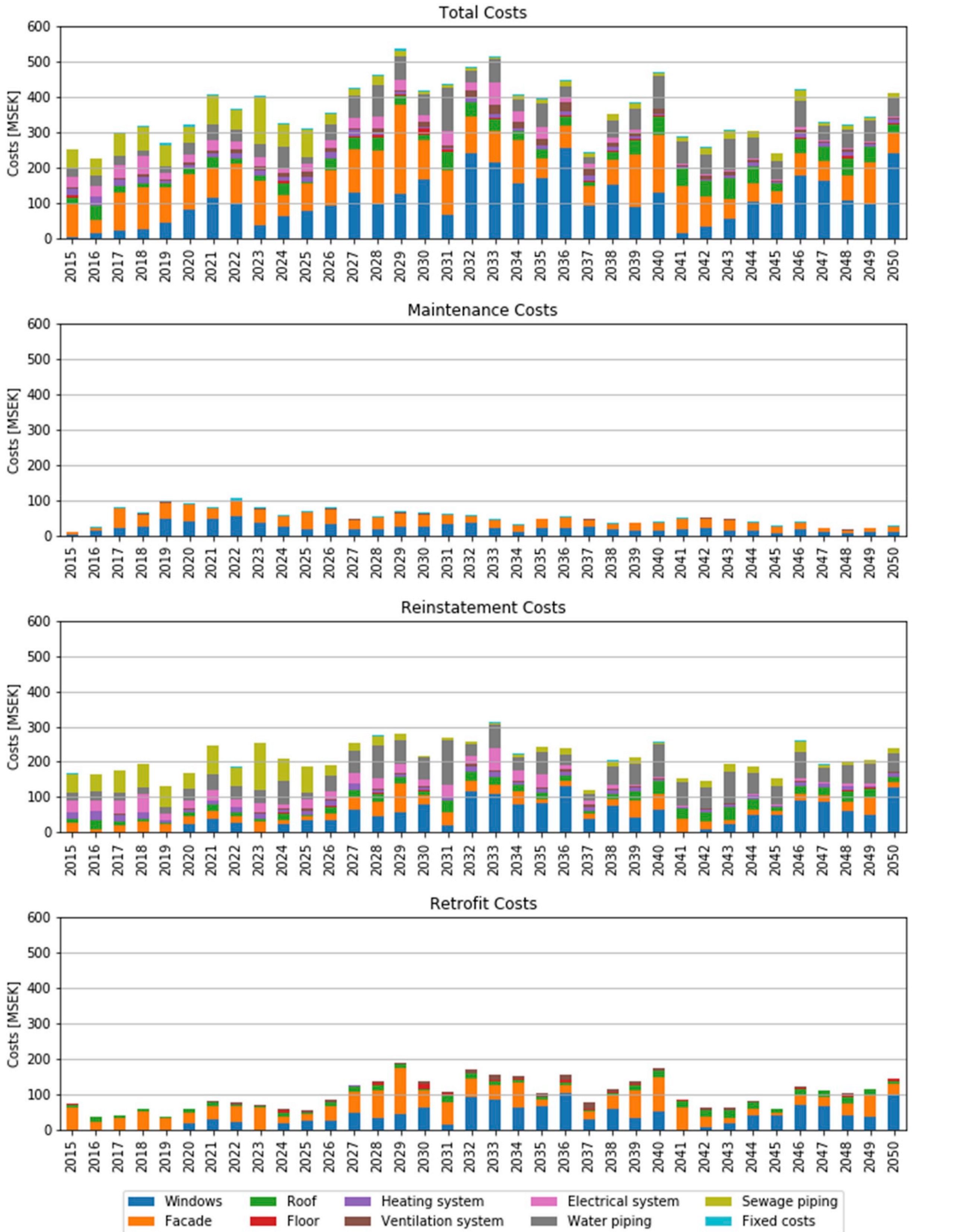

Fig. 14. Total, maintenance, reinstatement and retrofit costs according to building component for the retrofit scenario (optimized plan).

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