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ORIGINAL ARTICLE

From durability to circularity: ensuring service life and enabling reuse of concrete in circular construction

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Abstract Reusing reinforced concrete structures within a Circular Economy offers substantial environmental benefits, but requires reliable assessment of their remaining service life. Conventional approaches to concrete durability, based on prescriptive design parameters for new structures or carbonation depth measurements in existing ones, are insufficient to ensure reuse for an additional 50 or 100 years. This study addresses this gap by introducing a performance-based probabilistic framework for evaluating carbonation-induced corrosion, tailored to circular construction. The study incorporates parametric analysis and probabilistic modeling of corrosion initiation and propagation phases, and assesses two precast concrete buildings located in Nordic climates. The study also examines how storage period before reuse, changes in exposure class after deconstruction, altered carbonation rates during a second service life, and repair interventions, affect service life. Monte Carlo simulations are used to estimate the total service life under various conditions, with outdoor carbonation rates reflecting typical Nordic exposures. Corrosion propagation is modelled following fib Model Code 2020 and fib Bulletin 112. The results demonstrate that reused concrete elements can achieve service lives comparable to new structures, provided that performance-based assessment and appropriate repair interventions are applied. The proposed framework supports data-driven decisions on service life, repair, and reuse strategies for structural concrete, considering exposure classes and performance. It can be complemented by non-destructive testing and durability indicators. It provides a scientific basis for extending the service life of reused concrete elements and supports design for circularity and resource efficiency, thereby advancing circular construction and the transition toward a sustainable built environment.

Keywords Carbonation · Concrete · Corrosion · Circular economy · Durability · Reuse · Service life

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1 Introduction

Concrete is the most widely used construction material, accounting for 8–9% of global man-made CO_2 emissions [1]. Reducing the life cycle environmental impacts of concrete is a crucial step towards a more sustainable built environment [2]. Adaptive reuse of entire buildings and service life extension is often seen as the most sustainable pathway [3]. When this is not viable, reusing building components holds significant potential for reducing environmental impacts [4–6]. In several instances, buildings may be demolished for other reasons than structural integrity, such as redevelopment and densification in cities, and building obsolescence in terms of adaptability to accommodate new uses, evolving functional and performance requirements, or user needs [7–9]. At present, most of the concrete from obsolete buildings is often recycled considering the CO_2 uptake potential from carbonation at end-of-life, repurposed for road base construction, or used as aggregate in new concrete production [10, 11]. One lesser-applied circular economy strategy for concrete is component reuse of concrete elements in new projects [8, 12]. Component reuse helps to avoid some of the greenhouse gas emissions (GHGe) associated with new concrete production, as well as reducing construction waste from demolition [13]. Additionally, concrete reuse offers significantly greater embodied carbon savings than recycling, even when considering carbonation during and after service life [10, 14].

Prior to reuse, concrete elements from existing buildings must undergo deconstruction, structural investigation (e.g., damages, structural capacity, durability, hazardous substances), and necessary refurbishment (e.g., removal of coverings, cleaning, repairs of damages) [15, 16]. Although there is research on repairing and extending the service life of existing concrete structures (from buildings and infrastructures) [17], less attention has been paid in the concrete literature to durability, repairs, and service life of concrete structures and components for reuse in new buildings [8, 10, 18].

The most common durability concerns for reinforced concrete structures are carbonation- and chloride-induced corrosion [19]. Chlorides are most of a concern for concrete structures exposed to a marine environment or de-icing salts [20]. On the other hand, carbonation affects all structures over time and can be a durability concern as it reduces the concrete's alkalinity [21]. This reduction may depassivate the protective film around the rebars and may lead to reinforcement corrosion and subsequent damage [22]. Additionally, practical experiences from Finland, Switzerland and Japan, shows that carbonation does not always cause significant damage in concrete, which may allow for longer service life and reuse potential [22–24]; it is moisture at the rebar interface that may lead to corrosion, while the concrete cover and other surface layers act as a protective barrier for outdoor exposed concrete during wet and dry cycles [22].

Several approaches for durability design and service life prediction models exist in literature and standards [25–30]. Among these, performance-based approaches, semi- or fully probabilistic, are considered the most robust, as they account for relevant material properties, influencing environmental variables, and consider directly measured properties such as carbonation depth or indirect correlations [27, 29, 31]. These approaches offer greater reliability compared to "prescriptive" approaches and are especially useful in assessing existing structures. For example, air-permeability tests have been correlated to carbonation rates for estimating the residual (also called remaining) service life in existing structures [32]. Another recent study investigating the interplay between lifespan, carbonation, and embodied carbon, found that concrete elements in Nordic climates may have a sufficient remaining service life for reuse [10, 33]. However, reuse of concrete will depend on the required service life and exposure conditions of the new recipient structure. In these prior studies, carbonation of concrete was considered in the remaining service life assessment, but the subsequent corrosion propagation phase was not.

Typically, the service life of reinforced concrete is modelled as two consecutive phases: the initiation phase, during which the carbonation front progresses through the concrete cover; and corrosion propagation phase, which may begin once carbonation reaches the steel reinforcement [34]. Other studies examined the lifespan associated with the propagation phase in carbonated concrete facades [35–37]. While the initiation phase is the main factor that ensures service life, the propagation phase significantly extends it by 10 to 40 years [35, 38]. In severe cases, precast concrete facades exposed to wind-driven rain had a propagation time of 5 to 8 years, requiring repairs during their service life [39].

While previous studies provide some evidence supporting the reuse of structural (precast or cast-in-place) concrete, they do not assess the full service life, nor determine whether they can meet the typical 50 or 100 year design service life required by codes and standards. Much of the current literature on concrete in a Circular Economy context pays limited attention to durability and service life [3, 8, 18, 33, 40–44]. Another part of the literature has overlooked reused concrete, focusing instead on service life modelling and the carbonation challenge in concretes with supplementary cementitious materials (SCM)—which carbonate faster than traditional Portland cement—and highlighting the need to consider corrosion propagation time in service life predictions and codes [22, 23, 45–47].

This research addresses this gap by proposing a novel performance-based durability framework for assessing the reuse potential of concrete structures and elements—arguably the first in the literature to explicitly link service life modelling with circular construction. The study investigates how to ensure the durability and service life of these elements for reuse in new construction, considering both initiation and propagation phases, the effects of storage before reuse, and repair strategies to prolong service life. Drawing on literature data from and insights from the ReCreate project [13], this study pursues the following objectives:

1. Propose a probabilistic framework to assess remaining service life concrete elements exposed to carbonation-induced corrosion, considering initiation, propagation, and total service life through Monte Carlo simulations.
2. Evaluate the effects of storage conditions, changes in exposure during the second life, and environmental factors on carbonation and service life.
3. Estimate remaining service life of two precast buildings of different typologies to evaluate reuse potential in a circular construction context.
4. Examine how repair strategies and surface treatments can extend service life during the propagation phase within the probabilistic framework.

The findings of this research aim to support researchers, practitioners, and stakeholders by offering methods and insights that enable the reuse of concrete and advance circular construction practices. Finally, the study also provides a decision-making flowchart on concrete reuse across different exposure class scenarios.

2 Methods

In this study, we rely on our carbonation depth measurements in buildings, complemented by relevant literature data, and service life prediction models. We consider exposure conditions in the first service life (before reuse), after deconstruction (reuse/second service life), and how factors like relative humidity (RH) and CO_2 concentration may change and affect carbonation and remaining service life. Additionally, we also consider the influence of the storage period on carbonation depth. Figure 1 provides an overview of service life and reuse based on Tuutti's model for corrosion of steel in concrete [34] As illustrated in Fig. 1, after depassivation and ending of the initiation phase, the propagation phase may be subdivided into crack formation from the expansion of corrosion products, spalling of the concrete cover, and eventual loss of structural capacity. As indicated in Fig. 1, repair interventions that can extend service life, will be examined within a probabilistic approach, to examine how it can enhance reuse potential. Repairs are usually done to fix visible damage, ensuring structural integrity and functionality for another service life. Reconditioning, on the other hand, is a proactive measure to extend an element's service life before visible damage appears. It includes any necessary cleaning, cutting and retrofitting measures to ensure the element is suitable for re-assembly and reuse.

2.1 Exposure conditions

EN 206 defines exposure classes for carbonation-induced corrosion, given in Table 1 [50]. These designations do not exclude surface treatments for concrete or steel. Concrete can be subjected to more than one environmental action, and in such cases a combination of exposure classes should be considered. In Nordic regions, concrete in buildings is generally protected from direct ground contact. For elements such

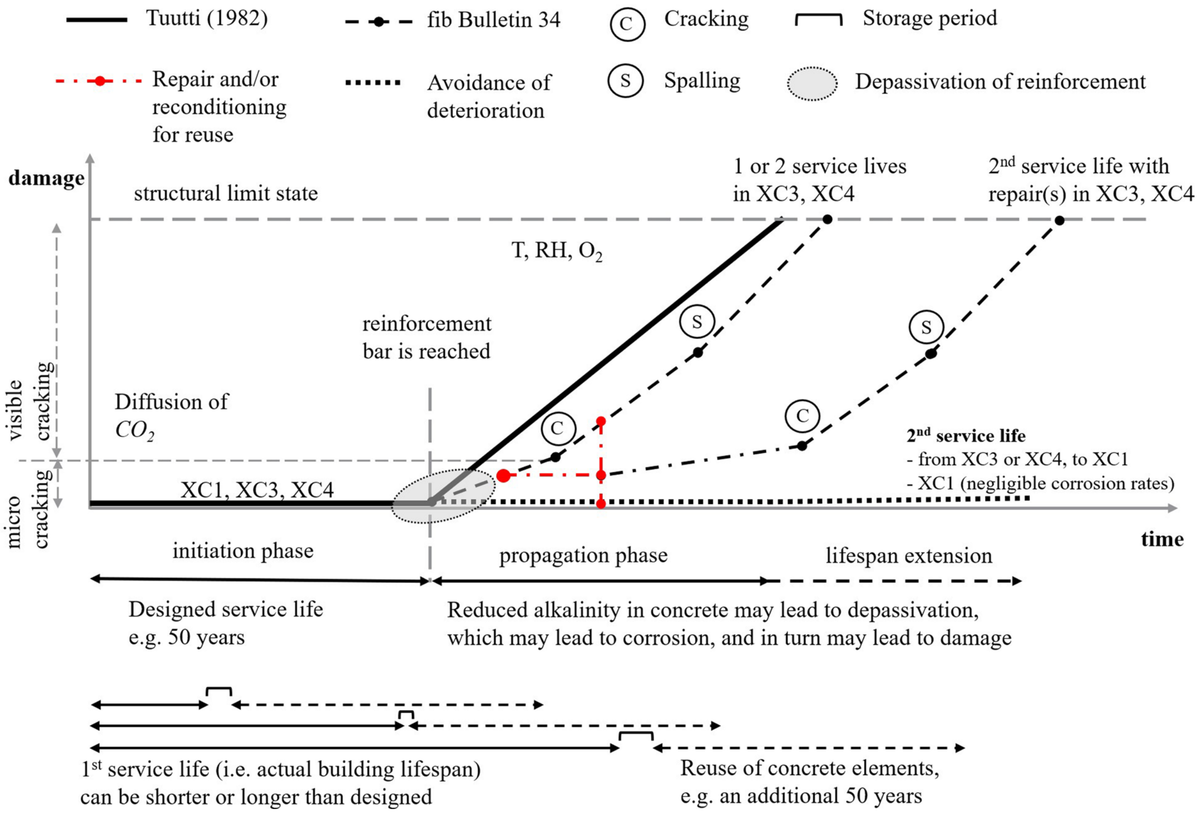

Fig. 1 Deterioration process of carbonation-induced steel corrosion in concrete, based on two-phase model for service life, including repair(s) for service life extension, storage phase, and reuse. Adapted from Tuutti [34] and fib Bulletin 34 [49]

Table 1 Exposure classes in EN 206

Exposure class	Description	Examples
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity; Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact; Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity; External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within XC2
XF1	Moderate water saturation, without deicing agent	Vertical concrete surfaces exposed to rain and freezing
XF3	High water saturation, without de-icing agent	Horizontal concrete surfaces exposed to rain and freezing

as foundations, a constant high relative humidity level of 100% is assumed (XC2). While multiple exposure classes can apply—including freeze thaw (XF) for outdoor elements—XC1, XC3, and XC4 are among the most relevant for assessing carbonation-induced corrosion, and are the focus of this study. Structures under XC2 are typically foundations, often in cast-in-place concrete, and designed not only for building loads and dimensions, but also to adapt to specific ground properties. Due to these customized design requirements, their reuse can be challenging. In the Nordic climate, unsheltered concrete facades may be subjected to freeze–thaw cycles, under XF1 or XF3 classes (see Table 1).

2.2 Service life prediction

The total service life of concrete structures in the probabilistic assessment is modelled as the sum of the two phases, initiation time (t_{ini}) and propagation time (t_{prop}).

$$t_{SL} = t_{ini} + t_{prop} \tag{1}$$

2.2.1 Initiation phase

While there are many mathematical expressions in literature for predicting carbonation depth in concrete, a square root of time is usually utilized. The carbonation depth is estimated with the following equation:

$$x = k \times \sqrt{t} \tag{2}$$

Where x is the carbonation depth (in mm), k is the carbonation rate (or carbonation coefficient in mm/$\sqrt{}$year), and t is the time (in years). In this study, the carbonation coefficient k is treated as an empirical parameter from field data taken after decades of exposure, implicitly accounting for the main variables, such as diffusion coefficient, environmental parameters, and concrete's chemical resistance (availability of carbonation reactants) [51].The remaining initiation time ($t_{r\ ini}$) can be calculated from the carbonation rate (or depth), concrete cover, and age of the structure [10]:

$$t_{r\ ini} = (c/k)^2 - t_a = (c \times \sqrt{t_x}/x)^2 - t_a \tag{3}$$

Where c is the concrete cover (in mm), t_x is the time (in years) when carbonation depth x was measured, and t_a is the age of structure (in years). A parametric analysis for the remaining Initiation time ($t_{r\ ini}$) was conducted, for various carbonation rates and concrete covers, with an assumed first service life (t_a) of 50 years (same as of design service life of 50 years). However, actual lifespans of buildings vary depending on typology, region, and construction period [52]; where demolitions are often driven by behavioral and economic factors—such as land value, demand for new development, and functional obsolescence, rather than structural degradation [53].

In addition, scenarios of partly carbonated concrete cover are considered (e.g. 5, 10 and 15 mm); In these scenarios, remaining time for carbonation to progress through the uncarbonated part of the concrete cover is calculated as:

$$t_{r\ ini} = t_{ini} - t_a = (c/k)^2 - (x_1/k)^2 \tag{4}$$

Where x_1 is the carbonation depth before reuse (specified for the parametric analysis or measured for the case studies assessment). In the literature and fib Model Codes, modification factors are often introduced to account for the effect of relative humidity and wetting–drying cycles [30, 49, 51]. While such refinements are important in diffusion-based modelling and in the durability design of new concrete structures, the empirical square-root-of-time model remains sufficiently accurate for assessing existing structures and has been validated and outdoor exposures in the Nordic climate [48].

2.2.2 Storage period

The effect of storage on carbonation depth of the concrete cover is evaluated for three cases, i.e. 1, 3, 5 and 10 years of storage. In Case 1, concrete elements are assumed uncarbonated from protective surface treatments (e.g. tiles, thick plasters) [54, 55]. Other examples for Case 1 include repurposed precast concrete products that did not meet geometric or project requirements. For instance, during the 2022 City Expo in Helsingborg (Sweden), a demonstrator pavilion was built with reclaimed hollow-core slabs sourced from Strängbetong's factory rejects [56]. For Case 1, Eq. (2) is used to estimate carbonation depth during storage. In Case 2, we assume that concrete elements are reused after a typical service life of 50 years. It is worth noting that donor buildings in Recreate had an approximate service life of 40 years (office buildings in Finland and Netherlands), and nearly 60 years (residential building in Sweden) [57]. For the parametric analysis, carbonation depth change is estimated as the difference between year 50 and 1, 3, 5, or 10 years after, with the following equation:

$$x_{storage} = x_{(t=50+z)} - x_{(t=50)} = k \times \left(\sqrt{t+z} - \sqrt{t}\right) \tag{5}$$

Where z is the number of years in storage. Unchanged carbonation rate during storage and first life is assumed. In case 3, carbonation depth during storage is evaluated from a known depth, e.g. 10 mm. This reflects situations where the concrete's age is unknown, such as if documentation is missing, or traceability of elements was not part of the reuse process. As a reference, the Norwegian standard NS 3682:2022 "Hollow core slabs for reuse" requires assessing the remaining service life of reused concrete elements only when carbonation depth exceeds 10 mm, but without justifying this threshold [58]. In Case 3, the time to reach the carbonation depth of 10 mm is determined for each k value with Eq. (2), and afterwards, the change in depth during storage is estimated with Eq. (5).

2.2.3 *Carbonation rates*

Table 2 presents carbonation rates derived from natural carbonation depth measurements (i.e. excluding accelerated tests), including data from donor buildings in the ReCreate and Återhus projects, as well as other studies in a Nordic climate, EN 16757:2022 standard, and from a statistical study based on 1999 depth measurements [16, 59–62]. We also report the standard deviation when available. Carbonation rates in the literature have a median of 3 and a standard deviation of 4, with a skewed distribution towards smaller carbonation rates [59]. In the Nordic climate, the mean rate in facades was around 2,55 mm/$\sqrt{}$year, with values of two standard deviations not exceeding 6 mm/$\sqrt{}$year; The mean value of the standard deviations is 1,33 and the median is 1,29. Although the carbonation rates may sometimes deviate from normality, a normal distribution is commonly assumed in probabilistic service life modelling [30, 38], and in this study. The mean of standard deviations from Table 2 is 1,12. Standard deviations in Table 2 are sometimes below 1, especially for indoor concrete, arguably due to high quality concrete and dry indoor environment reported in concrete reuse pilot projects. Based on this data, the parametric analysis is limited to carbonation rates ranging from 1 to 6 mm/$\sqrt{}$year, as well as used to inform the probabilistic assessment detailed in Sect. 2.5

2.2.4 *Propagation phase*

In carbonation-induced corrosion, cracking or spalling is usually considered the durability limit state (DLS) due to the uniformity of the corrosion process and volume of rust produced, which can lead to structural damage [30, 49]. In this study, the time to crack formation is considered the DLS, aligning with the approach in fib Bulletin 112 [30]. The corrosion rate, also referred to as thickness loss, represents the reduction of cross-sectional area of reinforcing steel over time [30]. Propagation time (in years) is calculated as [30]:

$$t_{\mathrm{prop}} = P_{\mathrm{corr}}/V_{\mathrm{corr}} \tag{6}$$

Where P_{corr} is the penetration of corrosion attack fulfilling the durability limit state (in µm), and V_{corr} is the corrosion rate (in µm/year). Various P_{corr} limits in the literature are given in Table 3.

2.2.5 *Corrosion rates*

Corrosion limits and literature data on corrosion rates were used to conduct a parametric analysis of Propagation times for different exposure conditions; Data in graphical format were extracted using 'WebPlotDigitizer' [71]. Based on Faraday´s law, a corrosion current density (i_{corr}) of 1 µA/cm^2 corresponds to a steel corrosion rate of approximately 0,0115 mm/year [72]. This conversion factor was applied to the data in Table 4. It is worth noting that the average yearly extrapolated corrosion rates in Finland concern South-facing facades exposed to the most severe weather with wind-driven rain [37]. Additionally, the large scatter in the data in Table 4 is due to the parameters affecting corrosion rates in carbonated concrete, where relative humidity played a significant role [73].

2.2.6 *Corrosion rates after repairs*

While literature data on corrosion rates in carbonated concrete is limited, a few studies have investigated corrosion rates after repairs, with some data available for Nordic climates given in Table 5 [22, 69, 74]. The three façade repair methods in Table 5 exhibit comparable corrosion rates, with a mean thickness loss value of 1,5 µm/year post repair. These paint-based methods were chosen as they are the most common repairs. They are also applicable to various element types, not only facades. The effects of other methods of repair on corrosion rates are not part of this study, but are of interest

Table 2 Carbonation rates from natural carbonation depth measurements in buildings

Concrete Element	Exposure class	Mean k [mm/$\sqrt{\text{year}}$]	Std. dev., σ [mm/$\sqrt{\text{year}}$]	Details	References
Precast Façade sandwich elements, ceramic tile cover	XC4	0,25	0,65	N = 15 ReCreate project, Finland, built in 1982	[16, 57]
Precast Indoor elements, plastered	XC1	0,15	0,09	N = 30 ReCreate project, Finland, built in 1982, beams and columns	[16, 57]
Indoor	XC1	1	0,14	Återhus pilot, donor buildings from 1970s	[61, 62]
Ceramic tile covered façade elements	XC4	0,7	1,4	N = 27, buildings built 1948–1996	[24]
Parapet outer/inner	XC4	2,2	1,3/1,1	N = 160, normal distribution, 80% of samples	[24]
Slab panels soffitm Brick tile	XC3; XC4	3,1; 1,7	1,2; 2,3	N = 190, N = 48 normal distribution, 80% of samples	[24]
Exposed aggregate	XC4	1,59	0,24	N = 17, Built 1967–1969, C25/30	[63]
Balcony side panels	XC4	3,02	0,69	N = 4, Built 1967–1969, C25/30	[63]
Exposed aggregate; brushed painted; balcony soffits	XC4; XC4; XC3	2; 2,7; 3,08		N = 443 facades, N = 331 balconies, built 1965–1995, close fit to a normal distribution	[38]
Brick tile; painted; white concrete	XC4	1,06: 2,62; 0,59	1,31; 1,64; 0,7	Facades and balconies, 72 buildings, built 1990 or after	[39]
Slab upper/lower part	XC4; XC3	1,15; 3,21	0,9; 1,42	Facades and balconies, 72 buildings, built 1990 or after	[39]
Side panel, outer/inner	XC4; XC3	1,5; 1,63	1,02; 1,24	Facades and balconies, 72 buildings, built 1990 or after	[39]
Parapet, outer/inner	XC4; XC3	1,09; 1,48	1,13; 1,02	Facades and balconies, 72 buildings, built 1990 or after	[39]
Brushed and painted, exposed aggregate; balcony soffit slab; balcony side panels	XC4, XC4, XC3, XC3	2,2; 1,59; 2;55; 2,24	0,86; 0,9; 1,04; 0,71	18 buildings, built between 1969 and 1992, second assessment	[48]
Indoor with cover; unsheltered, sheltered	XC1; XC3; XC4	2,7 (> 35 MPa) 4,6 (25–35 MPa); 2,7 (> 35 MPa) 4,4 (25–35 MPa); 1,1 (> 35 MPa) 1,6 (25–35 MPa);		EN 16757 based on Lagerblad´s model	[64, 65]
Natural carbonation rates, excluding accelerated tests		3 (median), 4,08 (mean)	4,02	1999 literature measurements	[59]

Table 2 (continued)

Concrete Element	Exposure class	Mean k [mm/$\sqrt{\text{year}}$]	Std. dev., σ [mm/$\sqrt{\text{year}}$]	Details	References
Brushed painted, exposed aggregate, balcony soffit and side panels	XC3; XC4	2,55 (mean value), 1,4–3,24 (range of data)	1,33 (mean of σ); 0,84–2,01 (range of σ)	3542 measurements from database of 947 buildings, built between 1965–1995	[60, 66]

Table 3 Penetration of corrosion limits for crack formation in literature

Minimum reported value [μm]	Design value [μm]	Maximum reported value [μm]	Further details	References
22	50	200	P_{corr} with partial safety factor = 50/1.5 = 33.3 μm	fib MC 2020 and Bulletin 112 [25, 30]
22,2	67,5	119,1	Finnish climate	[66]
14,5	53,6	90,4	Range of values from evaluated samples	[67]
10	100		0,01–0,1 mm crack	[68]
	30		Value used for facades with protective coating	[69]
	50		Value for other elements not mentioned	[69]
	100		Value for ventilated cladding systems, where aesthetic relevance is not considered	[69]
15		50	Range of values for first visible crack (< 0.1 mm width)	[70]

for further studies. It should be noted that the estimation of post-repair propagation times (Table 5) relies on limited literature data, and corrosion rates involve considerable variability and uncertainty; these values should be interpreted as indicative rather than generalizable to all repair scenarios.

2.3 Effect of environment and exposure condition

Some studies examined the effect of surface treatments on carbonation using accelerated tests [76–78]. Carbonation depth measurements in buildings also indicate how concrete façade types and surface treatments affect carbonation [60]. However, differences in modeling, test setups, and limited data (only prior to reuse at the time of writing), make predictions in reuse scenarios complex. Carbonation may also be affected to some extent by changes in exposure and surface treatments between service lives. Nonetheless, the literature contains some useful approaches that can be used to relate the diffusion coefficient (or the carbonation rate k) to relative humidity and CO_2 concentration. The effect of relative humidity on CO_2 diffusion was evaluated in some models [79], but subsequent studies applied varying parameter values [80]. Due to such uncertainties, we relied on the more recent approach in the fib Model Code 34, using the environmental function k_e (-) calculated as:

$$k_e = \left(\frac{1 - \left(\frac{RH_{real}}{100} \right)^{f_e}}{1 - \left(\frac{RH_{ref}}{100} \right)^{f_e}} \right)^{g_e} \tag{7}$$

where RH_{real} is the relative humidity of the carbonated layer, RH_{ref} is the reference relative humidity (65%), and g_e (2,5) and f_e (5) are dimensionless constant parameters. In fib MC 34, the environmental function accounts for the effect of humidity on the diffusion coefficient, is included within the square root term of the carbonation depth equation, and is multiplied by other parameters [49].

Secondly, urban areas have higher atmospheric CO_2 levels than rural areas, with a proposed urban correction factor (k_{urban}) of 1,15 (dimensionless) [81]. Thirdly, many carbonation models assume the

Table 4 Corrosion rates for carbonation-induced corrosion in literature. Corrosion current values (i_{corr} in µA/cm^2) used for conversion to thickness loss rates in [µm/year] are indicated in brackets

Element type or exposure condition	Minimum corrosion rate [µm/year]	Average corrosion rate [µm/year]	Maximum corrosion rate value [µm/year]	Reference
Façade panels (inland), 2001–2002, monthly averages	0,575 (0,05)	9,66 (0,84) in 2001; 3,68 (0,32) in 2002	23,92 (2,08)	[37, 66]
Façade panels (coast), 2001–2002, monthly averages	1,265 (0,11)	7 (0,61) in 2001; 4,3 (0,37) in 2002	14,49 (1,26)	[37, 66]
Façade panels (inland), predicted from weather parameters 1979–2009		13,8 (1,2)		[37]
Façade panels (coast), predicted from weather parameters 1979–2009		19,55 (1,7)		[37]
Balcony soffits	0,115 (0,01)	0,805 (0,07)	1,84 (0,16)	[37, 66]
50% probability of literature data, i.e. 50 publications (1980–2016)	0,529 (0,046)		23 (2)	[73]
90% probability of literature data, i.e. 50 publications (1980–2016)	4,83 (0,42)		40,365 (3,51)	[73]
Range of all values	0,023 (0,002)		230 (20)	[73]
Average value of minimum or maximum	0,092 (0,008)		23 (2)	[73]
XC3, indoors	0,023 (0,002)		8,05 (0,7)	[73]
XC3, 60–75% RH	0,115 (0,01)		23 (2)	[73]
XC3, 80–90% RH	2,3 (0,2)		34,5 (3)	[73]
XC3, 95%-100% RH	0,23 (0,02)		44,85 (3,9)	[73]
XC4	1,15 (0,1)		34,5 (3)	[73]
XC3, XC4	0,345 (0,03)		33,35 (2,9)	[73]
RH 40–55%	0	0,3	4,7	[22]
RH 60–75%	0,096	1,9	21,9	[22]
RH 80–90%	0,15	5,1	34,4	[22]
RH 95–100%	0,17	6	39,6	[22]

Table 5 Corrosion rates after repairs based on literature [69, 75]

Element	Average yearly corrosion rate [µm/year]	Repair
Façade (baseline)	7	Silicate paint permeable to water and water–vapor
Façade 1	1,5	Silicon-based water-repellent but water vapor-permeable paint
Façade 2	1,4	Water-repellent primer and organic paint for coating substrate
Façade 3	1,7	Polymer-containing finishing mortar (2 mm) and organic paint
Balcony frame panels (baseline)	7	No repair (reference for comparison)
Balcony frame panels	4	Balcony glazing
Balcony slab (baseline)	2	No repair (reference for comparison)
Balcony slab	1	Balcony glazing
Balcony frame panels (baseline)	11	No repair (reference for comparison)
Balcony frame panels	5	Ventilated sheet cladding

diffusion coefficient (or diffusive flux) is directly proportional to CO_2 concentration (or concentration gradient) [80–82]. Accelerated tests are usually correlated with natural carbonation through this relationship, although empirical fitting factors are required [83]. Thus, modeling the impact of climate change on carbonation may be more straightforward, as it primarily involves changes in CO_2 concentration [80]. The following equation is used for determining a third influencing factor (k_{CO2}) on carbonation rate in the second service life:

$$\sqrt{k_{CO_2}} = \sqrt{\frac{C(CO_2\ second\ life)}{C(CO_2\ first\ life)}} \tag{8}$$

where $C(CO_2)$ is the concentration of ambient CO_2 (in kg/m^3), using a conversion factor of 1 ppm $= 0{,}0019 \times 10^{-3}$ kg CO_2/m^3 of air [81]. The Million Program in Sweden started in 1965 and ran for about a decade, during which around a million residential units were built using prefabrication and precast concrete [84]. These buildings offer significant potential for renovation, or reuse of their precast panels. For example, the rise in average atmospheric CO_2 from 320 ppm in 1965 to 422 ppm in 2024 [85], yields a k_{CO2} of 1,319. We tested whether carbonation rates from the first service life, together with environmental parameters, can be used to approximate the carbonation rate under changed exposure conditions in the second life, proposing the following equation:

$$k_2 = \sqrt{k_e \times k_{urban} \times k_{CO_2}} \times k_1 \tag{9}$$

where k_2 is the carbonation rate (in mm/$\sqrt{}$year) in the second life/exposure, and k_1 in the first life/exposure.

2.4 Case studies

Service life predictions were investigated in two case studies, using donor buildings in the ReCreate project [15]. The Swedish donor is a residential building from 1965 featuring a cross-wall structure with load-bearing precast walls and slabs [10]. The Finnish donor is an office building from 1982, featuring a skeletal frame with precast columns and beams, hollow core slabs, and facade sandwich concrete panels with insulation [57]. The production of precast concrete in Sweden is considered to have been sufficiently reliable during the Million Program [84]; Concrete covers in the assessed structure in Drottninghhög area in Helsingborg, were found to be within 10 mm standard deviation with Ground Penetrating Radar (GPR) measurements, and within the values found in drawings of 22,5 mm [10]. Återhus reuse pilot projects in the Stockholm region reported comparable concrete covers in the range 22–24 mm [61, 62]. Therefore, we assumed a constant/deterministic value of the concrete cover for assessing the Swedish case in Sect. 4.4.1. However, in Finland, the concrete cover of precast facades and indoor elements in the case study were found to have greater variation (See Appendix). For the Finnish case, parametric analyses were carried out using a set of fixed cover depths (10, 20, 30, 40 mm), corresponding to minimum values from standards. These values were not sampled probabilistically but kept constant within each scenario of remaining service life prediction in Sect. 4.4.2, i.e., based on average carbonation depth ($d_{k\ mean}$) and maximum depth ($d_{k\ max}$) (see EN 14630:2006), and conservative assessment considering increased k in the second service life of 1 mm/$\sqrt{}$year (Återhus project in Sweden, indoor concrete in XC1), and 2,55 mm/$\sqrt{}$year (outdoor average rate in Nordic climate, and in XC3, see Tables 2 and 6).

2.5 Monte Carlo simulation

The principle Monte Carlo (MC) method is that, by running a sufficiently large number of simulations with randomly generated input parameters, the probability distribution of an outcome can be estimated based on the frequency of its occurrence [86]. Simulations are performed using a Python script with a sampling number of 10,000 to estimate the probabilistic distribution of total service life.

Initiation and propagation times are treated as probabilistic variables to capture the variability and uncertainty in material properties and exposure conditions. MC simulation integrates these two different distributions into a probabilistic assessment of the total service life. This is not explicitly addressed in literature or current/previous fib Model Codes, where initiation and propagation phases are treated separately. This integration represents one of the novel contributions of the present study.

Initiation time is modelled using a normal distribution, in line with fib Model Code 34 and fib Bulletin

Table 6 Monte Carlo simulation parameters

Parameter	Mean	Std. Dev. (σ) of carbonation rate (k)	COV [%] for V_{corr}	Unit	Distribution	Reference
Concrete Cover	22,5	–	–	mm	Constant	Million Program buildings in Dröttninghög area in Helsingborg, Återhus pilots in Stockholm region [10, 62]
Carbonation rate in XC3	2,55	1	–	mm/$\sqrt{}$year	Normal	Table 2, median in XC3 exposures in [38, 48], mean of outdoor exposures in Nordic climate
Carbonation rate in XC4	1,6	0,9	–	mm/$\sqrt{}$year	Normal	Recurrent value in several studies in Table 2 in XC4, EN 16757 value for XC4
Corrosion rate in XC1	0	–		µm/year	Deterministic	fib Bulletin 112 [30]
Corrosion rate in XC2	4	–	150	µm/year	Weibull	fib Bulletin 112 [30]
Corrosion rate in XC3	2	–	150	µm/year	Weibull	fib Bulletin 112 [30]
Corrosion rate in XC4	5	–	175	µm/year	Weibull	fib Bulletin 112 [30]
Corrosion rate in XC4 with repair ~ XC3	1,5	–	150	µm/year	Weibull	Table 5 and fib Bulletin 112 for probability distribution [30]
Penetration of corrosion limit (P_{corr})	67,5	–		µm	Constant	[66]

112 [30, 49]. This distribution was also found to provide a good fit to empirical data, covering 95% of the observed vales for concrete facades in the Finnish climate [38]. In the case of carbonation rate in XC4 in Table 6, it would lead to a small percentage of very low or negative values, leading to very long initiation times. However, using log-normal distribution would eliminate negative values but also shift the distribution and overestimate the number of higher carbonation rates [38].

Propagation time is modelled using a Weibull distribution following fib Bulletin 112 [30], with further details in Table 6. The selected carbonation and corrosion rates were chosen for their broader relevance beyond the evaluated case studies, reflecting a larger number of buildings from measured and literature data, exposures and surface types.

A constant (fixed deterministic value) for cover depth of 22.5 mm was assumed (Table 6). This simplification was made as: (1) it aligns with covers for historic precast concrete elements in Sweden from the Million Program, and (2) covers depths below 20 mm would not satisfy durability requirements based on the parametric analysis presented later in Sect. 4.1, and would not be permitted by prescriptive rules in EN 1992-1-1:2023, which would require at least 20 mm covers for XC1, XC3 and XC4 exposures. Although actual measured covers in the Finnish case (Fig. 11) showed variability, the chosen value is considered representative and conservative for the analysis.

Figure 2 illustrates the possible service life scenarios based on different carbonation and corrosion rates (further discussed in the results and discussion sections). In the context of Fig. 2, the start point of reuse (second life) is defined as the moment when a building—or parts of it—are selected for deconstruction and reused, which may occur before or after the typical 50 years of designed service life. The reuse potential depends on the condition of the elements at the end of their first life (i.e., carbonation depth, corrosion state), as well as on exposure conditions in the second life. In the MC simulation, total service life results will be presented in 50-year intervals: the first 50 years correspond to the first life (donor building), after which, elements transition into a second (reuse) service life, meaning that achieving a 100 year total service life corresponds to two service lives (i.e. first service life and the subsequent reuse life).

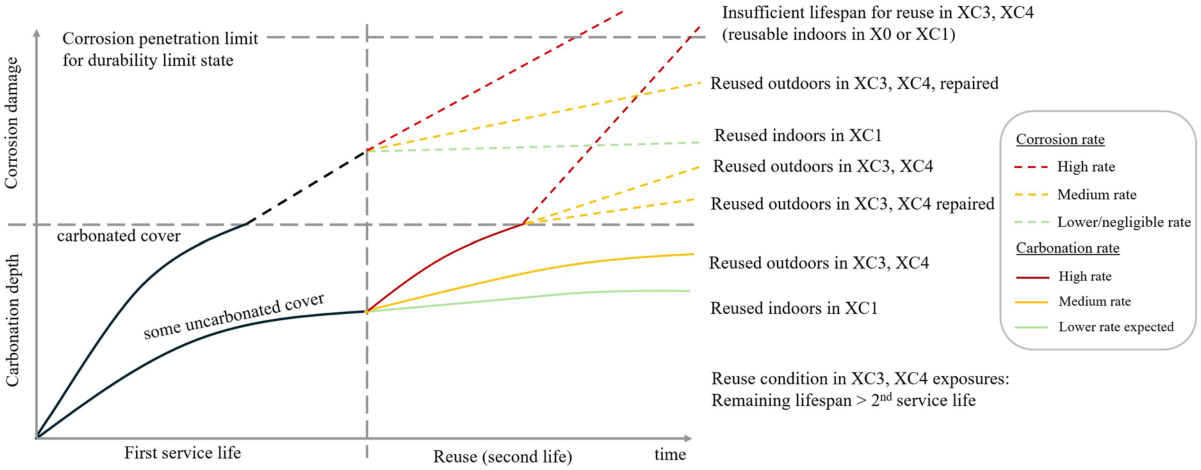

Fig. 2 Service life scenarios considering two life cycles, and carbonation and corrosion across exposures

3 Results

This section presents a parametric assessment of initiation and propagation times of carbonation-induced corrosion in concrete, effects of storage and exposure conditions on carbonation depth, remaining service life across two case studies, and probabilistic assessment of total service life via MC simulations, including the impact of repair strategies on extending service life. Results presented in Sects. 3.1 through 3.4 are deterministic.

3.1 Initiation phase

Figure 3 illustrates the remaining initiation times based on expected carbonation rates in buildings (ranging from 1 to 6 mm/$\sqrt{}$year; see Table 2). Part (a) shows the remaining service life as a function of the carbonation rate after 50 years of first service life, calculated using Eq. (3). Parts (c), (b), and (d) show the remaining service life of reused concrete elements in their second life calculated using Eq. (4), as a function of the carbonation rate and initial carbonation depths of 5 mm, 10 mm, and 15 mm, carried over from the first service life. To show the influence of the propagation phase on the service life, error bars indicate an assumed propagation time of 50 years. This reflects a conservative scenario for outdoor reuse in sheltered conditions (XC3), based on fib's expected corrosion rate with a corrosion penetration limit of 100 µm [30, 68]. Comparable minimum propagation times—such as 45 years for XC3—are also found in Portuguese codes [77].

Concrete elements with covers of 10 mm are generally insufficient for ensuring another 50 years of service life, even with the inclusion of the propagation time, except under low carbonation rates (≤ 1 mm/$\sqrt{}$year) mostly found in concretes with surface treatments, such as tiles or white concrete in XC4 (Fig. 3a and Table 2). Negative values in Fig. 3 represent the estimated number of years that have passed since the carbonation front reached the reinforcement. In Fig. 3c, for carbonation depths up to 5 mm, propagation time could suffice for 50 years, though some elements may show the first cracks during the reuse life, requiring repairs.

As carbonation depth can be assumed to be proportional to the square root of time, a 20 mm cover will be sufficient for reuse, for carbonation rates up to 2 mm/$\sqrt{}$year, 30 mm covers for rates up to 3 mm/$\sqrt{}$year, and so forth. While the propagation phase extends the service life, it is not always sufficient for achieving 50 years (Fig. 3a). However, part (b), (c) and (d) of Fig. 3 show that when carbonation depth is known (e.g. depth measurements before reuse), propagation time can sometimes allow for reaching 50, or even 100 years of total service life, compared to results in Fig. 3a (e.g. from old carbonation depth data or modeling assumption).

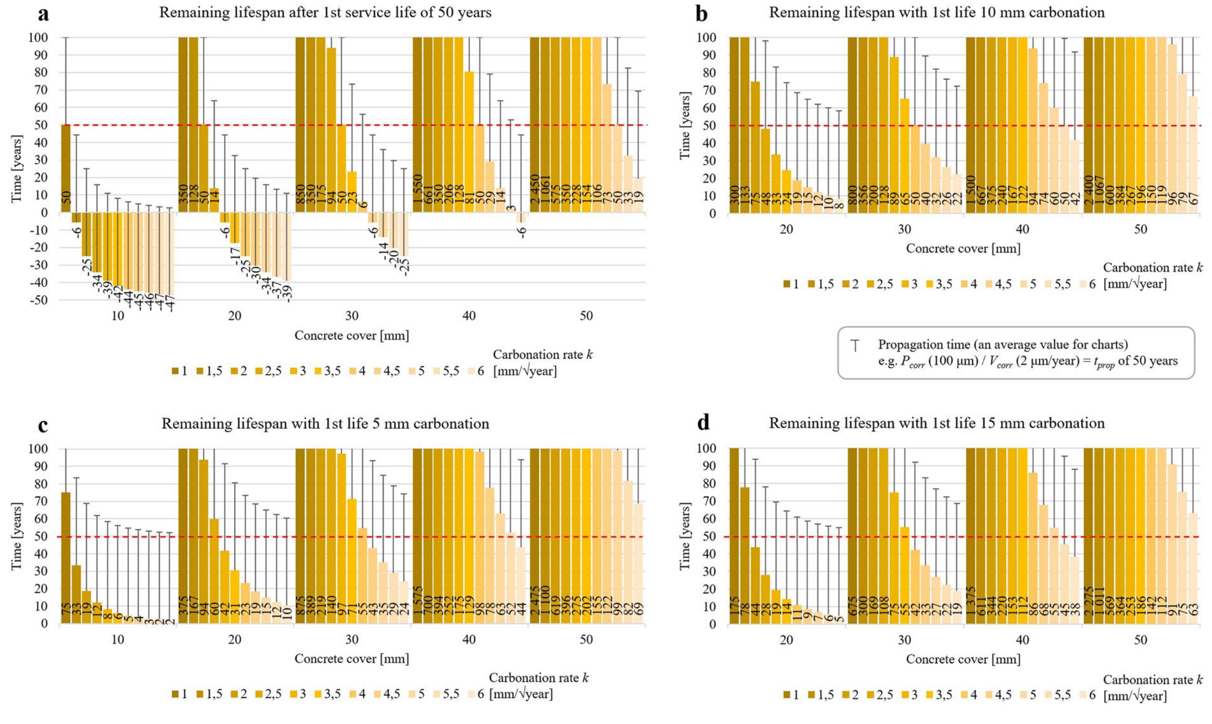

Fig. 3 Remaining initiation time for carbonation-induced corrosion, after 50 years of first service life in part **a**, and scenarios of carbonated depths of 5, 10 and 15 mm in parts **c**, **b**, and **d**, respectively

3.2 Influence of storage period on carbonation

The parametric analysis applies the same range of carbonation rates (1 to 6 mm/√year) expected in buildings to storage conditions as well, covering both sheltered and unsheltered exposure after the first service life or from a known carbonation depth.

Carbonation progresses faster in the early years of service life, having more effect on new/uncarbonated elements, as shown in Fig. 4a; The longer the storage period and/or higher carbonation rate, the greater the advance of the carbonation front, as indicated for depths of 5, 10, and 15 mm, potentially impacting service life. This is especially relevant for elements lacking surface treatments that could slow down carbonation. Removing surface treatments or cementitious grouts during deconstruction, or alternatively preserving them, will influence carbonation during storage.

In Fig. 4b, storage after 50 years appears to influence little carbonation depth by less than 5 mm, even for durations of up to 10 years or increased carbonation rates such as due to environmental factors. For elements with a known carbonation depth (e.g. 10 mm, Fig. 4c), storage has noticeable effects for longer periods (> 5 years) and higher rates (> 3.5 mm/√year); Carbonation depths of 10 or 15 mm may still provide sufficient service life, depending on carbonation rate and concrete cover (see Fig. 3). In cases of direct reuse after 50 years (Fig. 4d), carbonation during a second 50 year life accounts for roughly 29% of the total depth, (assuming same *k*). When including storage before reuse (Fig. 4e), total depth increased by up to 1%, and storage contributes 0.7% (1 year storage), 2.1% (3 years), 3.4% (5 years), and 6.4% (10 years) of total, with the second life then representing 26–29% of the total depth depending on storage duration. Figure 4f compares storage depths between two cases, part (c) and (b) in Fig. 4, showing that both modeling approach and carbonation rates impact carbonation depth. The carbonation rate and its change could be observed by performing depth tests at the start of storage and after 1 or a few years within this period, or non-destructively through correlations with air-permeability tests [87].

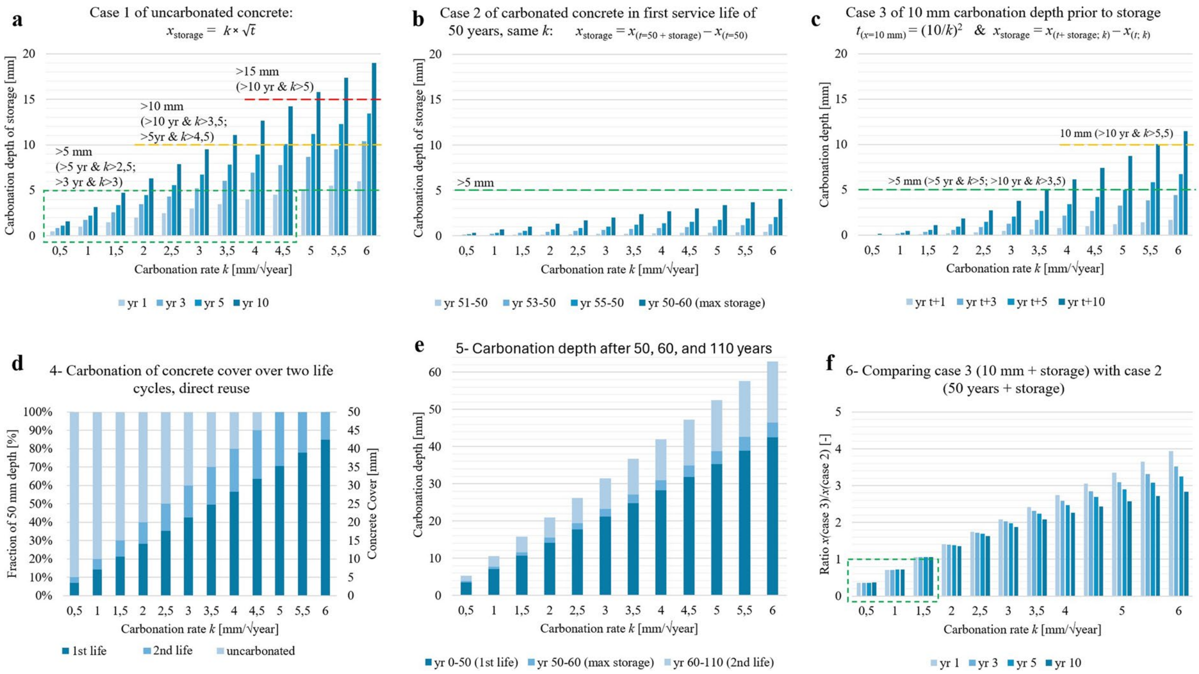

Fig. 4 Effect of the storage duration before reuse on carbonation depth. The same carbonation rate is assumed for both first and second service life

Even at similar starting depths, concretes may carbonate differently depending on material properties, age, and storage conditions compared to the previous exposure. As such, maintaining a digital record, by tracing an element's history using data carriers for circular construction, can support monitoring its condition and reuse suitability [15, 40, 42, 88].

3.3 Propagation phase

Figure 5a presents propagation times based on the median corrosion rates from a recent review on steel corrosion in carbonated concrete, and from façade and balcony data in a Finnish coastal and inland climate [22, 37]. Propagation times exceed 50 and 100 years at lower relative humidity but drop significantly to decades or even a few years under high humidity. Balcony soffits, sheltered from direct contact with water, exhibit longer propagation times (over 27 years) compared to facades exposed to wind-driven rain (under 10 years in severe cases). The time to cracking is also affected by the corrosion limit assumed.

Figure 5b provides propagation times based on upper and lower bounds of corrosion rates for Portland cement concretes, various w/b ratios and environmental conditions. Environmental conditions with higher humidity, and having higher corrosion rates, result in reduced propagation time. Even within similar environments, the range of results for lower and upper bounds of corrosion rates show large variability, from a few years, to decades, or very long service lives.

Corrosion can lead to visible cracks in concrete, but these early cracks usually do not influence the structural capacity of the elements and are often viewed as an aesthetic issue [89, 90]. However, even small cracks can reduce service life, during initiation or propagation phases, by allowing CO_2 or aggressive substances to penetrate, leading to increased carbonation depths and/or steel loss section at crack locations [91, 91, 91]. If some level of cracking is acceptable, spalling may occur with cracks up to 3 mm [90]. However, the significance of cracking and corrosion also depends on its location, whether it affects load-bearing zones (and loss of strength) [89]. Time for cracks to appear ranged between 5.7 and 37.5 years in façades in Finnish climate conditions, depending on the geographical location [39]. In colder climates (at

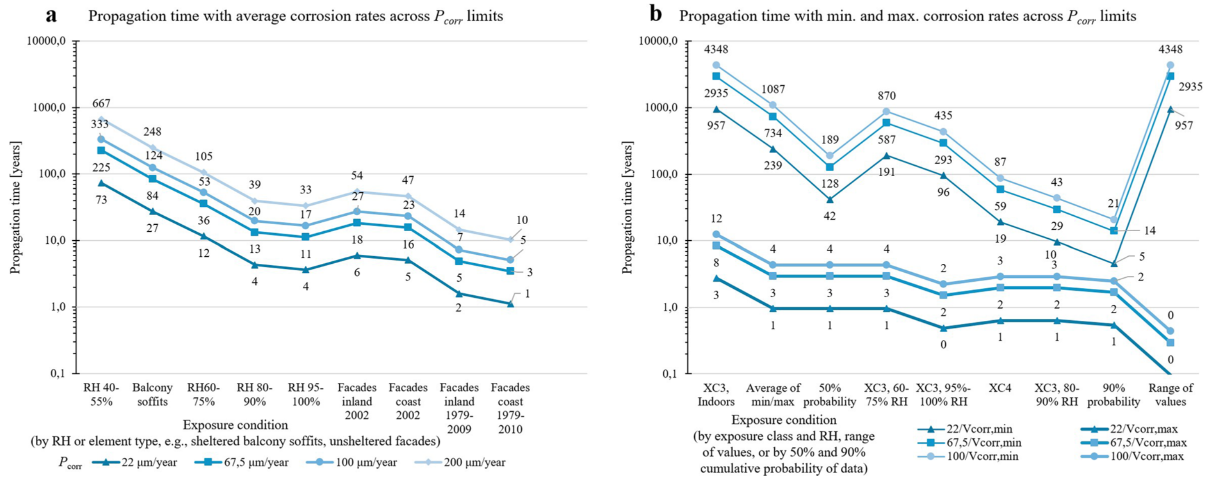

Fig. 5 Propagation times based on corrosion rates from literature: average values from [22, 37] in part **a**, and minimum/maximum values from [73] in part **b**, shown across different corrosion penetration limits (P_{corr})

higher latitudes), propagation times tend to be longer due to the smaller amount of wind-driven rain [66].

In the context of reuse, the structural acceptability of cracks depends on their width, location, and whether they compromise durability or structural capacity. For instance, elements with minor surface cracks (< 0,3 mm) may be reused if durability can be ensured through surface treatments or if the exposure conditions in the second life are less severe. Clear documentation of crack patterns and repair history becomes critical in assessing reuse, for evaluating structural reliability and remaining service life.

3.4 Remaining service life in evaluated buildings

This section presents the estimated remaining service life and reuse potential of two different, typical precast concrete structures: a Swedish residential building and a Finnish office building.

3.4.1 Swedish residential building from the million program

The remaining initiation time for the Swedish case study is presented in Table 7. Precast concrete elements are grouped by their exposure class, indicating elements with one side indoors or outdoors. Most elements (75%) are located indoors in XC1 conditions. Outdoor walls with an indoor-facing side account for 7% of elements, while 13% of slabs have one side exposed to the outdoor environment. Additionally, 5% of precast slabs are outdoors.

Remaining initiation time after the first service life (60 years) is calculated for the mean carbonation rate, and within one and two standard deviations, covering approximately 68% and 95% of the data, respectively. Based on the mean carbonation rates, a remaining service life of more than 50 years can be expected for all types of elements. Longer service lives are possible for elements with lower carbonation rates, due to prior surface treatments or unsheltered conditions, where rain exposure may have slowed down the diffusion process during certain periods of the year. The shortest average initiation time occurs in sheltered outdoor walls (40,9 years), but adding an average propagation time (e.g. 25 years based on fib Bulletin 112 values for P_{corr} and V_{corr} in XC3) can help achieve beyond 50 years of remaining service life. However, calculations within one and two standard deviations suggest a few years or a couple of decades for outdoor elements, and some cases with carbonated covers within the first service life. As such, probabilistic assessment of service life could provide a more robust understanding and data-driven assessment of reuse potential.

Carbonation depths and uncarbonated covers from the first service life (shown in Table 7), are used in Eq. (4) to predict remaining initiation time under assumed changes in carbonation rates due to altered environmental exposure in the second life. For each

Table 7 Remaining initiation time for carbonation in concrete in evaluated case

Type of element	Exposure class	Count	Fraction of total [%]	Carbonation rate k [mm/$\sqrt{\text{year}}$]	Standard deviation σ	Concrete Cover c [mm]	Carbonation depth x_1 [mm]	Uncarbonated cover after 1st life [mm]	Fraction of uncarbonated depth to concrete cover (1st life)	Remaining initiation time (Mean + 2σ) [years], Eq. (3)	Remaining initiation time (Mean + 1σ) [years], Eq. (3)	Remaining initiation time (Mean) [years], Eq. (3)	Remaining initiation time, both sides i.e. outdoor/indoor (Mean) [years]	Remaining initiation time, both sides i.e. outdoor/indoor (Mean + 2σ) [years]	Remaining initiation time, higher $k = 2{,}55$ scenario e.g. reuse in XC3, Eq. (4)	Remaining initiation time, medium $k = 1{,}6$ scenario e.g. reuse in XC4, Eq. (4)
Total precast concrete walls		**198**	**44%**													
Outdoor walls brick tile cover, with an indoor side	XC1 & XC4	12	3%	1,6	0,9	22,5	12,4	10,1	45%	− 13,2	21,0	137,8	138/292	− 13/201	54,2	137,8
Outdoor walls sheltered, with an indoor side	XC1 & XC3	18	4%	2,24	0,7	22,5	17,4	5,1	23%	− 18,8	− 1,4	40,9	41/292	− 19/201	31,6	80,2
Indoor walls	XC1	168	37%	1	0,2	22,5	7,7	14,8	66%	201,3	291,6	446,3	292/292	201/201	68,6	174,3
Total precast concrete slabs		**252**	**56%**													
Outdoor roof slabs protected, with an indoor side	XC4 & XC1	57	13%	0,7	1,4	30	5,4	24,6	82%	16,5	144,1	1776,7	1777/840	16.5/168	133,9	340,1
Outdoor roof slabs protected, with a soffit side	XC4 & XC3	6	1%	2,55	1	30	19,8	10,2	34%	− 13,5	11,4	78,4	1777/78	16,5/− 13	78,4	199,2

Table 7 (continued)

Type of element	Exposure class	Count	Fraction of total [%]	Carbonation rate k [mm/$\sqrt{}$year]	Standard deviation σ	Concrete Cover c [mm]	Carbonation depth x_1 [mm]	Uncarbonated cover after 1st life [mm]	Fraction of uncarbonated depth to concrete cover (1st life)	Remaining initiation time (Mean + 2σ) [years], Eq. (3)	Remaining initiation time (Mean + 1σ) [years], Eq. (3)	Remaining initiation time (Mean) [years], Eq. (3)	Remaining initiation time, both sides i.e. outdoor/indoor (Mean) [years]	Remaining initiation time, both sides i.e. outdoor/indoor (Mean + 2σ) [years]	Remaining initiation time, higher $k = 2{,}55$ scenario e.g. reuse in XC3, Eq. (4)	Remaining initiation time, medium $k = 1{,}6$ scenario e.g. reuse in XC4, Eq. (4)
Outdoor slabs with tiles, soffit side	XC3	12	3%	2,55	1	30	19,8	10,2	34%	− 13,5	11,4	78,4	1777/78	16,5/− 13	78,4	199,2
Indoor slabs with parquet/paint sides	XC1	114	25%	1	0,5	30	7,7	22,3	74%	168,0	340,0	840,0	Unaffected/840	Unaffected/168	129,2	328,1
Indoor slabs with parquet/ground protected sides	XC1	57	13%	0,8	0,5	30	6,2	23,8	79%	220,8	472,5	1346,3	Unaffected/1346	Unaffected/221	132,5	336,6
Outdoor slabs tiles/ground protected sides	XC3	6	1%	0,8	0,5	30	6,2	23,8	79%	220,8	472,5	1346,3	1777/1346	221/16,5	132,5	336,6

The bold is used to highlight the partial sums and percentages for precast walls and slabs element type, two scenarios are calculated, where carbonation rates tend towards the higher expected rate in XC3 ($k = 2{,}55$) or towards the carbonation rate in XC4 ($k = 1{,}6$). In case of increased carbonation rates in the second life, calculations can be considered conservative as the contribution of the new diffusion process will require some time before affecting the carbonation rate. Calculated results also suggest that remaining initiation time can be extended significantly depending on environmental conditions and/or by slowing down carbonation through surface treatments.

Reuse potential in terms of service life would increase by locating outdoors the side of the precast element with less carbonation depth, such as the indoor sides. However, careful consideration should be made for reusing indoor elements outdoors, whether (a) freeze–thaw durability is required in the local climate and (b) if the concrete has protective pore system. Indoor concrete constitutes most elements in a Swedish cross-wall precast concrete structure, with potentially longer remaining initiation times and greater reuse potential compared to outdoor elements. Visual inspection of reclaimed indoor precast walls and slabs for the Swedish H22 pavilion showed no visible cracks. However, cored specimens for strength and carbonation tests were checked with polarized light and UV light under a microscope. The concrete contained a small portion of air pores less than 0,3 mm, consisting of natural entrapped air in the pore structure. Frost durability depends not only on pore size but also on the distribution and spacing of entrained air voids, typically 0,01–0,3 mm in diameter (from EN 206) with a spacing factor below 0,2 mm [50, 94]. The recommended spacing factor can vary between countries. In Finland, the equivalent spacing factor should be within the range of 0,23 mm to 0,30 mm, depending on both water-cement ratio and the XF exposure class [95]. However, even non-air-entrained concrete takes years before visible cracking appears, around 22 years in the southern coastal areas and 24 years inland, in Finland [60].

3.4.2 *Finnish case and remaining service life including propagation time*

Remaining service life predictions, inclusive of propagation time for Swedish and Finnish cases are given in Fig. 6. For the Swedish case (Fig. 6a), estimations focus on outdoor elements, which have shorter lifespans than indoor elements (see Table 7) and may lack sufficient reuse service life if only initiation time is considered. Based on average data, initiation time dominates the service life for both walls and slabs (> 55% of total service life). The relative share of propagation time increases when: (1) initiation time is reduced, and (2) in sheltered conditions, in which the corrosion propagation phase contributes to achieving a sufficient reuse lifespan for walls in XC3 (> 50 years) and slabs in XC3 (> 100 years).

Due to variability in measured concrete covers in the Finnish case, results are presented in Fig. 6b for minimum cover depths of 10, 20, 30 and 40 mm. Given the low carbonation rates observed in indoor elements, service lives of 50 or 100 years are achievable even with a concrete cover as low as 10 mm. Full service life calculations in Fig. 6b presents scenarios with carbonation rates based on: (a) mean carbonation

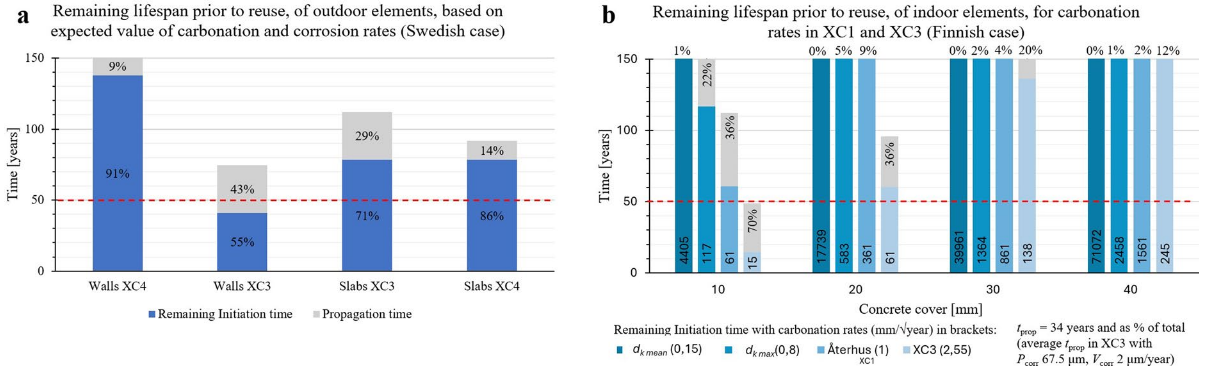

Fig. 6 Remaining service life of Swedish and Finnish cases

depth ($d_{k\ \mathrm{mean}}$), (b) maximum depth ($d_{k\ \mathrm{max}}$) as per EN 14630:2006 [96], (c) increased indoor rate in the second life (1 mm/$\sqrt{}$year, comparable to the Återhus project) [61, 62], and (d) reuse outdoors with average outdoor rate in a Nordic climate ($k = 2{,}55$ mm/$\sqrt{}$year) [60, 66]. Given the high concrete quality and carbonation resistance of concrete in this building, the carbonation rate may not be expected to increase substantially in the reuse life or exceed the average in a Nordic climate, highlighting the high reuse potential of indoor concrete elements. Of the 501 precast structural elements, 27% are wall and façade panels, while 73% are indoor elements, comprising 23% columns, 12% beams, and 38% hollow core slabs. Additionally, future studies are needed to investigate and measure the changes in carbonation depth, rate and diffusion process in adaptive reuse of concrete structures or reused concrete elements. For façade elements, the reuse potential may be limited due to (1) insufficient insulation of sandwich panels to meet current energy codes, (2) insufficient freeze–thaw resistance of reclaimed elements.

3.4.3 *Carbonation rates in the second service life*

The change in carbonation rates is explored through the scenarios presented in Table 8. Scenarios represent changes in environmental exposure after reuse, with humidity being a key factor affecting carbonation depth [97, 98], while also accounting for the gradual increase in CO_2 concentrations over time and in densifying urban environments in Nordic countries. For the Swedish 1960s buildings, the analysis in Table 8 varies only the exposure factor k_e for second-life conditions, while k_urban and k_{CO2}, are held constant.

Recurrent values of k_1 (carbonation rate in first life) are selected from Table 2. In Northern-European climates, the highest carbonation depth and rate is expected for outdoor sheltered concrete at 60%–65% RH [99]. In the tested scenarios, relative humidity for XC3 was assumed to be around 65% (same as the RH_{ref} in fib MC 34), with higher RH values expected in unsheltered conditions (XC4). The results in Table 8 indicate that it may be possible to expect changes in carbonation rates towards comparable values measured in buildings for the new exposures in the second service life. The proposed Eq. (9) can be validated in future work using condition assessments from concrete reuse projects, and applying any necessary corrections for the influence of RH on k_e. In Scenario 6 (Table 8), values in brackets show results considering only one factor, k_e, as factors like outdoor CO_2 concentration may have less influence for indoor reuse, indicating some reduction in carbonation rate.

A parametric analysis of k_e values is shown in Fig. 7. According to fib MC 34 [49], Eq. (7) yields $k_e > 1$ for $RH_{real} < 65\%$. However, when outdoor concrete is reused indoors, where RH typically ranges from 30 to 60%, lower carbonation rates (and $k_e < 1$) would be expected. To reflect this, the modified Eq. (7) used in Fig. 7a reverses the positions of RH_{real} and RH_{ref}. This formulation produces $k_e < 1$ when second life exposure (RH_{real}) is lower than 65% (reference RH_{ref}, first life exposure)—e.g. reuse from XC3/XC4 to XC1. It would also yield a k_e slightly above 1 in cases of RH_{ref} lower than a RH_{real} of 65% (e.g. reuse from XC1 to XC3).

Table 8 Change in carbonation rate from first (k_1) to second service life (k_2), based on three factors for: relative humidity (k_e), ambient CO_2 concentration (k_{CO2}), and increased CO_2 levels in urbanizing environments (k_{urban})

Scenario	RH_{ref}	RH_{real}	Environmental function k_e [-]	$\sqrt{k_{CO2}} \times \sqrt{k_{urban}} \times \sqrt{k_e}$ from Eq. (9) [-]	k_1 [mm/$\sqrt{}$year]	k_2 [mm/$\sqrt{}$year]
1 (From XC3 to XC4)	0,65	0,86	0,2778	0,65	2,55	1,65
2 (From XC4 to XC3)	0,78	0,65	1,722	1,62	1,6	2,58
3 (From XC4 to XC3)	0,78	0,65	1,722	1,62	1	1,62
4 (From XC4 to XC3)	0,87	0,65	4,123	2,5	1	2,5
5 (From XC1 to XC3) with modified Eq. (7) as in Fig. 7a	0,3	0,65	1,352	1,43	1,6	2,29
6 (From XC3 to XC1) with modified Eq. (7) as in Fig. 7a	0,65	0,3	0,739	1,06 (0,86)	1,6	1,69 (1,38)

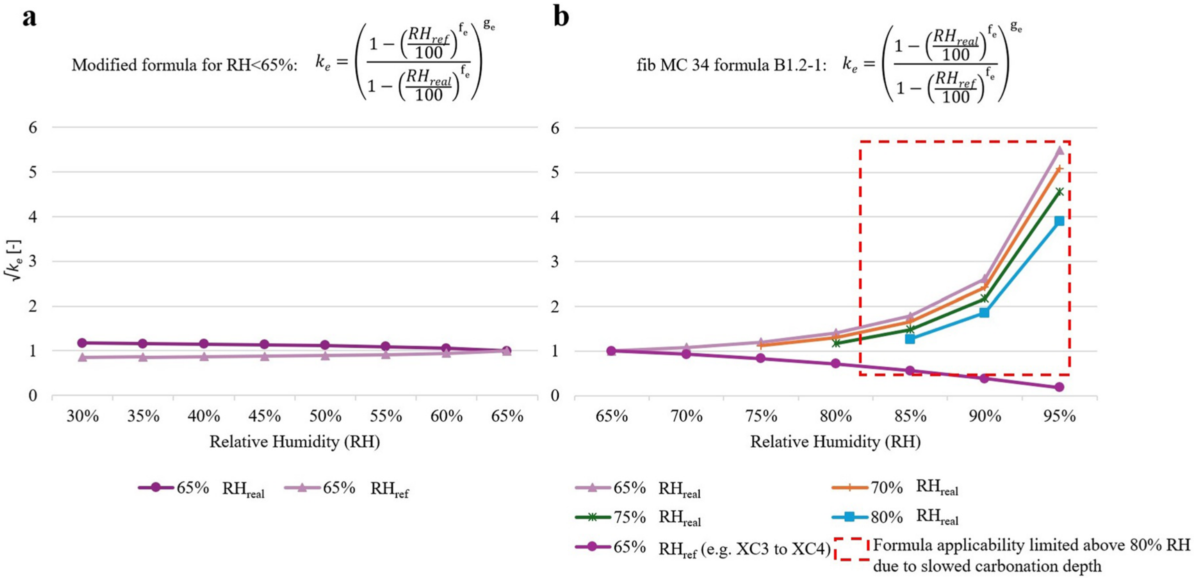

Fig. 7 Square root of k_e (-) with constant or changing RH, RH_{real} (second life exposure, reuse) or RH_{ref} (previous service life exposure, i.e. reference exposure in fib MC 34)

Weather data can be used for determining k_e; fib MC 34 recommends using mean daily values and suggests that mean yearly values could be sufficient [49]. For instance, the average yearly RH of the most recent weather files for Tampere (FIN_TR_Tampere.Satakunnankatu.027440_TMYx) is 78,6%, and for Helsingborg (SWE_SN_Helsingborg.026110_TMYx) is 82,1%. These average yearly values are relatively close to the selected and tested RH values in unsheltered exposures (XC4) in Table 8.

The red dashed-line rectangle in Fig. 7b indicates conditions where the applied k_e function may be unreliable; this is because carbonation depth increases first with an increase in RH, and then decreases above 80% RH [97, 98]. Future experimental are needed to validate the k_e equation, and any refinements to account for exposure and humidity effects from climate and microclimate conditions. Lastly, climate change is expected to increase atmospheric CO_2, which could raise carbonation rates by approximately 17.0% by 2050 and 48.2% by 2100 [39]; however, increased rain and sleet may counteract this effect, reducing carbonation by 5.7% and 15.4% over the same periods.

3.5 Probabilistic service life assessment

Section 3.5.1 describes the probabilistic modelling of carbonation and corrosion rates, followed in Sect. 3.5.2 that presents the probabilistic total service life assessment.

3.5.1 *Probabilities of initiation and propagation times*

Figure 8a shows the probability distribution of carbonation rates representative of a larger group of buildings and outdoor exposures (see Tables 2 and 6). The secondary axis indicates initiation time for a typical concrete cover assumed for precast concrete elements in Sweden; carbonation rates are modelled with a normal distribution, defined by their mean value (μ) and standard deviation (σ). Figure 8b shows the probability distribution of corrosion rates for carbonation-induced corrosion, modelled with a Weibull distribution and characterized by the shape factor (α) and scale factor (β); the secondary axis shows the propagation time calculated with Eq. (6). As fib Bulletin 112 does not specify Weibull parameters, these were derived from mean corrosion rates and COVs in Table 6, using approximation methods and Weibull lookup tables in literature [100, 101].

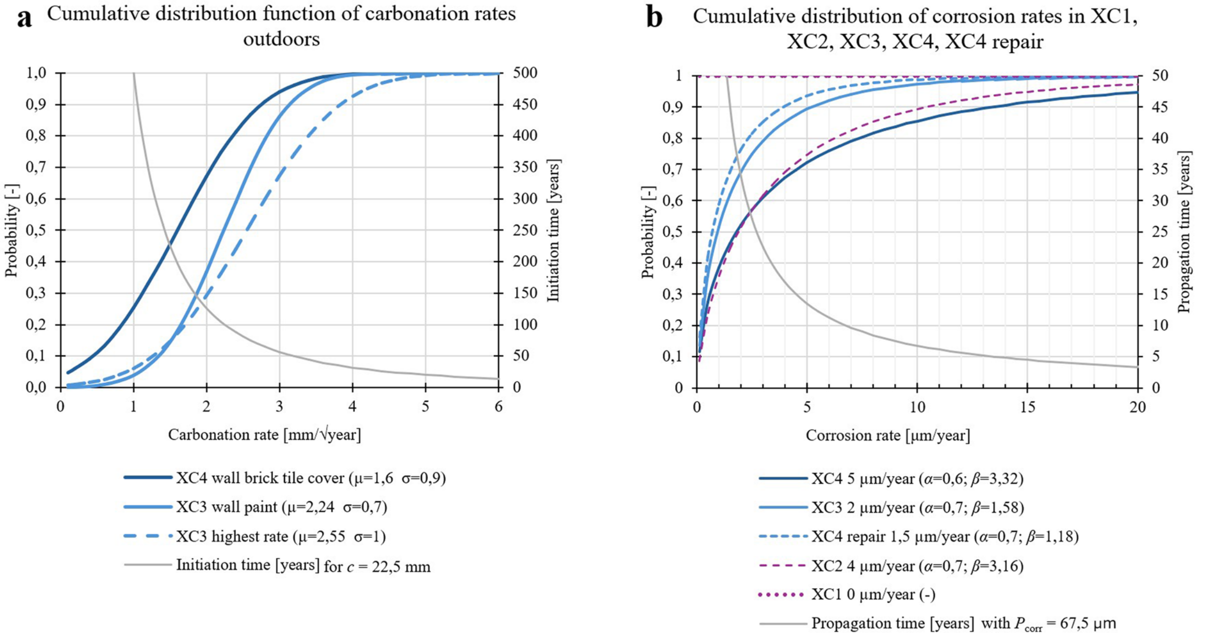

Fig. 8 Cumulative probability distributions of **a** carbonation rates, and **b** corrosion rates from fib Bulleting 112 and post-repair conditions (Weibull mean, shape, and scale factors for each exposure)

3.5.2 Total service life probabilities

Total service life probabilities for outdoor concrete exposures are presented in Fig. 9.e., total initiation time combined with propagation time using Eq. (1). A small probability of reaching the end of service life (i.e. only the durability limit state) is expected for less than 5% of outdoor concrete elements (0,6% for XC4 in Fig. 9 and 2,9% in XC3 in Fig. 9c). In the case that unsheltered concrete elements were to be treated with water-repellent paints (Fig. 9b), the failure probability in the first service life (< 50 years bin) is minimized, and failure probability is reduced by 55% in the second service life (i.e. 50–100 years histogram bin, i.e. from 8,9% to 4%), highlighting the effectiveness of surface treatments on extending service life. The case of Fig. 9b could be considered as XC4 with reconditioning or repair for reuse of structural concrete, or as equivalent to reuse in sheltered XC3 conditions, since surface treatments reduce water exposure; Additionally, similar corrosion rates between "XC4 with repair" and "XC3", support this consideration (see Tables 5 and 6). The case in Fig. 9a could also be considered a very conservative assessment of reusing indoor concrete (XC1) in outdoor conditions (XC3 or XC4), as carbonation rates indoors were usually within 1 mm/$\sqrt{}$year (see Table 2). Further, Fig. 9c can also be considered representative of most conditions of concrete facades in the Finnish or Nordic climates (see Tables 2 and 6).

In all cases shown in Fig. 9, the frequency of concrete elements with lifespans exceeding than 100 or 150 years decreases slightly with each additional 50-year bin. This leads to a fraction of probabilistic results with lifespans over 1000 years, which are grouped into the overflow bin in each histogram. Consequently, parts (a), (b), and (c) of Fig. 9 display a sharp increase in the cumulative percentage polyline at its end, a feature that is absent in part (d), where the cumulative distribution is shown without binning. Table 9 presents lifespan percentiles from the cumulative probabilities of Fig. 9d. Acceptable probability limits for performance-based assessments to ensure service life will depend on the thresholds (target failure probability or level or reliability) set in standards or national regulations. For instance, a 10% acceptance for depassivation was applied in Norway for its "deemed to satisfy" criteria and other thresholds were being considered in other European countries

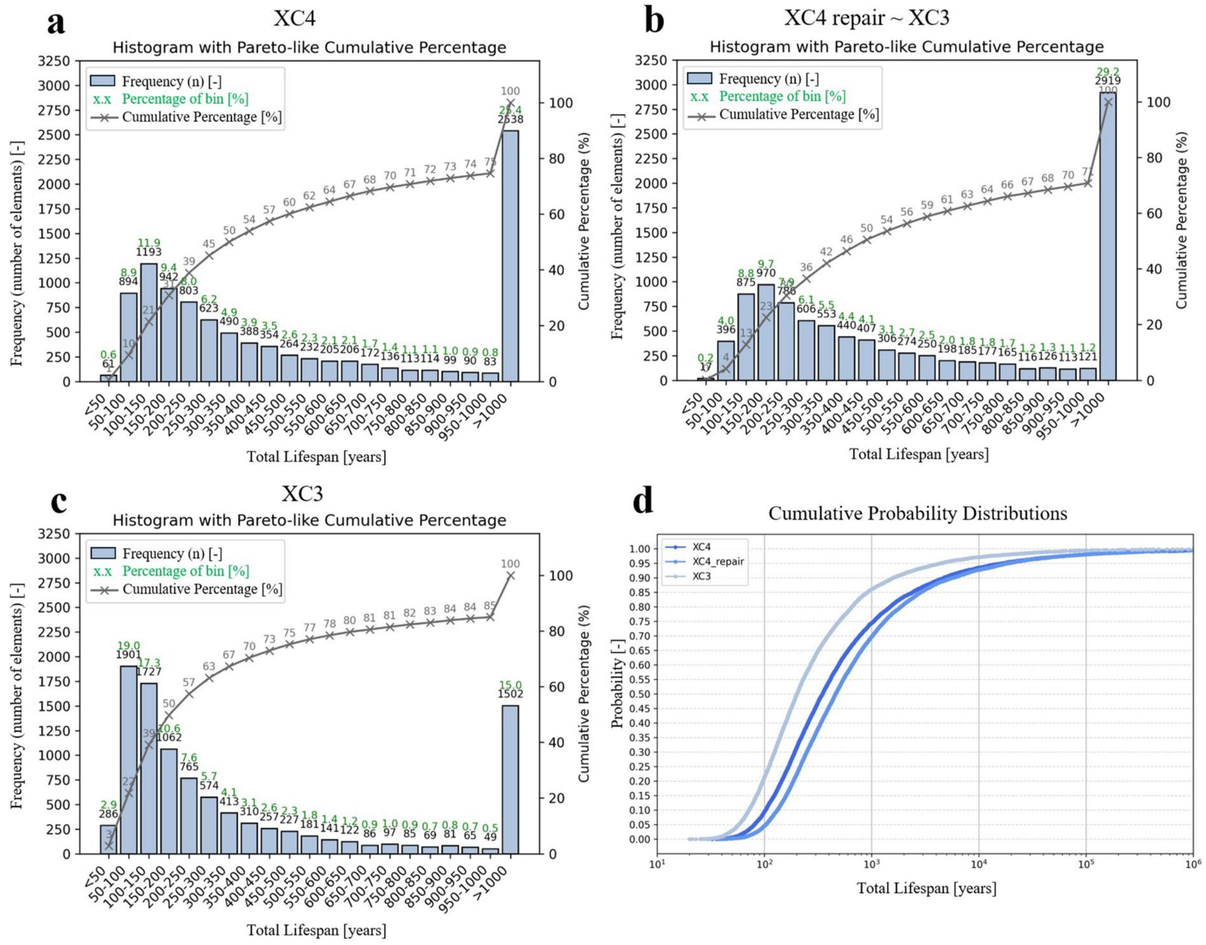

Fig. 9 Probabilistic service life assessment (initiation and propagation phases) via Monte Carlo simulation

Table 9 Percentiles of probabilistic total service life and frequency probabilities for two service lives of 50 years each

Percentiles [%]	t_{SL} in XC4 [years]	t_{SL} in XC4 with repair [years]	t_{SL} in XC3 [years]
5%	78,93	102,03	57,51
10%	99,8	133,22	72,38
20%	142,04	187,14	97,59
25%	164,8	216,61	110,45
50%	343,18	449,47	204,41
Frequency probability	[%]	[%]	[%]
Failure probability of less than 100 years (i.e. sum of histogram bins '<50' and '50–100' in Fig. 9)	9,5%	4,2%	21,9%
Probability of more than 100 years (a first service life of 50 years and second service life of over 50 years, sum of all histogram bins, excluding bins '<50' and'50–100')	90,5%	95,8%	78,1%

[26]. Different threshold choices would yield a range of estimated service lives for the same structure under comparable environmental conditions [26]. In our study, a 10% limit yields service lives of 100 years in XC4, 133 years in XC4 with repair, and 72 years in XC3 for existing structures, while a 25% limit would result in 165, 217 and 110 years, respectively. For cases in Fig. 9, a minimum service life of 50 years for reuse can be ensured in XC4, and with higher safety margins when including repairs, but not for XC3 for 10% acceptance criteria, i.e. 72 (total lifespan)—50 (first service life) = 22 (remaining service life) < 50 (design service life for a new building). Using a higher limit of 25% would result in all three cases allowing for the reuse of structures and concrete elements, for an additional 50 years of elements in XC3, and at least 100 years in XC4. In our analysis (see also Fig. 6), and consistent with literature, where carbonation rates follow the order sheltered > exposed > indoors [59], initiation time is longer in XC4, dominating total lifespan, despite shorter propagation times, whereas XC3 exhibits shorter initiation and longer propagation periods. The Monte Carlo input parameters predict a longer total service life for XC4, although sheltered conditions or protective measures in XC3 or XC1 can be more favorable for reusing elements.

3.6 Performance-based procedure for reuse

Based on the findings, a performance-based durability assessment procedure for the reuse of reinforced structural concrete under carbonation-induced corrosion is proposed in Fig. 10. It is worth noting that the assessment of the concrete cover may be needed also for reusing concrete indoors, when determining the structural capacity and fire resistance, see for example EN 1992-1-1:2023 (Eurocode 2) [102]. Further, freeze–thaw durability of concrete is largely determined by its original design specifications, such as air entrainment, water-cement ratio, and material composition [103]. Depending on climate, this will influence its suitability for storage and possible reuse outdoors. If concrete lacks freeze–thaw resistance, its reuse in XC4 may not be recommendable in cold climates. In these situations, outdoor protective measures may be needed to prevent direct water exposure and freeze–thaw deterioration.

4 Discussion

Service life prediction models can be applied to both new designs and existing buildings [104]. Since relevant properties are measured directly on existing structures for concrete reuse, the uncertainty from material and environmental factors may be reduced. The findings demonstrate considerable reuse potential for indoor elements, as well as for outdoor elements under Nordic climate conditions.

4.1 Standards and their requirements

The lack of standards, regulatory frameworks, and certification of reused building elements can constitute a barrier to their effective reuse [105]. The Norwegian standard NS 3682:2022 focuses only on the reuse of hollow core slabs [58]; while it includes a condition assessment process, which includes carbonation depth, it does not provide guidelines on estimating the remaining service life. Current Eurocode 2 describes a new performance-based method for durability design of concrete structures, with Exposure Resistance Classes (ERC) system regarding carbonation and chlorides [102, 106]. However, this approach concerns new concretes, based on concrete performance, exposure class, and design service life, excluding performance-based methods for reuse of structures. Additionally, in Sect. 6.1, EN 1992-1-1:2023 defines the end of service life as the point at which corrosion attack occurs in the reinforcement [102]. This type of assumption can lead to considering only the initiation period in service life of new structures (with new or reused concrete). While in service life design with new concrete elements this approach can be seen as less problematic, as concrete is newly produced, in existing structures carbonation may have been little, or up to a certain depth in the cover, and could reach the reinforcement after the first 50 years, thus preventing reuse. Moreover, the Finnish code considers the end of the corrosion initiation phase as the end of service life [60]. While the remaining initiation time for precast buildings from the 1960s may be sometimes sufficient for ensuring service life (see Sect. 3.4), it may be beneficial to extend the analysis

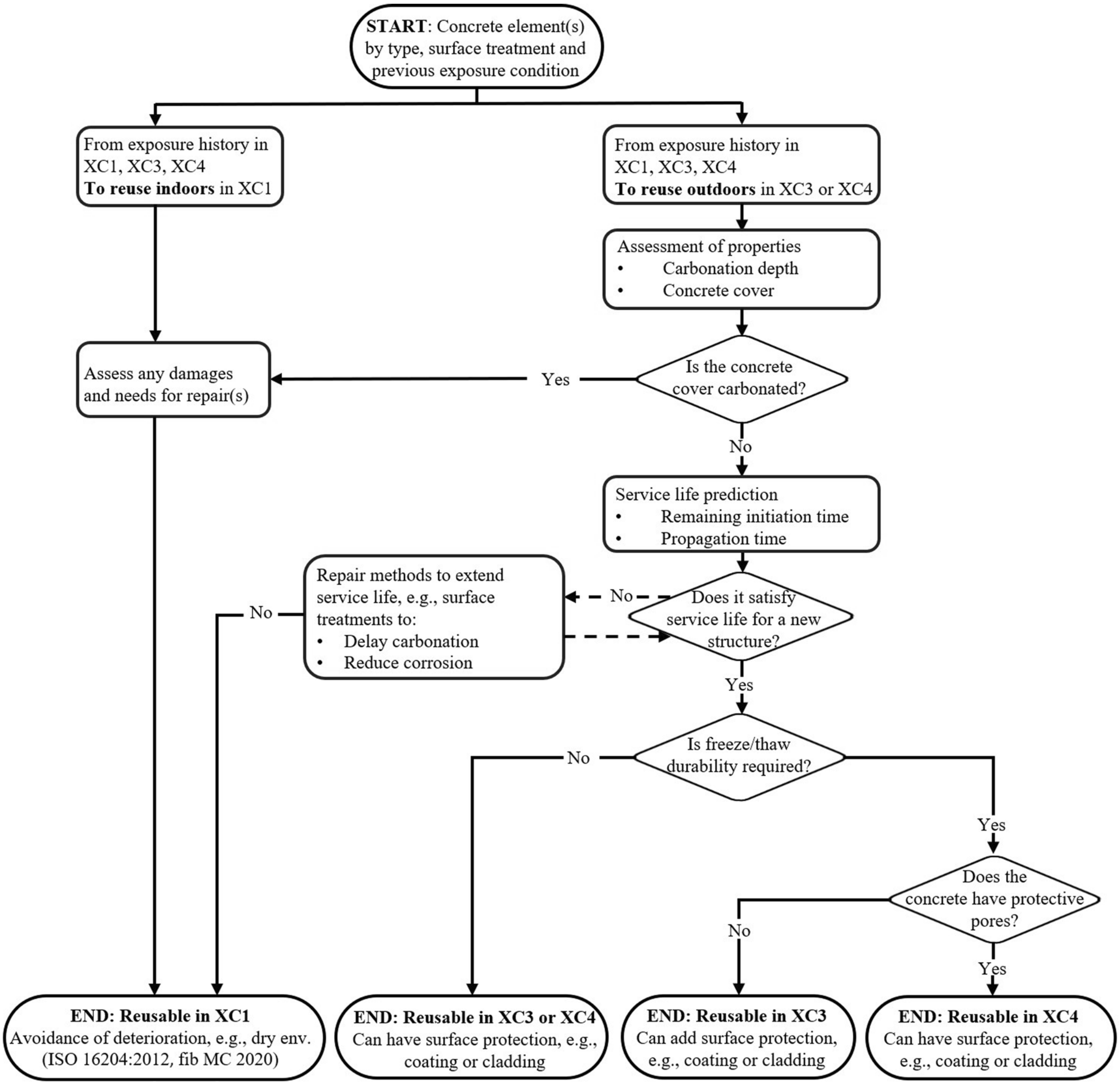

Fig. 10 Decision making process for structural concrete reuse affected by carbonation-induced corrosion

to include the corrosion propagation period to ensure service life, and to consider variations in the new exposure and environment. The findings of this study can inform technical standards and guidelines for the reuse of precast concrete, including current national standardization efforts in Sweden (SIS/TK 191/AG 02, *Reuse of precast concrete products*), where KTH authors are involved, as well as potential future European-wide standardization.

4.2 Extending service life and influencing factors

The square root of time model, proposed by Papadakis et al. [107], has been questioned under XC4 exposure (wet–dry cycles), as it assumes a constant diffusion coefficient and relative humidity, which is not always valid in outdoor exposures [48, 51]. Cyclic saturation can slow carbonation, causing the model to overestimate depth, particularly in durability design for new structures, which is not the focus of this study. However, the empirical square root of time model, based on field measurements, fits well for existing facades under XC3 and XC4 exposures in the Nordic climate [48]; two consecutive measurement campaigns spanning 7–12 years across 18 buildings showed predicted carbonation depths (50-year period) between campaigns differed by less than 5%. Although diffusion laws in XC4 remain debatable, the empirical model for 27–35 years old existing structures proved reliable [48]. Our assessment concerned existing precast concrete elements that have undergone decades of exposure, in the ReCreate project and Finnish national database. Thus, measured carbonation depths inherently reflect the effects of wet–dry cycles and climate. Consequently, the empirical square root of time model is appropriate for assessing reuse potential in circular construction.

The storage period influenced carbonation of the concrete cover, depending on carbonation rate, years in storage and concrete age scenarios (new concrete, reused after 50 years, or depth determined during storage). Carbonation depth during storage was less than 5% of the total depth for periods up to 5 years, or less than 7% for up to 10 years. Hydrophobic impregnation may or may not reduce carbonation due to concrete composition and humidity levels [22], but it may play some role in providing freeze–thaw durability for concrete [108, 109]. However, it is uncertain how deeply impregnation penetrates in practice and whether it has an effect on cracks. The data on corrosion rates with hydrophobic coatings is scarce, with reported rates for chloride-induced corrosion rates to be low (0,1–0,5 μA/cm^2), and negligible (<0,1 μA/cm^2) using silane coatings [109]. The long-term protection of coatings may not be guaranteed due to aging and weathering, especially for epoxy and polyurethane paints, while cement or silane coatings could have longer service lives [109].

4.3 Service life and durability considerations

If carbonation depth is not expected to reach the concrete cover in the second life, reuse can be ensured in the case of conservative regulations that are unclear or exclude the propagation phase. If the initiation phase ends in the second life, the propagation period may help ensure service life, where reusing will depend on environmental factors affecting carbonation and corrosion (e.g., surface treatments, humidity, ambient CO$_2$). Since exposure in an indoor and dry environment does not lead to significant corrosion of steel [72], concrete can be safely reused indoors; In this case, lifespan of carbonated concrete elements can be significantly longer than service life predictions, and the principle of ‘avoidance-of-deterioration’ will often apply [22, 26]. For reusing outdoors, repairs and protection measures may guarantee a sufficient service life, as demonstrated with the probabilistic assessment in Sect. 3.5. Further, the presented probabilistic method provides a data-driven approach to assess elements for reuse in outdoor environments classified as XC3 or XC4.

We tested various critical crack limits in the literature, which showed to influence propagation time. In addition to protective measures, the actual penetration attack to cause cracks will depend on cover depth, rebar diameter, and cementitious matrix, as main factors [22]. Other types of damage and reconditioning interventions may be necessary, beyond those related to the exposure class, which were out of the scope of this study. For example, previous research has categorized damages when demounting and reusing concrete from existing structures into 6 areas: spalling of angles, pullout at anchorages, rebar corrosion, bending cracks, screed or residues, and residual deformation [110].

Additionally, not every reinforced concrete element will automatically be fit for a second life. The need for repair depends on whether the predicted probability of failure (or insufficient service life) exceeds the acceptable target reliability for the intended new use. In our study, elements from XC3 exposure, which, without repair, may not meet a 95% probability target for 50 year reuse service life. In such cases, preventive repairs, reclassification to a less demanding exposure, or downcycling reuse may be required. Moreover, sometimes concrete may require repair interventions during their first or second service life, and their performance should be supported by proper inspection, monitoring, and maintenance strategies. Previous studies have proposed grading framework for reusability of reinforced concrete components, in which damages, maintenance, strengthening, and reconditioning measures are considered as part of an assessment of reuse potential (e.g., recent Swiss case studies demonstrating up to 95% reusability of concrete elements when such protocols are applied) [8]. Our probabilistic approach could be integrated with these prior reusability frameworks.

A study analyzing 124,096 demolished buildings in Denmark found that office buildings generally have much shorter expected lifespans than previously assumed [52]; newer buildings (constructed within the last 30 years) often exhibited shorter lifespans compared to older structures. Since the service life of concrete elements can be ensured for another 50 years, reusing elements from buildings with short lifespans, rather than demolishing, offers significant potential for sustainable construction and in creating a circular built environment.

4.4 Design for reuse considerations

The durability requirements for new or reused structures should be the same, guaranteeing normal function during service life without reaching the limit state. When reusing concrete elements, concrete properties and structural performance are given, and within these limits, architects and engineers look into incorporating retrofitted elements into a new building. They must ensure the service life of reused elements in the new exposure. In this context, Building Information Modelling (BIM) becomes an important tool for managing building information from various donor buildings into the model of the new design [88, 111, 112]. Tracking and tracing technologies can provide a link to relevant information in the reuse process, to designers and stakeholders [40, 44]. Open standards for long-term storage of information will facilitate accessing digital models in the future when buildings need to be renovated or deconstructed at the end of life [5].

4.5 Limitations of the study

The data set used for the probabilistic modelling of carbonation-induced corrosion relied mostly from buildings in a Nordic climate. Service life modelling followed validated formulas for natural carbonation [48, 63]. However, changes in carbonation rates during storage before reuse and in the second life should be evaluated with measurements in future studies. Service life predictions and correction factors for carbonation in the second life, including the use of the environmental function from fib MC 34, should be validated with measurements in emerging and planned buildings with reused concrete.

It is worth noting that the accuracy of probabilistic models depends on the quality of input parameters, which can exhibit a large variance and uncertainty in reused or older concrete elements with unknown histories (e.g. concrete mix, past exposure, missing original documentation). In such cases, a combination of destructive and non-destructive testing may be needed to determine material properties, possibly complemented by recent carbonation models that incorporate NDT data and durability indicators [51, 113, 114].

Reuse offers greater climate benefits than recycling, even when considering CO_2 uptake from carbonation at end-of-life [10]. Future research could integrate service life estimations into LCA and in combination with circularity metrics, to assess the sustainability of reused structures [6, 112].

Protective and repair measures may not provide absolute protection against degradation for the whole service life. Additionally, protective coatings cannot be applied to the case of precast elements with exposed aggregates as it cannot guarantee continuous impregnation against water across the surface [60].

This study focused on carbonation-induced corrosion, which is a reasonable assumption for building structures, whereas for structures exposed to marine environments or de-icing salts (e.g. bridges), both chloride ingress and carbonation need to be considered. While most studies investigate these deterioration mechanisms separately, few studies have examined the interaction between carbonation and chlorides [115–118]. In accelerated chloride tests, carbonation increased chloride transport and could potentially increase chloride concentration near the reinforcing steel [116, 118]. Future work could explore coupled service life prediction models that consider both chlorides and carbonation, and extend the proposed methodology to cover also chloride ingress and a wider range of exposure conditions and structures for reuse.

This study focused on the durability limit state as defined in fib Bulletin 112 [30], i.e., the initiation and early propagation stages of corrosion up to the onset of damage such as first cracking, but does not include subsequent structural capacity loss (e.g., reduction in bending or shear strength). Future work could couple the presented probabilistic durability framework with structural reliability assessments to evaluate performance beyond the durability limit state, thus

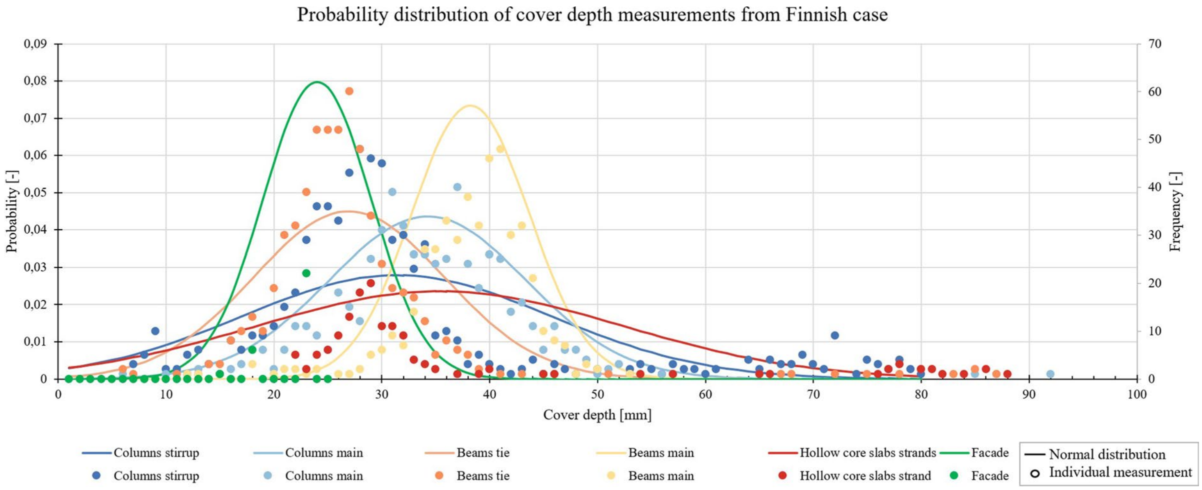

Fig. 11 Cover depth measured in the Finnish case of the ReCreate project

integrating service life and mechanical performance considerations for structural reuse.

5 Conclusions

We presented a novel, integrated probabilistic framework for ensuring service life and enabling reuse of concrete structures subject to carbonation-induced corrosion. The study also investigates and proposes how to assess the effects of storage before reuse, second service life exposure variations and related carbonation rate changes, and the repair interventions within a unified probabilistic durability framework. We also put forward a decision-making workflow for structural concrete reuse based on service life predictions and exposure classes. While individual components of the research methods such as carbonation models, Monte Carlo simulations, and corrosion propagation are established in the engineering field, the innovation of this work lies also in its application-driven integration of these methods, with relevance for engineering practice in circular construction. Additionally, the probabilistic assessment was representative of Nordic climates, and to some extent to similar international and European contexts. Furthermore, the use of real-world data from two precast concrete buildings enhances the practical relevance of the findings.

Our results demonstrate that concrete elements, when assessed for reuse, and when necessary repaired, can achieve service life estimates comparable to those required for new structures (50 or 100 years), enabling their reuse in new designs. For instance, failure probability for elements exposed in XC4 conditions was reduced from 9.5% to 4,2% after repair interventions, meaning that over 95% of the elements could meet the target service life. However, failure probability (less than 50 years of reuse life) for elements from XC3 exposures was 21,9%. In such cases, the decision to repair and protect elements becomes necessary if the predicted failure probability exceeds the acceptable reliability target. If repairs and protection measures are not feasible, such as insufficient to achieve the required service life, not cost-effective, or not aligned with architectural design requirements, concrete elements could be reused under more moderate requirements, such as indoors in a dry environment, in recipient structures with shorter design lives (e.g., 30 years), or through downcycling strategies (e.g., reuse in applications subjected to lower loads and environmental stress).

The findings show the potential of performance-based durability assessment as a decision-support tool for safe structural reuse into new building designs. As highlighted in the introduction, this work is, to the authors' knowledge, one of the first to address the service life of reinforced concrete elements in the context of reuse and circular construction. The probabilistic approach and findings support prior studies on concrete reuse—which, until now, have rarely addressed service-life considerations. The proposed approach is also applicable when evaluating repair strategies and service life extension in adaptive reuse and renovation of existing structures. The proposed framework can be complemented by non-destructive testing and durability indicators for carbonation. Future standards should incorporate the corrosion propagation phase in service life assessments, not only to support the design of structures with climate-friendly concretes containing SCMs, but also to enable reuse of the existing building stock and avoiding premature demolition and recycling. As demonstrated through the evaluated Swedish and Finnish case studies, there is potential for reusing most concrete elements in both outdoor (XC3/XC4) and indoor (XC1) exposure classes.

Service life estimations can support Circular Economy goals by facilitating reuse, towards reducing life cycle environmental impacts of concrete. The proposed assessment method can inform future standards and regulations and could be integrated into digital tools to support circular construction. Further research may investigate and assess new structures that combine new and reused elements, assessing their environmental performance, durability, and circularity potential.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Concrete covers in the Finnish case were measured using a concrete cover meter, as shown in Fig. 11. Stirrups and ties have shorter cover depths than main bars and would be more prone to carbonation-induced corrosion. For stirrups in columns, 47% had 20–29 mm cover, 42% had over 30 mm, 3% had less than 10 mm, and 8% had 10–19 mm. For ties in beams, 69% had 20–29 mm cover, 19% had more than 30 mm, and 8% had 10–19 mm; three measurements were below 10 mm. All strands in hollow core slabs had at least 20 mm cover, with 55% falling within the 20–29 mm range.

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