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Reusing of concrete building elements – Assessment and quality assurance for service-life

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ABSTRACT

Strategic reuse of demounted concrete elements in new buildings may be one of the solutions that will support the transition to circular construction. To ensure wider application of concrete reuse, RISE developed a methodology for the assessment of the structural condition of existing buildings, and the selection of elements suitable for reuse, including guidelines for their disassembly, storage, and installation. However, one of the main obstacles for wide application of concrete reuse is the uncertainty concerning the remaining service-life of concrete elements and evaluation of quality over the future service-life in a new building. This paper describes a methodology for material and structural assessments which combine non-destructive, on-site testing with traditional laboratory tests of samples extracted from the structures. The results are intended to support the decision-making process on reuse and give a technical basis for the design of new buildings. Great consideration is put on various deterioration mechanisms for concrete and steel corrosion affecting structural condition of housing and office buildings. To assess the impact of degradation processes, theoretical models are considered, while the remaining service life is estimated by means of a simplified approach that provides the basis for evaluation of likelihood and severity of consequences entailed by material degradation on the structural performance. The proposed approach was validated on the results from three pilot projects, where real buildings in Stockholm and Uppsala, Sweden, were reused or prepared for reuse to different extent. The analysed buildings had different functions (housing, office, parking) and structures (prefabricated elements and in-situ casted concrete), being representative for Swedish building stock. One of the buildings has been already dissembled and the prefabricated, where prestressed hollow-core slabs have been successfully reused for a new office building construction. Based on these experiences, a simple classification system for quality of concrete elements for reuse was proposed with three main parameters, namely calculation of remaining service-life, extent of cracking and the target exposure class. The proposed system is not complete and must be further validated for various types of elements and structures by wider group of market actors.

1. Introduction

When a structural element is dismantled from a building, it loses its legal status as a building part and becomes waste. The social and economic perception of waste has evolved in the last decades and its potential as a resource for reuse, recycling, or energy production (depending on its material properties, ease to reuse or recycle, financial, and environmental value) has gained considerable attention. Reuse is the second step in the waste pyramid after prolongation of the service-life due to preservation of the embodied value and, as such, it has minimal impact on the environment. To accelerate the transition from linear to circular economy, it is mandatory to ensure the quality of the concrete elements for reuse in terms of mechanical performance, as well as fire-safety, acoustic or thermal properties, and longevity required by building standards. The most logical approach to achieve that is to apply existing standards and regulations for new structures. Mechanical properties or other functional requirements can be assessed with the same experimental methods used for new materials or structures. However, this approach is not applicable for durability, which is normally ensured by design than evaluated

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by testing on building and element levels. Moreover, most of current regulations and standards are formally restricted to production of new materials and elements, and do not apply to the assessment of existing ones. Therefore, current building norms and standards have to be updated to meet the challenges posed by circular economy.

1.1. Service life

All structures must maintain their key performance indicators like load-bearing capacity, fire resistance, acoustic and thermal properties over time. The service life is obviously affected by the material/product quality which is decided at the design and production stage in relation to the intended use, target environment and the expected level of performance required over the service life. The end of service life can be detected by the loss of performance that results from aging, frequent failures, and increased repair expenses. The design process of structures for the service life takes into consideration three main factors:

- Limit values for performance indicators (in Eurocodes called limit states),
- Required period for the service life (in Eurocodes expressed as structure class),
- Reliability level of not passing over the limit values in the defined service life period (accounted for by safety factors applied on loads and material properties).

In the design of new structures, the amount of required reinforcement to satisfy structural limit states is calculated by knowing the expected loads and material resistance. The durability of the structure (that is, the duration of its structural performance in time) is ensured by prescribing a depth of concrete cover from material with specific quality (cement content, water to cement ratio etc.), which protects the steel reinforcement against corrosion for the required service life (depending on the Class of the structure).

All methods for the estimation of residual service life of concrete structures involve the following general steps: determining the condition of the materials, defining the end of service life of each material in the structure, and making some type of time extrapolation from the present state to the state that characterizes the end of service life. [1,2] the reported research on predicting residual service life of RC structures focused on the corrosion of concrete reinforcement. Most existing methods refer to the conceptual model introduced by Tuuti [1] including initiation time and propagation time. Some methods focused exclusively on the initiation time, while others encompassed both phases. Models may be derived from fundamental physical principles or directly estimated from empirical data.

The main differences between the service life of existing concrete structures and elements for reuse are the loss of its legal character as a structure and need to consider elements as products for new buildings subjected in EU to Construction Products Regulation. In consequence the current standards are applicable for reused elements and thus, the limit values concerning durability may be different from the original. For instance, the minimum required reinforcement concrete cover for 50 years of service life in Sweden for exposure classes XC2 and XC3 (related to carbonation) have changed significantly over last four decades [2]. In case of structures constructed before the 80′s, the required concrete cover was nearly double (45 mm) comparing to today's values (25 mm), which is favorable for reuse. In other words, if carbonation depth for concrete element built according to the rules from the 70′s is less than 20 mm it still fulfils the requirement of the current standards.

Another aspect of reuse is that it involves additional steps: disassembly, intermediate storage with different conditions than initial and placing it in the new environment. Those aspects make it especially important to precisely analyze the condition of the material at different stages (before disassembly and after installation) and to consider acceleration or limitation of possible degradation due to the new environment. The disassembly opens also the possibility to introduce additional protection or revalorization steps for the elements by, for instance, adding new thermal insulation, repairing cracks or applying extra layers of carbonation protection. In that case, the performance of the elements can be upgraded to fulfil current standards comparing to the requirements from the past, and the effect of these interventions should be included in the service-life calculations.

2. Deterioration mechanisms

The degradation of materials is a time-dependent phenomenon, and it is dependent on the material properties as well as the external environment. In the buildings considered in the case studies presented here, the focus was on concrete load-bearing parts, due to their large embedded environmental footprint and their potential to decrease the overall impact of the new buildings by reusing them.

In concrete structures, two materials are usually combined to provide required load-bearing capacity and the elements integrity. The basic material is concrete, which is easy to shape, it has good compressive strength, it is affordable, and durable. However, concrete is brittle, and it has a tensile strength in range of 1/10 of compressive one. Therefore, it is usually reinforced with steel in form of rebars or prestressing tendons, which are subjected to corrosion. Concrete is relatively durable material, resistant to weathering and most aggressive environments. The transport of degrading chemical elements in concrete take years or decades, but eventually it reaches the reinforcement level opening way to corrosion.

2.1. Carbonation

Carbonation of concrete is a natural process of CO_2 absorption by the products of cement hydration in presence of water/humidity. Calcium hydroxide turns into calcium carbonate, which lowers its pH from around 13 down to 8–9. The reinforcement steel may begin to corrode when the surrounding concrete achieves the pH of 11–12. The process occurs in almost all concrete structures but at different rates depending mainly on the humidity level. The most severe conditions accelerating carbonation occur in around 50–70 % RH which in practice often means wetting and drying cycles (ex. buildings facades). However, the process happens also at lower pace in drier environments (e.g., in-house). Considering these aspects, the study used a basic diffusion model with effective diffusion coefficient estimated from data collected during condition assessment (namely, carbonation depth measured with thymolphthalein) and age of the structure. In this way, prediction of carbonation depth in the same environment (same humidity, temperature and CO_2 concentration on the surface) was possible [4,5].

2.2. Chloride ingress

Concrete in contact with salts (chlorides - NaCl) from sea water or de-icing salts close to roads and in parking lots absorbs chlorides similarly to carbon dioxide. The diffusion is the main phenomenon for chloride ingress in structures that are not in direct contact with water (marine structures, swimming pools etc.).

Similarly, as in case of carbonation, based on the assessment of existing structure (chloride concentration and specific depth from analysis of drill cores and structures age), the diffusion coefficient could be calculated. The estimated diffusion coefficient was used to extrapolate the concentration at different depths at given time (the so-called chloride profile) or chloride concentration at specific depth at different time periods. The latter approach was used to evaluate the time to achieve critical chloride concentration at reinforcement level, which is it the condition that leads to corrosion initiation (the standard threshold value of 0.10 % was assumed) [3].

2.3. The role of cracks

Cracking is one of the basic phenomena in all brittle materials, including concrete. It occurs when the internal stresses exceed tensile strength of material (concrete has around 10 times lower tensile strength than compressive strength). Cracks are accepted in most reinforced concrete structures (the steel reinforcement is effective in loads transfer after cracking), but we tend to limit their width by applying reinforcement or using fibers. The understanding of the effect of crack width on the durability of reinforced concrete has changed over time. The admitted crack width values for specific service-life in Sweden were gathered by Fagelund [2]. The maximum allowed crack width depends on the reinforcement type (normal reinforcement or prestressing) and the reinforcement grade (moderate, high and extreme). Most of prestressed structures are designed to avoid decompression (cracking) and thus the limits for those are generally stricter. Practically, acceptable crack widths are in range of 0.4–0.3 mm for structures with expected service-life of 50 years, which is in line with the requirements of Eurocode 2, that is maximum design cracks with equal to 0.4 mm (for exposure classes X0 and XC1),0.3 mm for reinforced concrete, and 0.2 mm for prestressed concrete.

If the cracks are large enough, they affect the concrete performance by diffusion of chlorides [3] and they accelerate the rate of carbonation [4]. Some of the mentioned studies define the effect of crack width on the diffusion coefficient of chlorides or CO2 in concrete, providing guidance for simple modifications of the diffusion models which improves the accuracy of their predictions. In general, it is agreed that cracks finer than 0.05 mm do not affect the diffusion properties. However, diffusion is not only affected by the surface crack width, but also by its depth, interconnection with other cracks or voids, and the location of cracks with respect to reinforcement. For the sake of simplicity, in the presented calculation tool crack width was considered by increasing diffusion coefficient based on literature data. The crack width was also included as a criterion for disassembled elements quality classification.

2.4. Steel corrosion

The carbonation–induced corrosion rate is variable and highly dependent on exposure conditions and atmospheric situations. The main parameter impacting the corrosion current density (I_{corr}) is humidity [5]. The corrosion rate of steel in carbonated mortar increased dramatically with increasing RH. Changing RH from 50 % to 99 % may raise the corrosion rate by up to two orders of magnitude [6] (Fig. 2a). The mean corrosion rates in carbonated concrete changes from 0.43 to 0.86 μA/cm^2 and 0.17 μA/cm^2 at 90–98 % and less than 85 % relative humidity, respectively. According to Research Project BE 95–1347 [7] under sheltered conditions, the recommended carbonation-induced corrosion rate is 0.087 μA/cm^2 with a COV of 1.56, and under unsheltered environments the corrosion rate increases to 0.32 μA/cm^2 with a COV of 1.47.

Corrosion of steel in concrete due to chlorides is a complex phenomenon. For the steel to de-passivate and to initiate corrosion, certain chloride concentration is required. For the sake of simplicity in engineering practice technical specification, EN 206 [8] limits the chloride content to 0.20 % and 0.10 % of cement mass for steel reinforcement and prestressing reinforcement respectively to avoid chloride induced corrosion. The higher chloride content, the higher corrosion current density [9] (Fig. 2b). Below 40 % RH the risk of corrosion is negligible thus only higher humidity levels are considered in this work. Moreover, in fully saturated concrete, the corrosion rate is very low due to limited access of oxygen. Therefore for 100 % RH corrosion is assumed negligible.

3. Service life calculation tool for reused elements

To support the decision-making process for concrete elements reuse by real estate owners and structural engineers and to provide a systematic way of calculation of remaining service life for reused elements a simple excel tool was developed and validated on examples from Återhus pilot buildings (Fig. 1). Within the project a developed condition assessment scheme, described broader in [11], was validated. The analysis of buildings to be reused included: (1) Analysis of existing documentation, (2) Site visit and non-destructive testing (evaluation of compressive strength with Schmidt hammer, reinforcement scanning with georadar, determination of concrete cover by reinforcement detector and inventory of eventual cracking and other types of visible damage), (3) Extraction of drill cores and reinforcement samples for destructive testing in the laboratory (compressive test for concrete and tensile test for steel, carbonation depth and chloride content) and (4) Evaluation of results and recommendation on elements classification for reuse.

Finally, the calculation tool was used utilizing data from the condition assessment. The element was always given two lives: (I) Degradation of concrete cover (initiation based on the Fick's 2nd law) and (II) Corrosion of steel (propagation based on corrosion rate in certain atmosphere). In the first life the diffusion coefficient was calculated based on status achieved from the laboratory tests and the age of the structure. Application of that value in simple diffusion models gave conservative extrapolation of the remaining time until the initiation of steel corrosion. The elements during disassembly were cut at the ends when being removed from supports, thus reducing their span. The coefficient for the span reduction was used to calculate the additional load-bearing capacity gained by the span reduction in relation to limit states (bending, shear, deflection) and tested materials strength with safety factors as for new design but the same design loads. In fact, the target loads should be used in this calculation, but these depend greatly on the actual design and can be simply added by the user of the tool. The user is also asked to define the target environment (ex. if the element will be used in garage and exposed to chlorides or just to carbonation and relative humidity). Using curves presented in Fig. 2, corrosion rate, and the remaining service-life of the element are calculated. Finally, additional factors are added based on [12], considering: (A) Inherent performance level, (B) Design level, (C) Work execution level, (D) Indoor environment, (E) Outdoor environment, (F) Usage conditions and Maintenance level. The factors are arbitrary, and their values should be decided by experienced engineers. The reference service life is calculated as $L_{ref} = t_i + t_p$, where t_i is initiation time from *life I* and t_p is propagation time from *life II*. The residual service life L_{res} is a result of applying factors $L_{res}=(L_{ref})\phi_A\ \phi_B\ \phi_C\ \phi_D\ \phi_E\ \phi_F$.

4. Results of calculation from Återhus pilot buildings

The proposed methodology has been applied to four pilot buildings intended for reuse located in Stockholm and Uppsala. The

Fig. 1. The analyzed pilot buildings in Återhus project a) Billia Haga Norra (Stockholm), b) Yrket 3 (Stockholm) and c) kv. Hugin (Uppsala).

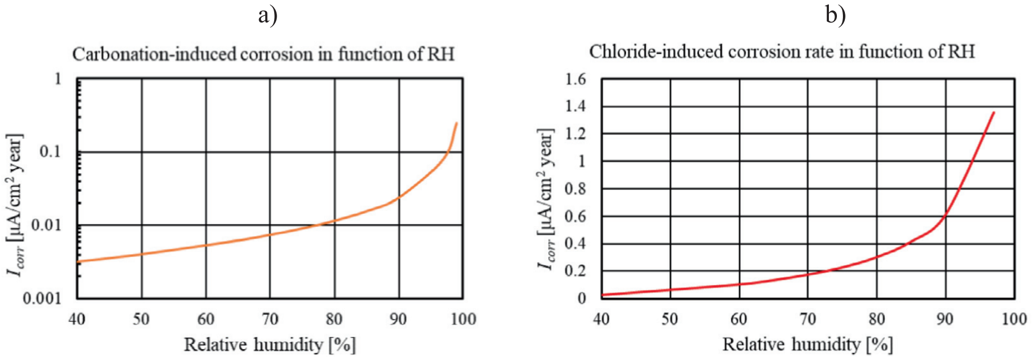

Fig. 2. The corrosion current density for a) Carbonation- and b) Chloride-induced corrosion in function of relative humidity based fitted to results from literature [10].

detailed reports from evaluation of materials' quality are in the ownership of the pilot project owners and only a general characteristic with relevant material parameters were presented in this report to explain the potential of calculation and analysis of the remaining service-life.

Pilot 1 Bilia Haga Norra (Fig. 1a) – The office building with car exhibition hall located in Solna (Stockholm) built in the 70′ with prefabricated concrete. The existing technical documentation included construction drawings, but no details of hollow core slabs (HCS) prefabricated elements were found. The material and structural data for static calculations for reuse was gathered during the site visit and by non-destructive (Schmidt hammer test) and destructive testing (compressive strength for concrete and tensile strength for steel). Moreover, the carbonation depth in the elements of interest was measured on the drill cores. For the new application, no chlorides were foreseen, and office/exhibition space was planned with assumed RH levels of 65 %.

Pilot 2 Yrket 3 (Fig. 1b) – The building consists of an office space and a storage hall with vehicle traffic and was built of prefabricated elements in the 80′. There are two types of prefabricated slabs in the building: the TT-slabs and the HCS. Drill cores taken from both materials, were investigated for strength and carbonation depth. The chloride content was analyzed for HCS samples from the areas with vehicles traffic exposed to de-icing salts. The chloride content exceeded the standard limit of 0.10 % of cement mass nearly five times, however no visible signs of corrosion were observed, neither during the inspection on-site nor in the samples analyzed in the laboratory. In the new building the elements from the parking exposed to chlorides will also be placed in parking space with chloride content of 6 % on the surface from de-icing salts. The relative humidity in the new office building was assumed to 50 %.

Pilot 3 Hugin (Fig. 1c) – The group of buildings from in-situ casted concrete from the 70′ located in Uppsala. Some buildings were used as offices and others as storage spaces. Some of the objects contained a garage. No technical documentation was available for analysis. A large number of drill cores was taken for analysis of concrete strength, carbonation depth and chloride content (in the garage). The in-situ casted concrete was of low quality (probably due to the high water/cement ratio popular at that times) and showed low compressive strength (mean value of 18.5 MPa) and very high carbonation depth, varying between 26 and 48 mm depending on the finishing of the concrete surface (only painted surfaces exhibited deeper carbonation than those covered with flooring material). The measured carbonation depths exceeded the reinforcement cover (10 mm) in all analyzed drill cores. However, no visible signs of corrosion were observed in the reinforcement. For this case a low RH of 50 % was assumed including no exposure to rain during intermediate storage and for the second scenario of storage outdoors without protection with average annual RH in Uppsala of 80 %.

A summary of the performed tests and the results are summarized in Table 1. The presented cases are extreme. The first pilot building had a very low carbonation depth of 7 mm and was not exposed to chlorides. The elements had an initial span of 10 m and were cut 30 cm from each side during disassembly, resulting in reduction of shear capacity by 6 % (for hollow core slabs shear capacity is the critical limit state). To initiate carbonation-induced corrosion, the element should be exposed additionally for 527 years in the same conditions as for now. To corrode the prestressing tendon to the failure with shortened span another 1074 years of exposure would be needed. These elements were recommended for reuse.

For Yrket 3, the carbonation depth was even smaller, however the chloride content in parking slabs of TT-beams was exceeding the standard threshold. Therefore, a corrosion process can be triggered when sufficient humidity will prevail. Assuming 65 % RH and 12 % increase in load-bearing capacity due to the cutting 60 cm of the slab at the disassembly, the element remaining service-life is calculated to 70 years.

For kv Hugin buildings the initiation of the corrosion will occur due to the carbonation at higher sufficient humidity level. The elements span is reduced from 7 to 6.6 m at disassembly and the bending capacity is critical for in-situ casted massive slab. Here two scenarios with indoor environment of 50 % RH and outdoor storage were considered. For the first case the residual service-life was 66 years, however at 80 % humidity it was only 12 years. It presents the relevance of proper intermediate storage of elements between disassembly and installation on new building.

5. Classification system

Based on literature review and the performed buildings condition assessment, as well as the calculations with presented tool for evaluation of service-life, a classification system was proposed for addressing in a simple way quality of disassembled concrete elements aimed for reuse in certain environmental conditions. The three levels with simplified definitions of service-life, extent of cracking and target environment were described (Table 2) to support decision-making and dialogue with public authorities deciding about building permits for buildings with reused structural concrete elements.

Based on the results of condition assessment and the service-life calculations of the analyzed elements of concrete slabs from pilot buildings, they were classified accordingly:

- **Pilot 1 Bilia Haga Norra – DCE Gold**, the cover degradation due to carbonation assessed for 527 years. No cracking observed (prestressed element), the elements to be installed in in-house environment (exposure class XC1-XC2) similarly as in the donor building. The elements were already reused.
- **Pilot 2 Yrket 3 – DCE Silver**, the cover has been already degraded due to exceeded chloride threshold at the reinforcement level and the corrosion initiation is possible. No cracks were observed (prestressed element). The assumed environment in the new building similar to the donor structure. The calculated remaining service-life of 70 years. The elements

Table 1

Summary of results of structures assessment from the pilot project and the results of service-life calculation. The first number is the mean value, while the number in brackets stands for standard deviation. The tested compressive strength $f_{c,k}$ stands for characteristic strength (lowest 5% of results) according to EN 13791:2019.

	Compressive strength $f_{c,k}$			**Concrete cover**	**Carbonation depth**	**Chloride content**	**Standard [5] limit for chloride content**	t_i / type	**Bearing capacity increase**	t_p	L_{res}
	Designed	$f_{c;m}$	$f_{c;k}$	Minimum	Avg. (Std. dev.)						
	[MPa]	[MPa]	[MPa]	[mm]	[mm]	[%]	[%]	[years]	[%]	[years]	[years]
Pilot 1 –Billia Haga Norra	45	60,4 (6,8)	47,6	24	7 (1)	No salt	–	527 CO_2	6 %	1074	1601
Pilot 2 – Yrket 3	45	59,6 (5,8)	45,8	35	3 (1)	0,46	0,10	0 NaCl	12 %	70	70
Pilot 3 – Hugin	**	18,9 (1,7)	18,5	10	28 – 48***	0,12	0,20	0 CO_2	11 %	66	66
								0 CO_2	11 %	12	12

*Only two drill cores were tested; **Lack of existing documentation to compare it with; ***High spread, but always exceeding concrete cover.

Table 2

Proposed classification system for disassemble concrete elements (DCE) for reuse.

Class	Service-life	Extent of cracking	Target environment
DCE Gold"As new"	The degradation of concrete cover will take more than 100 years according to theoretical model calibrated on the data from the structure.	Cracks lower than 0.05 mm do not affect the transport properties of concrete.	The same or milder environment that in the donator structure (ex. parking deck placed as a slab in residential building).
DCE Silver"second-hand"	The degradation of cover will take less than 25 years. The detailed structural analysis is required to correctly determine the bearing capacity. Requires detailed analysis of service-life with special attention to humidity conditions.	Cracks larger than 0.05 mm which may affect the transport properties of concrete. Increase of diffusion coefficient required based on literature.	The element can be subjected to more severe environment in the storage time between dismantling and installation that should be included in the corrosion risk calculation.
DCE Bronze	The cover is degraded or will soon be degraded. The assessment focuses on corrosion risk and consequences (reinforcement cross-section reduction). The static calculations should include reduction in reinforcement. Refurbishment recommended before reuse.	Cracks wider than 0.30 mm reducing functionality of the concrete cover in corrosion protection. Recommended cracks repair.	Element to be placed in aggressive environment (ex. residential slab to be exposed to salt or frost).

can be reused for building with service-life less than 70 years and should be periodically monitored for corrosion (ex. with potentiometer).

- **Pilot 3 Hugin – DCE Bronze**, the concrete cover degraded due to carbonation. Cracking of different widths in range 0.05 to 0.30 mm observed. Element to be placed in similar conditions. Refurbishment recommended before reuse.

Other works like the Norwegian standard NS 3682:2002 [13] or dissertation of Angelika Mettke [14] suggest apart of testing compressive strength of concrete, carbonation depth, chloride content and alkali reactivity performed within this study, additional full-scale test of the hollow core slabs to failure to verify its suitability for reuse. Full-scale tests will be considered in the future work.

6. Conclusions and future work

Durability and assessment of remaining service-life are main technical hinders in reuse of structural concrete elements due to the standards defining it by design approaches rather than performance-based regulations. The updates of Eurocode 2 may bring new opportunities in these terms.

The performed literature review of degradation models for concrete and steel corrosion indicated that cracking and relative humidity have major influence for the degradation and consequences for service-life and should be handled with special attention.

Prefabricated concrete elements from the 70′ and 80′ in Sweden have usually higher quality and resistance against carbonation than in-situ casted elements, thus being more attractive candidates for reuse in new buildings. Additionally, prestressed elements tend to be uncracked, which increases their durability and makes disassembly much easier.

A simplified calculation tool including two stages of degradation (cover degradation and reinforcement corrosion) was developed and validated on real buildings. The results indicated again the importance of considering target environment and intermediate storage conditions on the service-life of concrete elements. Different humidity conditions could lead to service-life reduction from 66 to only 12 years. The calculation tool should be further developed and evaluated by larger number of cases. Moreover, the buildings constructed from reused materials could be monitored to validate the performed calculations.

A simplified classification system for disassembled concrete elements based on condition assessment and service-life calculations was proposed to facilitate the decision-making of concrete reuse for engineers and real-estate owners. The system should be validated on a larger number of buildings of different types and in different conditions.

The first of the presented buildings, Billia Haga Norra, has been disassembled and new building “Sustainability House” was constructed where, 100 % of hollow-core slabs, door, division walls, pantry, stairs, taps, toilets 90 % of facades and floor materials and 70 % of lighting were reused from the donor building. Other pilot buildings will be reused soon.

CRediT authorship contribution statement

Jan Suchorzewski: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Fabio Santandrea:** Methodology, Writing – review & editing, Investigation, Formal analysis. **Katarina Malaga:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of Competing 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.

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