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Revamping corrosion damaged reinforced concrete balconies: life cycle assessment and life cycle cost of life-extending repair methods

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ABSTRACT

Facing the aging building stock, challenging times can be expected with a sharp increase of reinforced concrete buildings requiring maintenance, repair and/or replacement which induces an increase in construction and demolition waste and the use of new materials. To improve the sustainability of the renovation practice of existing concrete structures, a supporting analysis of the life cycle environmental and financial consequences has a high added value with regards to the selection of durable service life-extending repair strategy. As corrosion is the main contributor to the degradation of existing concrete structures, a residential building in a Belgian coastal environment with damaged reinforced concrete balconies is selected as case study in order to evaluate five different frequently used repair techniques by means of a life cycle assessment (LCA) and life cycle cost analysis (LCC): (i) patch repair, (ii) conventional repair, (iii) galvanic cathodic protection, (iv) impressed current cathodic protection and (v) total replacement of the element. For a short service lifetime extension (5y) of the balconies, a patch repair was revealed as the most preferable option as the existing situation is restored with a minimum of intervention. When a service life extension up to 40 years is requested, different options (conventional repair, cathodic protection) are found as competing performance options for both LCA and LCC. The total renewal of the balconies after demolition involves overall the highest LCA and LCC impact.

Keywords: LCA, LCC, life-extending repair methods, concrete balconies

Highlights:

- The amount of contaminated concrete has a decisive influence on the repair strategy
- Total replacement of the balconies has overall the highest LCA and LCC score and therefore is the less favourable repair option
- When a protecting coating is excluded, cathodic protection has a lower environmental and financial impact compared to a conventional repair
- The repair technique should be adjusted to the required service life extension

1 INTRODUCTION AND LITERATURE REVIEW

1.1 CHALLENGES, NECESSITY AND ADDED VALUE

In the late 1960s and the mid-1970s a substantial amount of reinforced concrete (RC) structures were built in Europe. These structures, exposed to outdoor conditions, usually have an estimated service life of approximately 50 years. This yields that many of them are approaching - or already reached - the end of their expected life span and therefore require maintenance (pro-active approach) and/or repair (re-active approach). So, due to the continued deterioration of our existing building inventory and infrastructure, a large volume of concrete repair can be expected for the foreseeable future (Whiteley et al., 2014) which will consume a considerable amount of the building revenue. As a matter of fact, numerous cases of collapsed concrete balconies are already known (Campione & Cannella, 2020; Soana, 2014; Souza & Araújo, 2011; Whittle, 2013), and furthermore it can be expected that the frequency of cases with collapsing concrete elements will increase in time if no actions will be taken. The main cause of deterioration is corrosion of the reinforcement (Jones et al., 1997): more than 75% of the damaged reinforced concrete structures are in a way related to corrosion, induced by carbonation of the surrounding cementitious matrix and/or chloride ingress (due to use of de-icing salts or marine environment). Corrosion affects the durability of a concrete structure, resulting in cracks and delamination of concrete parts due to the expansive nature of corroding steel. Furthermore, the structural safety of the structure can be jeopardized as corrosion reduces the cross section of the reinforcement bars in a uniform (due to carbonation) or local way (pitting corrosion initiated by chlorides) (Broomfield, 2007). Deterioration of reinforced concrete is critical to durability, safety and sustainability of construction, especially in a marine or saline environment. For rehabilitation of existing concrete structures, knowing the characteristics (e.g. strength) of the structure is mandatory. Assessment of the mechanical properties and bearing capacity of existing structures can be performed in a (non-) destructive way (Craeye et al., 2017).

Different repair options are possible to prevent or stop the corrosion process. Prior to the repair, the cause of corrosion must be detected and determined to select the repair strategy to mitigate corrosion (Qu et al., 2021). In a more traditional approach, a waterproofing and protective coating prevents the ingress of CO_2, chlorides or moisture. On the other side, cathodic protection (CP) (Chess, 2019) is proven to be an effective electrochemical technique to suppress the corrosion process and should always be considered as a repair option in case chlorides are present in a cementitious material.

In the near future, challenging times with a sharp increase of these reinforced concrete buildings requiring repair or replacement can be expected, with an increase in construction and demolition waste (C&DW) and the need for new construction materials as a result. Furthermore, it has been estimated that approximately 50% of Europe's annual construction budget is spent on refurbishment and repair of existing structures (Confederatie Bouw, 2014). Up to 40% of the total raw materials is globally extracted for the construction sector and 850 million tonnes of C&DW are generated in EU per year, which represent 31% of the total waste generation (Fischer & Werge, 2009). The production process of cement, an essential component for the production of concrete and repair mortar, uses approximately 12 to 15% of the total industrial energy demand (Ali et al., 2011) and represents around 5 to 7% of global CO_2 emissions from all industrial process and fossil-fuel combustion (Xi et al., 2016).

To date, the decision making process for selecting the best repair strategy mainly focuses on technical requirements and economic performance. However, a vision to minimise the induced impact on the environment should be included as well (Ribeiro et al., 2008). Such a holistic approach to sustainability is often enriched with strategies to enable the transition to the circular economy (CE). According to the definition of the European Commission, a circular economy aims to maintain the value of products, materials and resources for as long as possible by returning them into the product cycle at the end of their use, while minimising the generation of waste (European Commision, 2021). In contrast, it is known that only 4-5% of the Belgian concrete aggregates coming from demolished RC structures are used in high-value applications (Gillabel et al., 2016). So, in accordance with the vision on CE, service life extension and reuse of elements is an essential factor enhancing the environmental impact as fewer products are discards and less new materials are extracted. Therefore, the rehabilitation of the existing building stock in Europe will be one of the key factors in the future to reduce the environmental impact (Vilches et al., 2017) as the construction sector has a large contribution of resource extraction and waste production in our society (Yuan, 2013). Therefore, the necessity of objective information to support decision making, based on the financial and environmental impact of a selected repair strategy, makes this a study with a high added value for e.g. the repair industry and more specific the owners of residential buildings.

To increase the sustainability of the renovation of existing RC structures, selecting an appropriate repair technique should consider both the environmental impact and the cost over the life cycle of the preferred life-time extension of the construction. This is in contrast to the current practice, where decisions of the repair technique are mainly in function of the available budget, without considering a life cycle perspective. Given its prominence in academic research and policy documents, it is important that the concept of the circular economy is subjected to critical analysis and is assessed quantitatively by including a life cycle perspective (Gregson et al., 2015). Methods like life cycle assessment (Buyle et al., 2013) have proven their value for making well-informed decisions concerning the optimization of the environmental performance of products, processes and services. Combining the tools of life cycle assessment (LCA) and life cycle costing (LCC) endorse a holistic approach in decision making (Hoogmartens et al., 2014; Miah et al., 2017; Reich, 2005).

The availability of studies to support the decision-making process for the rehabilitation of existing concrete structures through LCA and LCC is almost non-existing. To fully grasp the state-of-the-art of this holistic approach applied on RC structures and to adequately identify the relevant repair techniques, a systematic literature review is carried out.

1.2 LITERATURE REVIEW

As the total cost in a traditional approach is of major influence in the decision making, LCC assessments on design and repair of concrete are commonly used. For deteriorating buildings exposed to chloride ingress and located in regions with high hazard of seismic activity, maintenance strategies such as steel supplementation, a patch repair, electrochemical chloride-removal and finishing renewal are compared by Chiu et al. (2010). The results revealed that maintenance strategies that include steel supplementation are the most effective in reducing the LCC. Furthermore the study revealed that the outcome depends on the assumptions made with regard to corrosion initiation and propagation.

The design and maintenance for RC bridges enhancing the total costs are studied by D. Frangopol et al. (1997), Ghodoosi et al. (2018) and Safi et al. (2015). These studies indicate that undertaking less costly minor repair actions may considerably reduce the life cycle costs as a result of decreasing the number of costly major interventions. However, the expected total cost is sensitive to the extent and severity of the corrosion damage. Polder et al. (2016) compared preventive measures such as the use of stainless steel reinforcement, hydrophobic treatment of concrete and cathodic prevention to a curative approach with a conventional repair or cathodic protection in corrosion damaged concrete infrastructures. A repair with Impressed Current Cathodic Protection (ICCP) has a lower cost compared to conventional repair for a 100-year service life. However, this study shows that preventive measures implemented during design stage are preferred. Similarly, five types of repair methods for infrastructure RC structures (e.g. bridges) are compared by Shafiqul Islam & Kishi (2010): cathodic protection with a conductive coating and with a titanium mesh, patching and two types of overlays (i.e. concrete and hot asphalt mix). Patching should have the largest life cycle cost, whereas a low slump dense concrete overlay has the lowest. A life cycle cost comparison of different cathodic protection systems for RC structures is evaluated by Polder et al. (1998, 2014) who show the effectiveness and possible economical advantage of CP systems based on an extensive study of 150 structures that are cathodically protected since 1987. On the average, global failure of the anode system is rare after approximately 20 years and only minor repairs and maintenance of the electronic parts is needed after 15 years. Moreover, anodes based on active titanium have sown longer working lives compared to conductive coatings.

A market study performed by Krishnan et al. (2021) indicates that patch repair without (galvanic) cathodic protection can lead to continued corrosion, mainly due to the halo effect and residual chloride effect. As a consequence another major repair in about five years can be expected and furthermore repeated patch repairs can lead to continued corrosion and eventual replacement of structures and huge life cycle costs. On the other hand, the strategy of cathodic protection using galvanic anodes can enhance the service life and reduce LCC. It was also found that the additional cost of galvanic anodes is only about 4% of the repair cost breaking the myth of high capital cost of CP strategy.

The study of Farahani (2019) investigated the influence of some repair or rehabilitation scenarios on the performance of a chloride-induced corroded circular RC column. The repair cost by increasing the concrete cover was found to be cheaper rather than using new reinforcement as the replacement of the corroded ones. Similarly, Binder (2013) analysed the life cycle cost of a variation of repair methods (i.e. concrete facing, patch repair, patch repair with hydrophobic impregnation, CP with titanium mesh and CP with conductive coating) for chloride contaminated columns. Patch repair with hydrophobic impregnation and cathodic protection with a titanium mesh, turned out to be the most cost effective.

The question whether refurbishment of an existing structure is environmentally and/or economically profitable compared to a new construction is investigated by Ferreira et al. (2015) in order to build earthquake safe buildings complying the current standards. The study indicates the need of an integrated decision-making process to select the most beneficial execution method. Besides, it also highlights national uncertainty and preferences, environmentally speaken, in the decision making process of refurbishment versus demolition and creating a new equivalent construction. The results of their case study indicate that refurbishment is environmentally beneficial compared to a new equivalent construction. In contrast, as far as cost is concerned, refurbishment was found as less competitive.

From a perspective to the implications on the environment, the technology of concrete as a whole is investigated by Hájek et al. (2011) and Vieira et al. (2016). These studies emphasize the importance of subjects like performing a detailed LCA using data sets with local relevance and the need for more attention for the lack of a holistic assessment of environmental impacts, the lack of applications that consider regional and technological variations, and the neglect of life cycle phases. Focussing on concrete repair strategies, a probabilistic sustainability design framework for the repair and rehabilitation of existing concrete is presented by Lepech et al. (2014). The relevance of such a framework in order to improve the quantitative environmental sustainability indicators is highlighted, but the need for more research still remains to allow further implementation. Moreover, according to the research of Kumar & Gardoni (2014) it may be more advantageous to have frequent repairs for a long-term service life but for a short-term service life it may not be advantageous or may even be disadvantageous. Results of a study by Palacios-munoz et al. (2018) show that strengthening existing structures (in order to restore its bearing capacity) is more sustainable than rebuilding a new structure, even in the case of damage. The suitability of a solution is however strongly depending on the characteristics of the original element and the required service load. Strengthening of RC structures with different types of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) are investigated by means of LCA by Habert et al. (2013) and Hajiesmaeili et al. (2019). In the case of a concrete bridge rehabilitation, these studies obtain a decrease up to 50% of the environmental impact compared to replacement or conventional restoration over the life cycle. The environmental impacts of a refurbishment versus a demolition of an existing house is investigated by Gaspar & Santos (2015). Similar to the previous bridge case studies, refurbishing options produce less environmental impact than the construction of new buildings. Moreover, two repair strategies namely patch repair with sprayed repair mortar and a hydrophobic surface protection were compared in terms of environmental impacts by (Arskog et al., 2004). It was pointed out that the impact from the patch repair strongly exceeds those of the hydrophobic surface protection. With regards to corrosion damage of RC structures, cathodic protection is proven to be a successful technique to stop the corrosion process, particularly effective where chloride contamination is the cause of corrosion (Byrne et al., 2016). One of the benefits claimed for CP is the reduced extent of contaminated concrete removal and repair work, which lowers the cost compared to a more conventional approach.

For a maintenance strategy for bridges in particular, an optimisation based on LCA and LCC results is performed by Navarro et al. (2019) and Xie et al. (2018). Both studies confirm the importance of a preventive strategy: every proactive maintenance action reduces environmental and economic cost compared to a curative strategy where repair is undertaken at the end of the service life (reactive approach). In addition to environmental and economic impacts, the social implications of different rehabilitation options for concrete highways are evaluated by Choi et al. (2016). This study also stresses the importance of a life-cycle perspective for decision making of RC repair projects.

Overall, LCA and LCC studies mainly focus on the material level, e.g. “green concrete” (Turk et al., 2015; Van Den Heede & De Belie, 2012), or on material choices during design phase (Hafez et al., 2021; Rohden & Garcez, 2018). However, renovation of the existing building stock is the key to reduce the impact and therefore the whole repair strategy to extend the service life of an existing concrete structure should be considered. In general, there is a lack of LCA results of service life extending concrete repair techniques. This is also confirmed by Palacios-Munoz et al. (2019) who mention that most of the literature on LCA focuses on new construction while refurbishment is dealt with at a lower extent. Furthermore, if available, LCA and LCC studies focus more on the maintenance strategy of bridges, less on sustainable repair strategies for corrosion damaged residential RC buildings: the majority of those LCA studies mainly focus on energy refurbishment (UNEP, 2009), whereas the environmental impact of structural building elements, is being studied to a lesser extent (Vilches et al., 2017). Furthermore, comparation between different sustainability tools considering the combination of LCA and LCC to increase the sustainability of maintenance strategies of concrete structures, is due to methodological choices rather difficult (Scope et al., 2021).

Table 1: LCC-LCA studies comparing different repair or maintenance options for RC structures

Subject	LCA	LCC	Conclusions	Ref.
Maintenance RC building located in regions with high hazard of chloride ingress and seismic activity		x	Maintenance strategies that include steel supplementation are effective in reducing the life cycle costs	Chiu et al., 2010
Maintenance RC bridges		x	Undertaking less costly minor repair actions may considerably reduce the life cycle costs	D. M. Frangopol & Soliman, 2016; Ghodoosi et al., 2018
Repair corrosion damaged bridge deck		x	ICCP has a lower cost than conventional repair for a 100-years service life	Polder et al., 2016
Structural concrete repair	x		Strengthening the existing structure, even is the case of degradation, has a lower impact compared to replacement. The suitability of a solution is strongly depending on the characteristics of the original situation.	Palacios-munoz et al., 2018
Rehabilitations with UHPFRC	x		Rehabilitation of bridge deck using methods witch UHPFRC decrease the environmental impact up to 50%.	Habert et al., 2013
Maintenance RC bridges	x	x	Implementation of preventive maintenance could reduce the frequency of essential maintenance and corresponding cost, leading to considerably lower environmental impact of maintenance	Xie et al., 2018
Maintenance RC bridge deck	x	x	Every prevention design considered in this study reduces both the economic and the environmental impacts throughout the service life of the bridge deck when compared to the impacts associated with the durability design of the actual bridge.	Navarro et al., 2019
Concrete highway rehabilitation	x	x	Including environmental, economic and social impacts, CRCP was found the most preferable solution for a life cycle of 50 years. Higher initial cost can be recoupled by long-term benefits, as a more durable solution reduces the impact of repair interventions during the lifetime.	Choi et al., 2016

The availability of studies to support the decision making process for the rehabilitation of existing concrete structures through LCA and LCC is limited. The key messages of the literature review are summarised in Table 1. Based on the insights gained, this study has the objective to evaluate the economic and environmental impacts of lifetime extending repair techniques of RC residential building, more in particular the cantilevered RC balconies of those buildings. Balconies are thin concrete slabs often with a limited protecting concrete cover, exposed to outdoor conditions which differ from infrastructure elements as a bridge deck and indoor elements. Therefore, results of LCA and LCC for maintenance strategies for bridges cannot be generalised and used for decision making of the repair strategy for this case study.

For the extension of the service life of a balcony, five different repair techniques are selected and evaluated: (i) patch repair, (ii) conventional repair, (iii) repair using sacrificial anodes, Galvanic Cathodic Protection (GCP), (iv) Impressed Current Cathodic Protection (ICCP) and (v) the total replacement of the existing balcony. These repair strategies are based on the principles of concrete repair according to European Standard EN 1504-9. Depending on used repair technique and additional maintenance, the service life of the balcony is extended for a short (5 years), medium (20 years) or long (40 years) period. An LCA and LCC study of these five techniques is assessed to a case study of a 40-year old residential building in order to reach the desired service lifetime extension of the balconies. More in particular, to the authors knowledge, no LCA studies nor combined LCC-LCA studies on CP exists to compare this method with a conventional concrete repair, making this study innovative and proving the added value of its content.

2 METHODS

2.1 ASSUMPTIONS AND DEFINITION OF THE FUNCTIONAL UNIT

The extension of the service life of the existing balconies can be obtained by the application of several repair techniques when corrosion is affecting the durability of the concrete slabs. These techniques, applied in different repair scenarios for 5, 20 or 40 years of service life extension, are evaluated by means of LCA and LCC (Norris, 2001). In this case, the assumption is made that the corrosion process has not yet corroded the reinforcing steel rebars of the cantilevered element to a degree in which the bearing capacity is no longer guaranteed, which is determined by means of the protocol suggested by Craeye et al. (2019). However, initiation of chloride and carbonation induced corrosion is already reached, depassivation of the steel occurred but the propagation stage has not yet set in meaning the bearing capacity is not affected and is sufficient and strengthening is not required.

Defining the functional unit (FU) is the first step for performing an LCA and is also commonly applied in combined LCA-LCC studies. The functional unit is here defined as:

“the service life extension of 15 cantilevered reinforced concrete to a condition score 1 (excellent condition according to NEN 2767, i.e. incidental minor imperfections) for an additional lifetime extension of 5, 20 and 40 years. The balconies have following properties: dimensions are length =1m, x 20 x 0.1 m^3 (length x width x height) and are reinforced with a double steel mesh 8/8/150/150 mm.”

As three different periods for the life-extending repair techniques are specified, there are three different functional units to be evaluated. A graphical representation of the three FUs is shown in Figure 3, including the techniques that are able to meet the technical requirements for each FU. A condition score 1 defines an excellent condition based on the severity, extent and intensity of the present defects according to of the Dutch Standard NEN 2767 (2019). As a more technical approach on concrete repair is intended, other aspects such as renewal of the railing, renewal finishing top of the balcony, insulation of the façade, etc. are not considered in this study.

2.2 CASE STUDY: TYPICAL HIGH RISE BUILDING NEAR BELGIAN COASTLINE

The cantilevered balcony slabs of a typical residential building situated near the Belgian coastline (i.e. saline environment) were selected to evaluate the different repair methods. The selected building itself is not a fictional one, yet rather a simplified representation of an existing residential building were investigated in the scope of the PWO research project Balcon-e from which the input data and research outcomes of this paper are extracted. The simplified case study is entirely based on best practices, gained knowledge and expert judgement of actual existing and cases of high rise residential buildings. In most cases of buildings situated near the coastline, chlorides were found in the concrete elements. Note that even for concrete structures in the mainland chlorides can be expected, e.g. by using de-icing salts or chloride containing cleaning products (chloride ingress) but also by mixed-in $CaCl_2$ as a concrete binding accelerator or other chloride contaminated materials (sand, aggregates,…). The selected case for this LCA/LCC study is an example of the latter.

The building which is considered in this study and which is a realistic approach/prototype of a high rise residential building in Belgium (Figure 1), has 15 floors containing a balcony slab of 20 meters in length and a cantilever span of 1 meter. Each balcony consist of a 10 cm thick RC plate (total concrete volume of 30 m^3 and 633 m^2 of exposed concrete surface, approximately 2.6 tons of steel reinforcement) and a finishing layer of ceramic tiles (see Figure 2). According to EN 206 (2018) and NBN EN 15-001 (2018) the considered building and its reinforced concrete structures are categorized in exposure classes XS1-XC4-XF3 and environmental classes ES1: structure exposed to airborne salt but not in direct contact sea water, also exposed to air, moisture, rainfall and freezing in a cyclic wetting and drying nature. The designed service life is 50 years. No maintenance was carried out during the 40 years of service life after construction. For this case it is assumed that the carbonation front has reached the reinforcement and the chloride content has reached a critical value on the level of the concrete cover. As such, the reinforced structure is no longer able to withstand the conditions of the exposure and/or environmental classes which can be determined in a fully probabilistic matter taking into account the concrete cover and the maximum allowed chloride migration coefficient and carbonation coefficient, as suggested by De Winter et al. (2017) and Minne et al. (2019). As a result of this exposure to the outdoor (CO_2, H_2O, O_2) and saline conditions (Cl^-, H_2O, O_2), depassivation of the steel reinforcement has set in, corrosion is initiated by carbonation in combination with chloride ingress causing visible rust stains, cracks and delamination of concrete parts with corroding rebars starting to become noticeable. As the building is situated near the coastline, chloride ingress and carbonation can be considered as the dominant contributor leading to rebar corrosion and concrete damage. The corrosion of reinforcing steel induced by chloride attack or carbonation is a primary cause of the degradation in the durability of reinforced concrete structures, and as such cathodic protection has been demonstrated to be an effective and direct electrochemical method for preventing the corrosion of RC structures (Guo et al. (2021), which should always be considered as a durable repair technique in case of (chloride induced) corrosion.

The coating on the underside is blistering and an effective waterproofing is missing at the top of the slab. An intervention (maintenance and durable repair) is therefore needed to extend the service life of the balcony slabs.

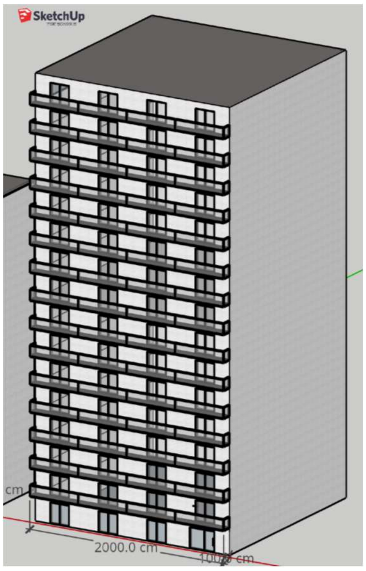


Figure 1: Residential building with 15 RC balcony slabs (l=1m; w=20m, h=0.1m)

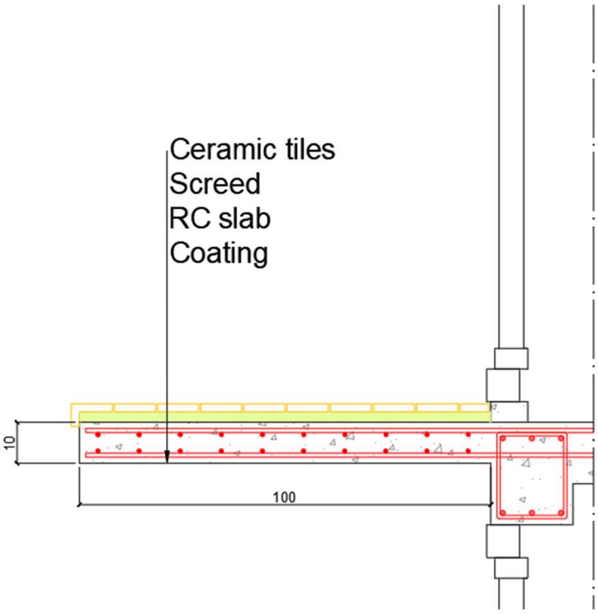


Figure 2: Detail balcony in original state: 10 cm RC slab, screed and ceramic tiles on top, coating underside RC slab

2.3 REPAIR TECHNIQUES AND SCENARIO DESCRIPTION

As mentioned in EN 1504-9 (2008), an investigation of the existing structure revealing the cause and extent of the damage prior to repair is essential in the whole process of rehabilitation (Craeye et al., 2017). The descripted techniques, selected materials and execution methods are chosen according to the principles of EN 1504-9 (2008) in order to fulfil the technical requirements. In this way, early failure of concrete repair (Tilly & Jacobs, 2007; Visser & Van Zon, 2012) is avoided. The potential of the repair methods to extend the service life is based on experience of professionals in concrete repair (repair contractors, suppliers of repair products, architect offices, investigation bureaus, etc.) in the Belgian context and supported by expert judgement.

Five realistic repair scenarios, typically applicable and frequently used for this kind of considered corrosion induced concrete damage in coastal areas, are evaluated in order to fulfil the FU:

- Patch repair (PR)
- Conventional Repair (CR)
- Galvanic Cathodic Protection (GCP)
- Impressed Current Cathodic Protection (ICCP)
- Total demolition and rebuild (NEW)

The first technique is called patch repair (PR). The delaminated concrete parts (3% volume) are repaired locally with a structural R4 class repair mortar in this scenario. As chlorides remain in the structure and ingress is continuing once the repair is performed, the corrosion process is not stopped adequately and will most likely continue, causing new corrosion problems in contaminated concrete surrounding the patched area, which is also known as the halo-effect (Qian et al., 2006; Raupach, 2006). The lifetime of this technique is short, estimated as 5 to 7 years based on expert judgement in this context, and confirmed by Krishnan et al. (2021).

The second method, a conventional repair (CR) according to the Belgian context, includes the removal of the delaminated and contaminated concrete parts (5% volume + balcony edges), removal of chlorides present on the reinforcement and protecting of the steel with an anti-corrosion coating. The reconstruction of the balcony is realised by means of a R4 repair mortar (5%) and the balcony edges are reformed by means of new concrete. The reinforcement of the edges is replaced. The existing finishing layers on top are removed and a new waterproofing (PU-based material) is provided on top. According to expert judgement in this context, a service life extension of 20 years is to be reached by means of CR.

As chloride ingress is identified as the main contributing factor leading towards corrosion of the reinforcement present in the balconies, CP has to be considered as a valuable repair technique. In contrast to a traditional approach where all contaminated concrete should be replaced to prevent corrosion, the technology of cathodic protection (CP) is based on an imposed current which inhibits the electrons transfer on the surface of the steel to effectively stop the corrosion process. Therefore, only the delaminated concrete parts (3% volume) should be removed and replaced. There are two types of CP: a passive variant using sacrificial anodes and an active with impressed current. Galvanic Cathodic Protection (GCP) uses sacrificial zinc anodes connected to the reinforcement to prevent corrosion (Sergi et al., 2021; Wang et al., 2020). The amount of zinc needed is depending on the reinforcement area to be protected and can be calculated by means of Faraday's law. In this case, four drilled-in anodes per m² balcony slab of 70g zinc/piece are used to protect the reinforcement for 20 years. As the existing finishing layers are removed because of the installation of the drilled-in anodes, a new waterproofing is provided on top.

A power supply delivers a low current to the anode in a Impressed Current Cathodic Protection (ICCP) system. A conductive coating with a primary titanium anode is selected as anode system for this case, applied to the surface (underside) of the balcony slabs (Wilson et al., 2013). A new waterproofing is placed on top of the balconies to avoid leakage which may disturb ICCP system and lead to a short circuit. Periodic inspections are included to ensure the effectiveness of the system. After a service life of 20 years the conductive coating needs treatment, based on experience of existing CP systems (Van Den Hondel & Van Den Hondel, 2018).

The fifth scenario (NEW) is the total demolition of the existing balconies and complete reconstruction of the balconies, including chemical and/or mechanical anchorage of the reinforcement and support of the cantilevered balconies. The same dimensions as the original state are taken. A renewal of the protective coating every 10 year is needed and included to ensure a service life of 40 years, based on the technical requirements provided by the supplier.

A protective coating is provided in each scenario to obtain the same degree of finishing in all scenarios, although this is not a technical requirement in case of GCP and ICCP. However, this is often applied in practice, mainly for aesthetic reasons. Maintenance of the coating every 10 years is only incorporated for scenario NEW. Table 2 summarises all the included activities of the five repair techniques. The main differences between the scenarios are (i) the quantity of concrete to replaced (PR (3%) vs. NEW (100%)) and (ii) the principle of protection of the reinforcement to corrosion (CR vs. CP).

	Patch repair	**Conventional repair**	**GCP**	**ICCP**	**New**
Potential service life extension (years)	5-7	20	20	20	40
Repair: Included activities intervention					
Demolition of existing finishing layers	-	x	x	x	x
Repair delaminated concrete	x	x	x	x	-
Removal contaminated concrete (edges)	-	x	-	-	-
Replacement balcony	-	-	-	-	x
Anti-corrosive coating (exposed reinforcement)	x	x	-	-	-
Installation sacrificial anodes	-	-	x	-	-
Installation ICCP system with conductive coating	-	-	-	x	-

Protective coating (underside & borders)	x	x	x	x	x
Waterproofing top balcony	-	x	x	x	x
Maintenance: renewal coating (10y)	-	-	-	-	x

Table 2: Potential service life extension and included activities of repair methods

The FUs encompass the lifetime extension of the existing corrosion damaged balconies for three different time periods (5, 20 and 40 years). As only NEW provides an extension of 40 years, the other scenarios need additional intermediate interventions to obtain a comparable service life of the balconies, visualized in Figure 3.
After the service life of the first patch repair (5 years), an increased volume of repair (resp. 7% and 15%), as a consequence of the continued corrosion process and the halo effect, is assumed for the next two interventions (2 x 7 years) for extending the service life of the existing situation. After 20 years, a local patch repair is excluded for further elongation in this scenario as structural safety can no longer be guaranteed after three interventions. The scenarios CR, GCP and ICCP presume an intervention to extend the service life for an additional 20 years. This intervention is smaller than the preceding one as the waterproofing is still effective. A concrete repair with R4 class repair mortar of 5% for conventional and 3% volume for CP scenarios is included. The sacrificial anodes are replaced in GCP, and renewal of the electronic components and conductive coating in ICCP. A renewal of the protective coating (underside and balcony edges) is provided in PR, CR, GCP and ICCP in the next interventions. A summary of the assumptions for the repair methods for the FU of 5, 20 and 40 years is given in Table 3. Details of scenario assumptions (materials, quantities, …) can be found in the supplementary materials (A).

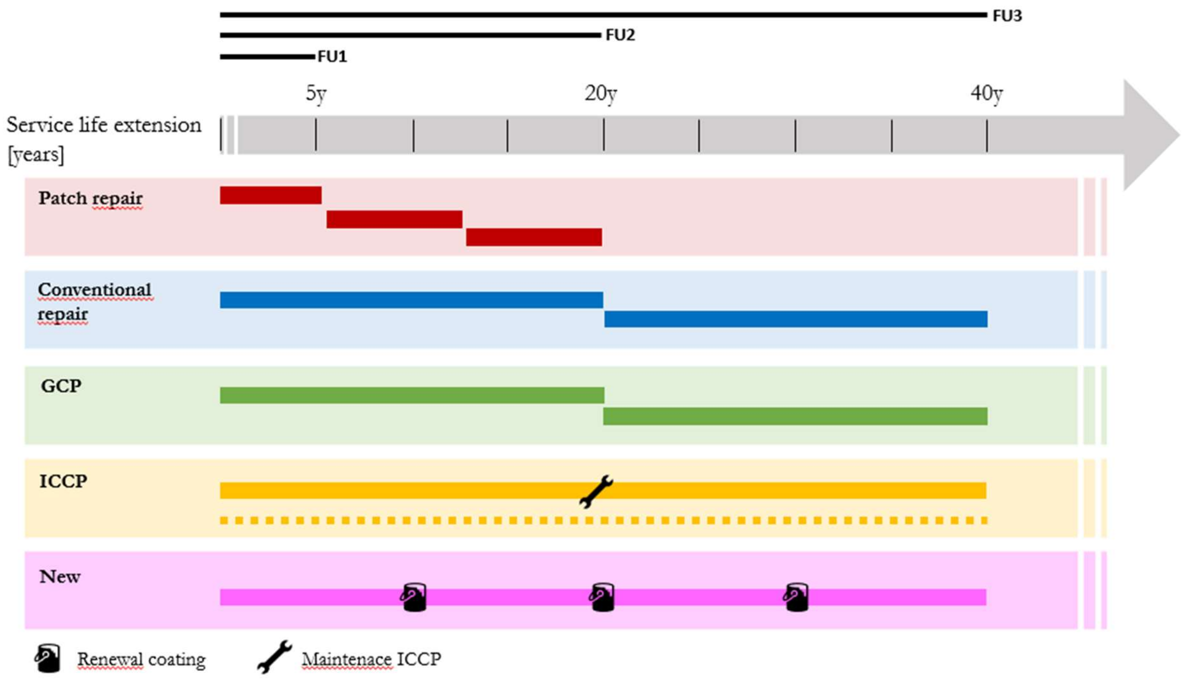


Figure 3: Scenarios Patch repair (PR), Conventional repair (CR), Galvanic Cathodic Protection (GCP), Impressed Current Cathodic Protection (ICCP) and total renewal (NEW) for a service life extension of 5, 20 and 40 years of the existing balcony slabs. The patch repair scenario is only repeatable up to 3 times and is therefore excluded at FU = 40y.

Table 3: Overview bill of quantities assumptions [in kg] for all repair methods: Patch Repair (PR), Conventional Repair (CR), Galvanic Cathodic Protection (GCP), Impressed Current Cathodic Protection (ICCP) and total rebuilding (NEW) for FU = 5y, 20y and 40y, inclusive sensitivity analysis (SA) scenarios.

	FU = 5y					**FU = 20y**					**FU = 40y**				
	PR	**CR**	**GCP**	**ICCP**	**NEW**	**PR**	**CR**	**GCP**	**ICCP**	**NEW**	**PR**	**CR**	**GCP**	**ICCP**	**NEW**
DEMOLITION															
Demolition inert fraction (tiles, screed, concrete)	2160	50190	33447	32910	102750	10800 [5040][1]	50190	33447	32910	102750	-	52350	33447	32910	102750
CONCRETE REPAIR															
New concrete 35 MPa	-	15840	-	-	24000	-	15840	-	-	24000	-	15840	-	-	24000
Repair mortar class R4	1890	3150	2100	1890	-	15750 [6300][1]	3150 [6300; 12600][3]	2100	1890	-	-	5040 [8190; 14490][3]	4200	3780	-
REPAIR/PROTECTION REINFORCEMENT															
Reinforcement	-	417	-	-	4167	-	417	-	-	4167	-	417	-	-	4167
Anti-corrosive coating reinforcement	24	80	-	-	-	200 [80][1]	80	-	-	-	-	104	-	-	-
Sacrificial anode	-	-	360 [540][4]	-	-	-	-	360 [540][4]	-	-	-	-	720 [1080][4]	-	-
Conductive coating	-	-	-	90	-	-	-	-	90	-	-	-	-	180	-
Primary anode	-	-	-	50	-	-	-	-	50	-	-	-	-	50	-
Electronics	-	-	-	30	-	-	-	-	30	-	-	-	-	60	-
Cable	-	-	-	59	-	-	-	-	59	-	-	-	-	59	-
PROTECTION BALCONY															
Primer (coating /waterproofing)	50	95	95	95	95	150 [100][1]	95	95 [45][2]	95	95	-	145	145 [45][2]	145	95
Protective coating concrete (PU based)	300	300	300	300	300	900 [600][1]	300	300 [0][2]	300 [0][2]	600	-	600	600 [0][2]	600 [0][2]	1200
Waterproofing (PU based)	-	858	858	858	858	-	858	858	858	858	-	858	858	858	858

1: SA1
2: SA2
3: SA3 – resp. 10% and 20%
4: SA5

2.4 LIFE CYCLE ASSESSMENT (LCA)

A consequential methodology is followed by assessing the LCA to analyse the environmental impacts of the selected repair methods. In this way, the change to environmentally relevant flows is described as a response to possible decisions (Buyle, 2018). According to Weidema et al. (2013), two of the most important aspects of consequential LCA are (i) the identification of marginal suppliers (i.e. the activities affected by a change in demand) and (ii) the substitution of non-determining by-products on the market (to avoid allocation as advised in ISO 14044 (2006)).

The studied system includes the entire life of the repair scenario as described in section 2.3 (including manufacturing of the materials and construction). The power supply for the ICCP is not taken into account, as the impact is limited because of the low required current, impact is less than 1% (0,35 kWh/year/m^2). Transportation is included in each phase, according to the Belgian context. As this case is situated in Belgium, typical Belgian construction methods are assumed, using products assembled in the EU. Default scenarios representative for the situation (*OVAM,* 2020) are considered in the end-of-life (EoL) scenarios.

For each FU (5, 20 and 40 years), the impact is considered which is necessary to extend the service life of the existing situation. This includes the demolition of the damaged parts and the reconstruction in order to fulfil its function for the defined period. However, the construction of the original balconies and demolition at the end of the total life span (20y Patch, 40y others scenarios) is excluded, in order to avoid considering profits of recycled products where no production impacts (original balconies) were taking into account. In addition, further interventions (next repair or total demolition) are subjected to the state of the total building.

Marginal suppliers are identified at country level. The required trade and production data are derived from UN Comtrade (United Nations, 2019), based on the practical method proposed by Buyle et al. (2018). The ecoinvent database v3.5 was used to model background processes and its principle of separating market and production processes was also applied in this case study (Weidema et al., 2013). ecoinvent records were used as a starting point for the production process, while data on the marginal mixes of energy production were modelled for concrete, repair mortars and coatings. Although concrete has the potential of carbon uptake due to the carbonation process (García-Segura et al., 2014; Xi et al., 2016), this is not considered in the emission inventory as a protective coating is used in all repair scenarios to prevent corrosion initiated by carbonation. Full details can be found in the supplementary materials (B, C, D).

ReCiPe v1.13 was selected as method for the environmental impact assessment, as implements both midpoint and endpoint categories and contains a set of weighting factors allowing the classification of an impact by a single score (Goedkoop et al., 2009; Sleeswijk et al., 2008). To facilitate interpretation of results, the single scores are used to evaluate all scenarios and sensitivity analyses in order to capture all environmental impact for the comparation of the repair methods. A selection of the midpoints is discussed for the reference scenario for the functional unit of 20 years.

2.5 LIFE CYCLE COSTING (LCC)

For the financial evaluation of the different repair scenarios, the same framework as presented for the LCA was used. Due to the absence of a general framework for LCC, the assumptions of ISO 14040/44 (2006) were adopted when possible. In addition to the LCA, costs of labour, equipment and monitoring an ICCP-system are included. The prices are based on the current practice in the Belgian renovation sector, however, it should be noted that the total cost may strongly depend on local market situations, the scale of the project and the complexity of the execution. Nevertheless, prices were determined in close cooperation with the concrete repair industry (repair contractors, suppliers and engineering & architectural consultancy companies) and supported by experts judgement, who were part of the Balcon-e PWO project. The Net Present Value (NPV) for the defined FU's is calculated according to equation

1. A typical value for discount rate of 4% in the public sector is considered, which reflects the time preference, risk and loss aversion and other psychological factors (Galle, 2016). Details of the quantities and prices can be found in the supplementary materials (E, F).

Equation 1

$$NPV = I_0 + \sum_{t=1}^{N} \frac{CF_t}{(1+d)^t}$$

I_0 : Initial investment (year 0)

CF_t : cashflow in year t

d: discount rate

N: study period

Varying the discount rate d was included in the first stage of the analysis. However, it was found that this did not have a substantial impact on the conclusions, since the cashflows are mainly situated in the long future (t > 20 years).

2.6 SENSITIVITY ANALYSIS

The previous descripted scenarios (section 2.3) are assumed as default scenarios. Several assumptions are made, including some that may strongly influence the results of the LCA-LCC, e.g. assumption of the life extending nature of PR, the use of aesthetic coating in case of CP, the amount of removal of contaminated concrete in case of CR, the amount of cement present in repair mortar, the effect of the amount of zinc needed for GCP and the uncertainty of the environmental impact of zinc in case of GCP. Furthermore, a closer look is taken at the effect of variation in material cost and labour prices. Therefore, seven additional analyses (SA) are evaluated:

- SA1: Given the uncertainty regarding the service life of a repair, the potential of extending the life time using Patch Repair is additionally assumed as 10 years. Therefore, only two interventions are necessary for the defined FU of 20 years. The extent of these interventions is estimated as equal to the first two interventions in the default scenario. Both environmental impact and the NPV are evaluated here. Achieving an FU of 40 years with a patch repair remains impossible, as Patch can only repeated three times.
- SA2: In the general scenario, all repair methods where finished with a protective coating at the underside of the balconies. However, when a CP-system (GCP and ICCP) protects the reinforcement, this coating is not a technical requirement. The impact of the coating on the LCA/LCC-score is compared with the general scenario.
- SA3: One of the advantages claimed for the implementation of a system of cathodic protection, is that the required concrete repair is limited to the delaminated parts instead of all the chloride contaminated zones. In a conventional repair, all the contaminated concrete should be replaced in order to prevent reinforcement corrosion and avoid the halo effect. Prior estimation of the required concrete repair is not straightforward and the volume can be considerable larger. The influence of the extent of the contaminated concrete with a R4 repair mortar for a CR scenario, is compared to the default CR, GCP and ICCP scenarios.
- SA4: In the GCP scenario, an uncertainty with a high influence on the environmental impact was pointed at the end-of-life scenario of the sacrificial zinc anodes. It is assumed that in-drilled anodes are sorted to the inert waste fraction as they are part of the concrete structure. This fraction is often reused in e.g. road foundation. However, more investigating is needed of the behaviour of the zinc and zinc-oxide/hydroxide compounds. The formed corrosion products are highly dependent on the environment (Vera et al., 2013) and the formation of zinc corrosion

products in an atmospheric environment is described as a complex and continuously changing process (de la Fuente et al., 2007). Kamde et al. (2021) investigated the long-term performance of galvanic anodes for the protection of steel reinforced concrete structures, remark that zinc reacts with both acids and bases to form salts. So, a variety of zinc oxides/hydroxides can be formed, in the presence of constituents (e.g. CO_2, SO_x, Cl^-), of which zincite (ZnO), simonkolleite ($Zn_5(OH)_8Cl_2$) and hydrozincite ($Zn_4CO_3(OH)_6 \cdot H_2O$) are frequently observed corrosion products in atmospheric conditions (Santana et al., 2012; Thomas et al., 2012; Vera et al., 2013). Corrosion products can include soluble products such as zinc chloride ($ZnCl_2$) and zinc sulfate ($ZnSO_4$) which can be leached by rainfall (Vera et al., 2013). This leaching is influenced by the environment and rainfall characteristics regarding the amount of corrosion products that will dissolve. However, there is a possibility that cementitious materials can well confine trace metals such as zinc (Maeijer et al., 2021). At this moment, it is uncertain if and in what extent leaching of concrete aggregates containing zinc corrosion products will happen. Therefore, an inert behaviour is assumed for the general scenario, and compared to the worst case of leaching to ground water (Sethurajan et al., 2016, Wuana & Okieimen, 2011)) in the sensitivity analysis.

- SA5: The amount of zinc needed to protect the reinforcement for a certain period via GCP is influenced by (i) the amount of steel in the RC structure, (ii) the desired service life extension and (iii) the current density per area of steel, and can be estimated by means of Faraday’s law. The effect of an increased amount of zinc is being considered, which for example is needed in case of a higher chloride contamination of the RC: the analysis is made for six instead of four anodes (70g zinc to protect the reinforcement for 20 years).
- SA6: Prices of materials and labour costs may increase in the future. Therefore, an increase of 10 and 20% of the prices of (i) the materials costs and (ii) the labour costs is being considered. Typical labour-intensive items are the removal of the contaminated concrete and manual concrete repair with mortar. Application of GCP and ICCP on the other hand induces higher material costs.
- SA7: Regarding uncertainties of material composition, the cement quantity in repair mortar is considered, as this is one of the basic components of concrete repair and cement production has a major environmental impact. A variation of cement content per m^3 repair mortar is evaluated (700 kg and 850 kg compared to the default value of 800 kg).

A summary of the assumptions of the SA was added to Table 3.

3 RESULTS AND DISCUSSION

3.1 ENVIRONMENTAL IMPACTS (LCA)

The total impact of the different repair scenarios is presented in Figure 4 and Table 4. The cumulative impact is shown on the timeline at the moment it occurs as a result of an intervention. Until the third intervention (service life extension up to 13 years), patch repair has the lowest total impact: 25% lower than the next option. Considering the high risk of new corrosion near the repaired areas (halo effect), an increased volume of concrete repair is required for the next life time extensions. Due to the sequence of several interventions, the owner are more frequently disturbed during the different repair periods. However, this cannot be qualified or quantified in LCA. The patch scenario is excluded for a life time extension of 40 years as the load bearing capacity may decrease to an unacceptable reliability level as a consequence of the reduction of the reinforcement area due to corrosion. GCP and CR show a similar impact (± 5%) during the first life time extension of 20 years. However, an additional intervention for GCP (replacement sacrificial anodes) involves a higher impact (15%). After 20 years, the scenarios CR, GCP and ICCP are subjected to a next intervention in order to extend the service life up to 40 years. The conventional repair method has in this case the lowest impact and NEW the highest (36% more than conventional).

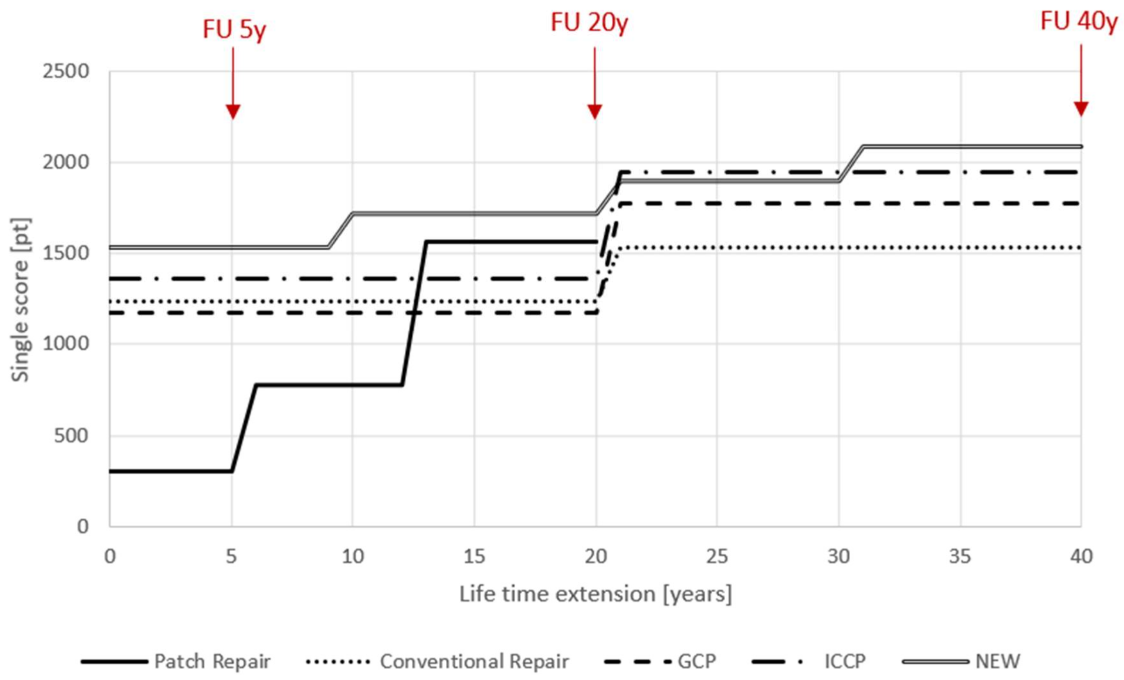


Figure 4: Total impact default scenarios during a life time extension up to 40 years

Table 4: Single scores [pt] default scenarios for FU = 5y, 20y and 40y

	PR	CR	GCP	ICCP	NEW
FU 5y	301	1234	1173	1361	1532
FU 20y	1563	1234	1173	1361	1716
FU 40y	-	1535	1772	1947	2084

The total impact consists of four subprocesses: (i) demolition (top layer existing balcony, delaminated concrete, corroded reinforcement), (ii) concrete repair (R4 repair mortar, concrete), (iii) repair and protection reinforcement (anti-corrosive coating or sacrificial anodes, ICCP-system, replacement of reinforcement) and (iv) protection of the refurbished balcony (waterproofing top side of the balcony, protective coating on the borders and the bottom of the balcony). The resulting impact of each subprocesses is shown in Figure 5, 7 and 9 for the FU's of 5, 20 and 40 years respectively. The protection of the balcony, including the waterproofing on top and a protective coating on the underside and edges, has a major part of the total impact. The production of the waterproofing and coating, based on polyurethane, causes the major impact here. The subprocess 'demolition' causes a negative impact, as a result of the recycled reinforcement. This effect is also visible in CR: although a larger part is demolished (5% concrete plus edges including reinforcement) than the CP-techniques (3% concrete), the impact of the demolition part is smaller. However, the reinforcement is replaced whereas the impact is retrieved by 'repair reinforcement'. To protect the reinforcement by means of cathodic protection, the ICCP-system has a higher impact as more components (electronic components, wiring, anode system) are required, compared to GCP where only sacrificial anodes are implemented. In the scenario NEW the entire concrete slab is removed and new concrete elements are installed whereas for CP only a part is renewed (5% volume + edges). Nevertheless, the impact of this part in CR is higher, as structural repair mortar involves a higher impact as a result of a considerably higher amount of cement fraction (approximately 2-3 times higher).

The scenarios CR, GCP, ICCP and NEW have the potential to extend the service life of the balconies for 20 or 40 years: as a FU of 5 years is defined, these techniques have a major part of ‘unused’ potential in this situation. The total impact and the ‘used’ potential (determined as a percentage of the years of the FU in relation to the maximum extension of the technique) are shown in Figure 6, 8 and 10. Decision making is based (i) on the lowest total impact and (ii) to maximise the potential of a technique. For a service life extension for 5 years, PR is clearly the most favourable option. As a FU of 20 years is requested, the potential of PR, CP, GCP and ICCP is exploited. CR and GCP have an equal total impact, where CP has a larger volume of concrete repair versus the sacrificial anodes for GCP. As a result of three interventions in the scenario where patch repair is executed, the total impact exceeds CR and the options with cathodic protection.

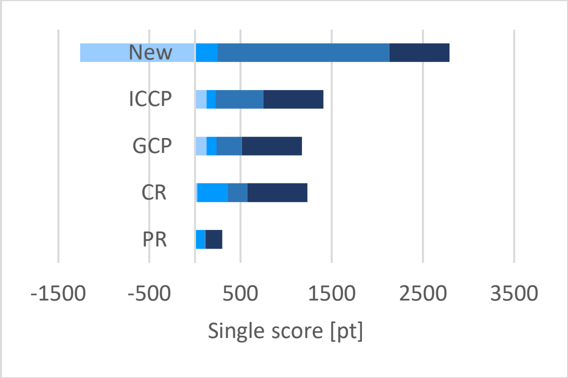


Figure 5: Single Score per subprocess (FU = 5y)

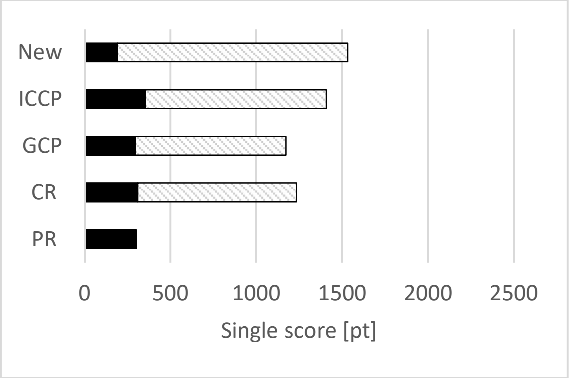


Figure 6: Total and 'used' potential LCA (FU = 5y)

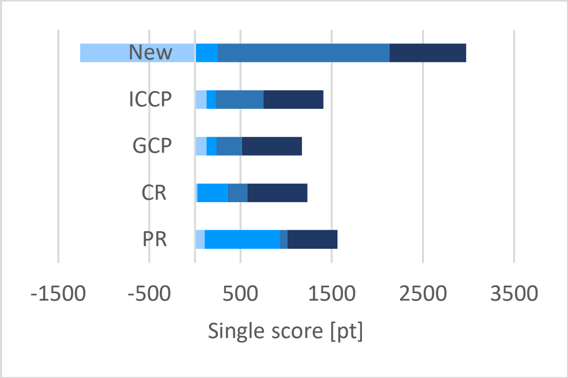


Figure 7: Single Score per subprocess (FU = 20y)

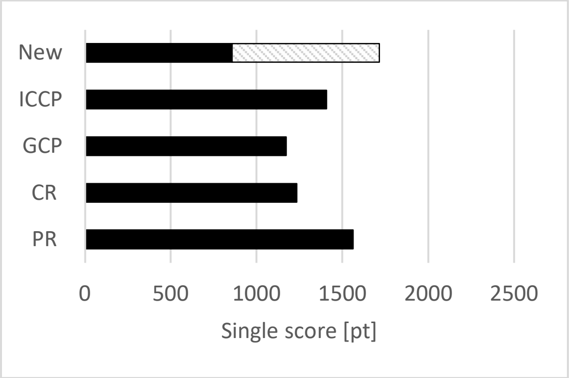


Figure 8: Total and 'used' potential LCA (FU = 20y)

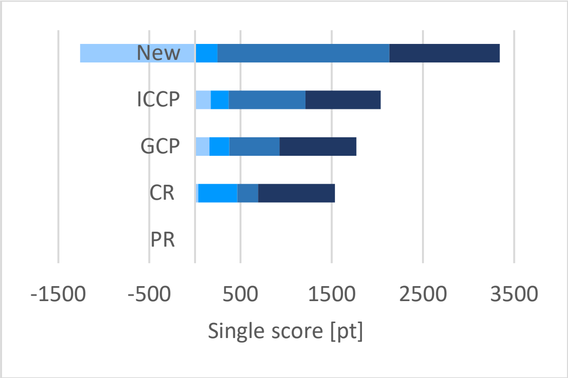


Figure 9: Single Score per subprocess (FU = 40y)

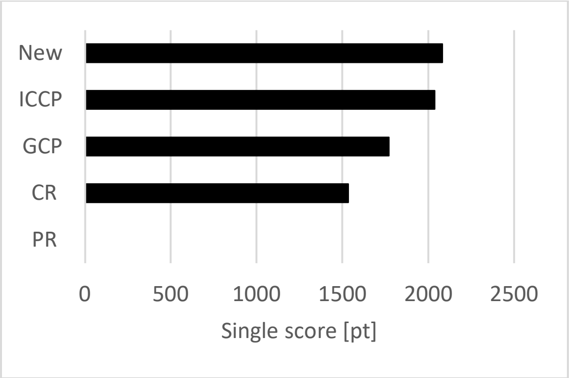


Figure 10: Total and 'used' potential LCA (FU = 40y)

■ Demolition
■ Concrete repair
■ Repair / protection reinforcement
■ Protection balcony

■ 'Used' potential
☐ Total Impact

To complete the analysis of the single score results, for the reference scenario (20y) a selection of midpoint indicators are analysed as well. The frequently used midpoint category 'Climate change potential', which expresses the impact in CO_2 equivalent, shows a similar trend to the Single Score results (Figure 11 and Figure 12). CO_2-emmisions are mainly linked to the cement content in concrete and repair mortar. A substantial difference compared to the single score results is noticeable in the midpoint categories linked to eco-toxicity, e.g. human and freshwater as shown in Figure 13 and Figure 14. These impacts are related to metals such as zinc used in the sacrificial anodes or titanium/copper in the ICCP-system. The implementation of cathodic protection may considerably reduce the amount of concrete renewal, which saves CO_2-emissions from new concrete/repair mortar, however, other effects such as ecotoxicity should not be neglected. The full results of the midpoint categories, which focusses on the FU of 20 years as most presumably life time extension, can be found in the Supplementary Material (D).

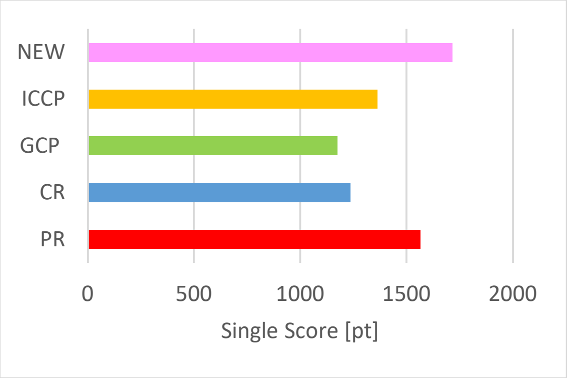


Figure 11: Results Singe Score [in pt] for FU=20y

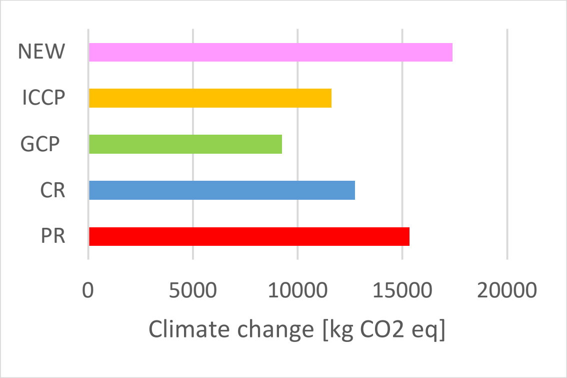


Figure 12: Results midpoint Climate change potential [in kg CO_2 eq] for FU=20y

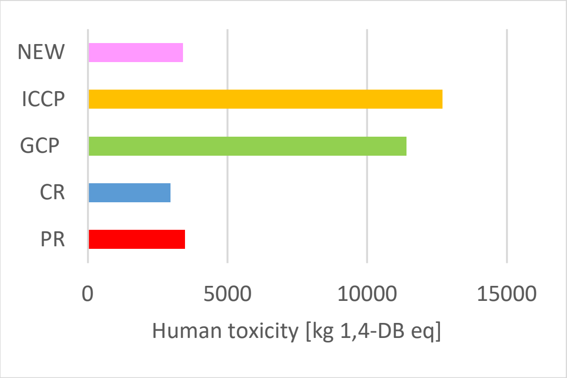


Figure 13: Results midpoint Human toxicity [in kg 1,4-DB eq] for FU=20y

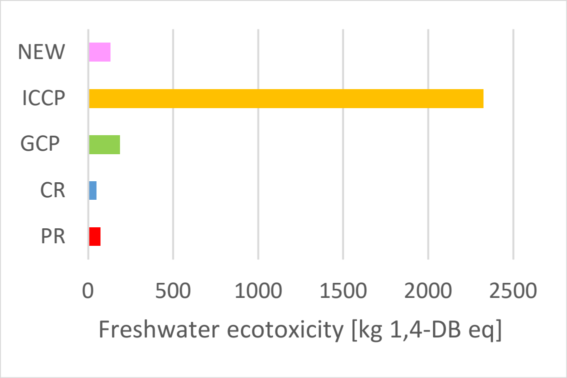


Figure 14: Results midpoint Freshwater ecotoxicity [in kg 1,4-DB eq] for FU=20y

3.2 Financial impact (LCC)

The NPV was considered to analyse the life cycle cost of the different repair techniques, these results are shown in Figure 15 and Table 5. Similar to the LCA, patch repair has the lowest impact until the third intervention for a service life extension up to 13 years and a total replacement involves the highest overall cost. Three interventions are required in the patch repair scenario to obtain a service life extension of 20 years, which involves a higher uncertainty concerning the future costs as other materials or execution techniques might be selected.

Previous research (D. M. Frangopol & Soliman, 2016; Ghodoosi et al., 2018) also indicate that undertaking less costly minor repair actions may considerably reduce the lifecycle costs as a result of decreasing the number of costly major interventions for bridge structures. However, local repair cannot accomplish all technical requirements for a longer period when corrosion is initiated by chlorides. Moreover, the studied lifetime of bridges is often longer than for buildings.

The implementation of CP-system reduces the amount of replacement of contaminated concrete. When corrosion is initiated by the ingress of chlorides, an ICCP system can be an efficient method to stop the corrosion process, as it is difficult to remove all the chlorides in a traditional repair. From a financial perspective, the implementation of ICCP appears to be the best option for a service life extension of more than 20 years, where replacement of the entire existing balconies by new ones has the highest cost

(NPV is twice as high compared to ICCP). In order to ensure the effective performance of the ICCP-system, the annual monitoring (as determined in the maintenance contract) is crucial. The induced costs of the first intervention of a conventional repair and GCP are similar (± 1,5%). When a life time extension up to 40 years is designated, the financial impact of the second intervention of CGP is 1,3 times CR. The LCC by (Polder et al., 2016) shows a lower cost for ICCP with conductive coating compared to CR (14%): the initial cost of ICCP is lower than CR and less interventions during the 100-year service life are necessary, but annual monitoring (incl. costs) is required. Overall, ICCP results in a lower NPV, which is a similar result to this case (-8%) for a period 40 years after the damage is repaired.

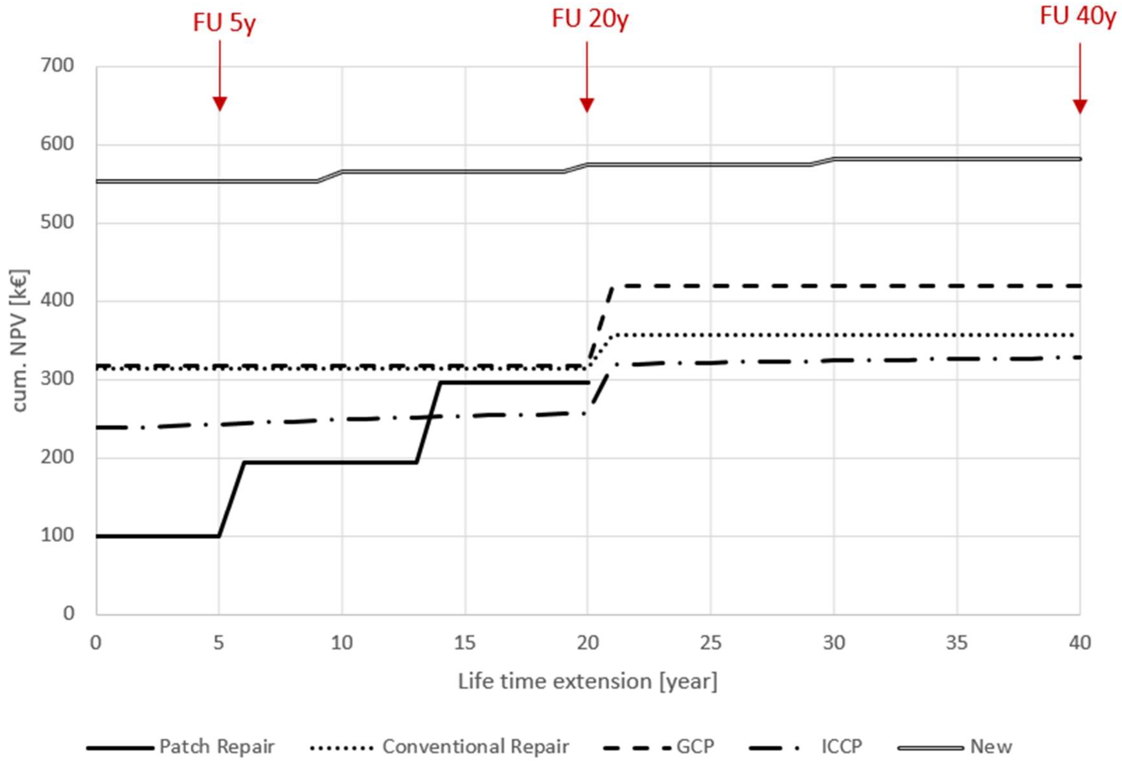


Figure 15: NPV default scenarios during a life time extension up to 40 years

Table 5: NPV [k€] default scenarios FU = 5y, 20y and 40y

	PR	CR	GCP	ICCP	NEW
FU 5y	100	313	317	243	552
FU 20y	295	313	317	257	575
FU 40y	-	357	419	327	581

Similar to the results of the LCA shown in Figure 5 to Figure 10, the NPV of the four subprocesses and total and 'used' potential for the defined FU's are shown in Figure 16 to Figure 21 respectively. General costs, such as site equipment which are not considered in the LCA, are allocated to the other subprocesses. The waterproofing in the subprocess of 'protection balcony' on top of the concrete slabs involves 70k€ additional cost during the first intervention compared to PR where this is not included. The potential of the techniques including waterproofing is 15 to 35 years longer, however, this potential is not 'used' in the FU of 5 years which make PR here more favourable. Except from the subprocess 'reinforcement protection'; GCP and ICCP have a similar cost profile. The difference between the active and passive variant of CP to stop the corrosion process are situated in the maintenance cost which are included in ICCP, but the installation of the sacrificial anodes involves a NPV of 60% more. The construction of a new concrete slab is the most expensive option: 50% of the total cost are related to subprocess of concrete repair here.

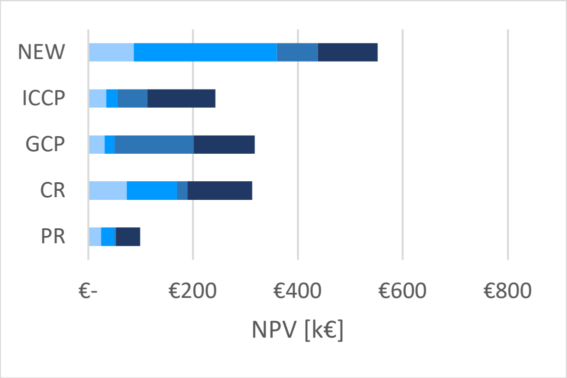


Figure 16: Net Present Value per subprocess (FU = 5y)

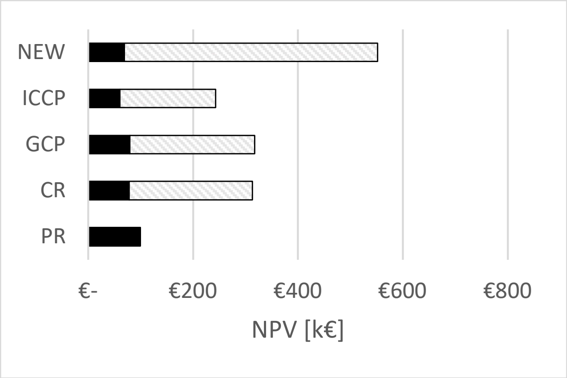


Figure 17: Total and 'used' potential LCC (FU = 5y)

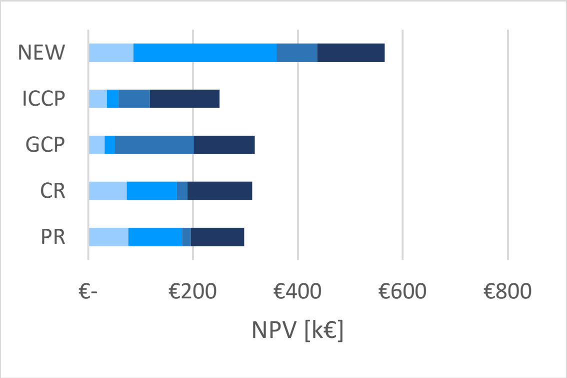


Figure 18: Net Present Value per subprocess (FU = 20y)

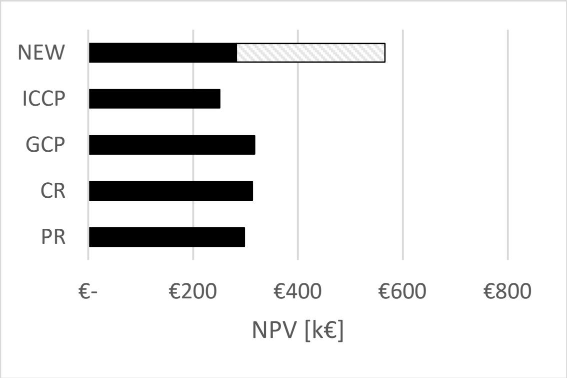


Figure 19: Total and 'used' potential LCC (FU = 20y)

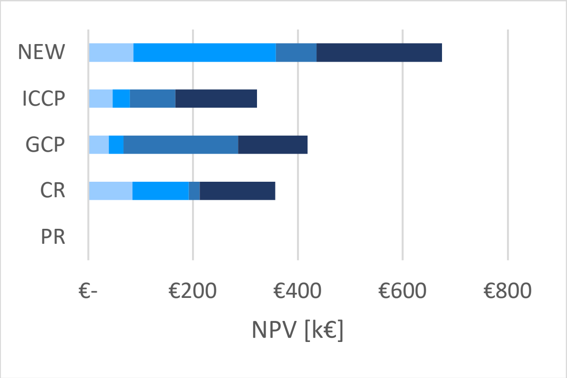


Figure 20: Net Present Value per subprocess (FU = 40y)

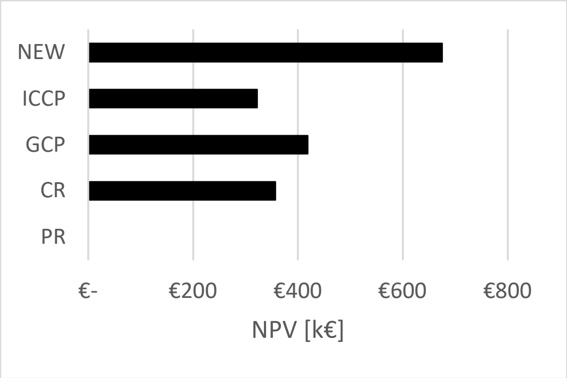


Figure 21: Total and 'used' potential LCC (FU = 40y)

■ Demolition
■ Concrete repair
■ Repair / protection reinforcement
■ Protection balcony

■ 'Used' potential
□ Total NPV

3.3 DECISION MAKING BASED ON COMBINED FINANCIAL AND ENVIRONMENTAL IMPACT

In order to endorse decision making based on both financial and environmental impact, benchmark charts visualise the LCA and LCC score for the defined FU's of 5, 20 and 40 years in Figure 22 - Figure 24. The results of the environmental impact (LCA, in pt) are shown on the x-axis and the life time cost (LCC, in k€) on the y-axis. In this chart, the best option is located near the origin, where the lowest environmental impact and NPV are situated. It appears that patch repair method is the most sustainable option in this case when a short extension is requested, whereas NEW is less favourable. It is obvious that the FU's of 20 and 40 years involves higher impacts and cost a more interventions are required to fulfil a longer service life extension of the existing balconies. For 20 years, GCP and ICCP are found as optima: GCP has the lowest LCA-score, whereas ICCP has the lowest cost. The other repair methods involves a higher environment impact for a lower cost (e.g. PR) or vice versa. The difference between GCP and CR is limited: 5% LCC and 14% LCA. As for the extension up to 40 years a next intervention for these methods is required, CR and ICCP are optima in this case. The total demolition and reconstruction of the balconies (scenario NEW) is the most extensive scenario and involves the highest environmental and financial impact for the described FU's. (Gaspar & Santos, 2015) made a similar conclusion for a 40y old house where the impact of refurbishment vs. demolition was studied. However, in this study the power supply is excluded (impact is max. 1%), so there is no impact during the use stage.

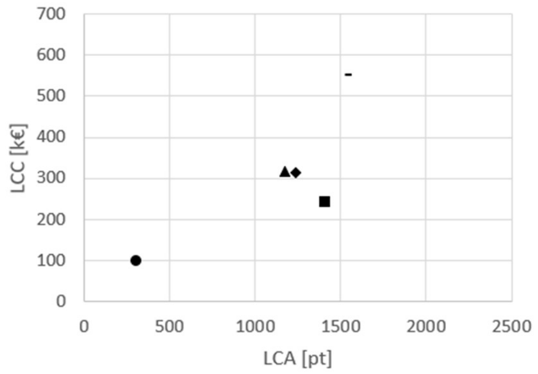


Figure 22: LCA vs. LCC (FU=5y)

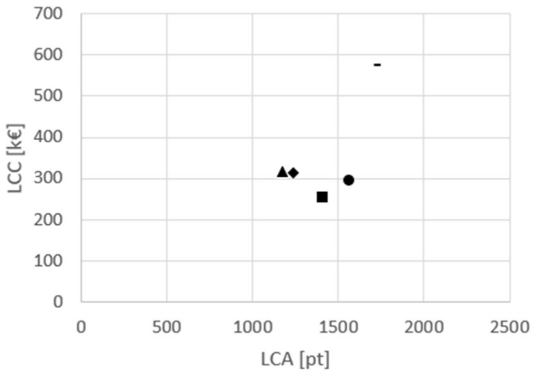


Figure 23: LCA vs. LCC (FU=20y)

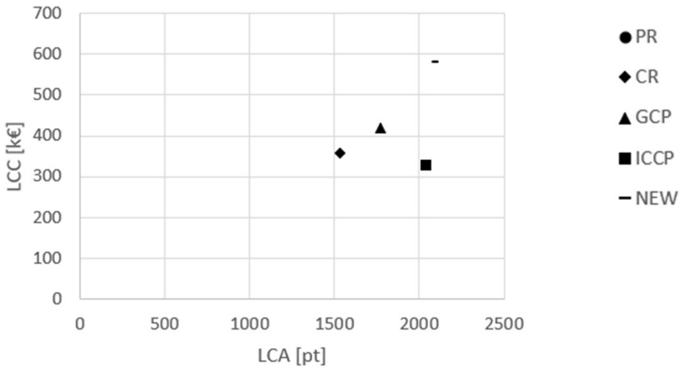


Figure 24: LCA vs. LCC (FU=40y)

3.4 SENSITIVITY ANALYSIS

Figure 25 and Figure 26 shows the results of the sensitivity analyses [SA1 – SA5] compared to the default LCA and LCC impact respectively for a FU of 20 and 40 years.

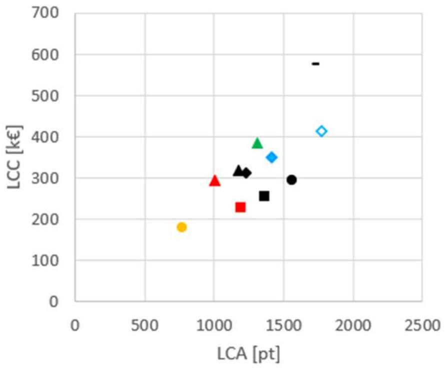
SA1: The potential of PR to extend the service life of the existing construction is assumed as 10 years in this analysis. The LCA score is the same as for the first two default interventions of a patch repair. In LCC, the NPV is influenced by the timing of the intervention, which is resulting in a lower NPV for two Patch repair compared to the default. On Figure 25, it is clearly shown that this is an optimum compared to the default scenarios: the LCA score reduces with 50% and LCC with 40% compared to the default PR. Combined LCA-LCC studies by (Navarro et al., 2019; Xie et al., 2018) indicated that the implementation of preventive maintenance could reduce the frequency of essential maintenance and corresponding cost, leading to considerably lower environmental impact of maintenances. This effect is also noticeable in this study.

SA2: In the default scenarios, a protective coating on the underside and borders of the balconies is included. When the reinforcement is protected by cathodic protection (GCP or ICCP), a coating to prevent ingress of CO_2 or chlorides is not required to avoid corrosion. GCP, excl. coating, has the lowest environmental impact for a FU of 20 years and ICCP has the best financial performance. Conventional repair was the optimum for 40 years life time extension in the default scenarios, however, when the coating is excluded in GCP, this is resulting in a lower single score in LCA than CR. In the default scenarios only CR was found as optimum, however, when the coating is excluded in GCP and ICCP, these options are optima as well. This effect is more prominent in the LCA score, as in LCC the cost of the second intervention at 20y is discounted for a FU of 40 years.

SA3: When reinforcement corrosion was induced by chlorides, all the contaminated concrete should be replaced in order to avoid new corrosion problems as a result of the ring-anode effect. In case of an excessive volume of contained concrete, CP is possible a more sustainable option as it responds to the corrosion process itself. The conventional repair was default evaluated with 5% replacement with R4 repair mortar and concrete for the edges in the first intervention. The impact on LCA and LCC of and increased volume (10% and 20%) with R4 repair mortar is show in Figure 25 and Figure 26. The LCA score exceeds the NEW for a FU of 20 years, as a result of the higher amount of cement in repair mortar compared to concrete. Whereas GCP and CR showed a similar result in the default assumptions, it is clear that CP-systems are more sustainable options in this case when the volume of replaced concrete is larger. For life time extension of 40 years, the performance of CR10% is more favourable than the default GCP, ICCP and NEW, however, less compared to GCP and ICCP excl. coating.

SA4: In the default scenarios, the environmental impact of the end-of-life treatment for a sacrificial zinc anode is assumed as inert, as the zinc compound is consumed and residual zinc-oxide is fixed in the mortar of the anode. In worst case, the zinc (if not all consumed) or zinc-oxide leaches to the soil as the concrete waste is used as road foundation. The total impact of one sacrificial zinc anode is three times higher in worst case than an inert EoL. Therefore, the assumption made for the EoL of the sacrificial anodes has a decisive value for the total impact of the GCP repair option. This effect is shown on Figure 26: as the sacrificial anodes needs replacement after 20 years, the environmental impact of the GCP scenario increases with 30% and exceeds therefore NEW. Changes to LCC are not considered here. The EoL of the used zinc anodes can highly influence the LCA-score (Wuana & Okieimen, 2011), but further investigation of the EoL of zinc anodes is designated.

SA5: Higher amounts of zinc can be needed to avoid (further) corrosion of the steel and extent the service life of the structure, for example in case of a higher degree of chloride contamination or an increased amount of steel reinforcement surface to be protected. The default GCP scenario (four in-drilled anodes per m^2 balcony-slab) is compared with the scenario in which an additional 50% of zinc (six anodes per m^2) is installed in order to protect the reinforcement for 20 years in case of higher chloride content. The LCA and LCC score increase respectively with 12% and 20% for FU=20y and 15% and 23% for FU=40y, which make GCP a less favourable repair method in case of high chloride content.



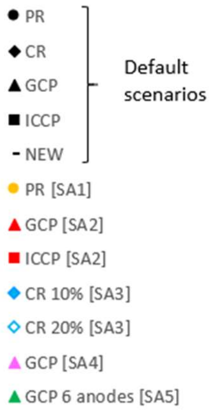


Figure 25: Sensitivity analysis (FU = 20y)

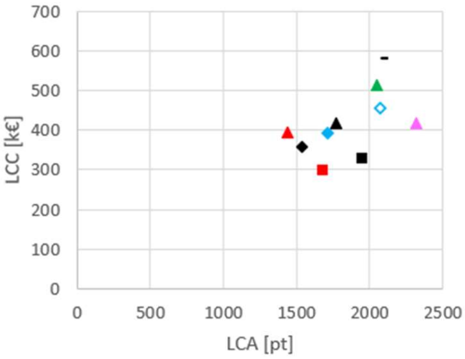


Figure 26: Sensitivity analysis (FU = 40y)

SA6: Regarding a possible increase of labour and material costs in the future, an increase of 10 and 20% of the labour-intensive actions and specific material components (e.g. electronic components for ICCP-systems is analysed and results are shown in Table 6 and Table 7 for the functional units of 20 and 40 years. The increase of the labour cost is more noticeable in the conventional scenarios as PR, CR and NEW. On the other hand, the possible higher material costs for CP-systems can also have a decisive influence on the total price. An increase in the cost of materials will be more noticeable for components of CP-systems. The ICCP-system has for both FUs the lowest life cycle cost for all pricing alternatives, a new construction the highest. The ranking between techniques only differs for FU = 20y, where the GCP-system is preferred over the CR when labour cost increases with 10%. For the FU = 40y it is also worth mentioning that ICCP has the lowest LCC score, NEW the highest, regardless possible labour and/or material price increases.

Table 6: Results SA6 – LCC score [k€] increased labour and material cost (FU = 20y). Ranking from cheapest to most expensive strategy is added between round brackets.

	PR	**CR**	**GCP**	**ICCP**	**NEW**
Default scenario	€ 297.995 (2)	€ 313.192 (3)	€ 317.648 (4)	€ 250.902 (1)	€ 565.469 (5)
Labour cost +10%	€ 311.265 (2)	€ 324.261 (4)	€ 322.105 (3)	€ 255.358 (1)	€ 582.314 (5)
Labour cost +20%	€ 324.535 (2)	€ 335.329 (4)	€ 326.561 (3)	€ 259.815 (1)	€ 599.159 (5)
Material cost +10%	€ 304.301 (2)	€ 320.586 (3)	€ 337.679 (4)	€ 262.233 (1)	€ 572.300 (5)
Material cost +20%	€ 310.607 (2)	€ 327.980 (3)	€ 357.710 (4)	€ 273.564 (1)	€ 579.131 (5)

Table 7: Results SA6 – LCC score [k€] increased labour and material cost (FU = 40y). Ranking from cheapest to most expensive strategy is added between round brackets.

	PR	**CR**	**GCP**	**ICCP**	**NEW**
Default scenario	-	€ 356.890 (2)	€ 418.579 (3)	€ 322.046 (1)	€ 674.698 (4)
Labour cost +10%	-	€ 369.414 (2)	€ 424.491 (3)	€ 327.958 (1)	€ 691.966 (4)
Labour cost +20%	-	€ 381.938 (2)	€ 430.403 (3)	€ 333.870 (1)	€ 709.208 (4)

Material cost +10%	-	€ 365.338 (2)	€ 445.425 (3)	€ 334.400 (1)	€ 686.588 (4)
Material cost +20%	-	€ 373.786 (2)	€ 472.272 (3)	€ 346.754 (1)	€ 698.492 (4)

SA7: Repair mortar contains significantly more cement compared to concrete compositions (up to 300%), but the amount may also differ individually, depending on product type and/or supplier. Considering the environmental impact of the cement production process, the LCA score has been evaluated and the results are shown in Table 8 and Table 9 for FU=20y and 40y respectively. The influence is most pronounced in the case of PR and CR, as the percentage of concrete repair mortar is higher compared to CP-systems. In case of CP repair, only the loose parts of the R structures need to be removed and restored whereas for PR and CR all contaminated concrete need to be treated. The score of the scenario NEW does not change as only new concrete and no repair mortar is used.

Table 8: Results SA7 – LCA score single score [pt] variable cement content repair mortar (FU = 20y)

	PR	**CR**	**GCP**	**ICCP**	**NEW**
Default scenario 800 kg cement /m³ repair mortar	1563	1234	1173	1361	1716
700 kg cement /m³ repair mortar	1518	1225	1168	1356	1716
850 kg cement /m³ repair mortar	1585	1238	1176	1364	1716

Table 9: Results SA7 – LCA score single score [pt] variable cement content repair mortar (FU = 40y)

	PR	**CR**	**GCP**	**ICCP**	**NEW**
Default scenario 800 kg cement /m³ repair mortar	-	1535	1772	1947	2084
700 kg cement /m³ repair mortar	-	1520	1760	1936	2084
850 kg cement /m³ repair mortar	-	1541	1778	1952	2084

The material choices (e.g. anode type in ICCP, type of coating), the extent of damage (e.g. volume of chloride contaminated concrete) influences the total impact of the repair method. Corrosion may affect the bearing capacity as well, resulting in the additional need of structural repair techniques. Social aspects, such as disturbance during multiple interventions or monitoring for ICCP, are not included in LCA or LCC. The outcome of this analysis and sensitivity study is not to be generalized and is based on a concrete high-rise building with cantilevered balcony slabs, with 15 floors containing a balcony slab of 20 meters in length and a cantilever span of 1 meter and with a total concrete volume of approximately 30 m³ and 600 m² of exposed concrete surface. However the obtained trends in the LCC/LCA decision making process are clear. More scenarios could be included in future research, to increase insights in the sustainability of concrete repair projects to support the decision making process of a repair strategy.

4 CONCLUSIONS

As sustainable repair, rehabilitation and retrofitting of the existing building stock is a key factor for reducing the environmental and financial impact during the total service life, LCA and LCC are used as quantitative tools for evaluating and comparing different repair techniques and facilitating the decision making. The repair method must fulfil the technical requirements and harmonise to the required service life extension.

As corrosion is the main contributor to the degradation of existing concrete structures, a residential building in a Belgian coastal environment with damaged reinforced concrete balconies (total concrete volume of approximately 30 m³ and 600 m² of exposed concrete surface) is selected as case study in order to evaluate five different frequently used repair techniques by means of a life cycle assessment (LCA) and life cycle cost analysis (LCC): traditional repair methods such as (i) patch repair and (ii) conventional repair, electro-chemical treatment to stop the corrosion process such as (iii) galvanic cathodic protection and (iv) impressed current cathodic protection and (v) total replacement of the element. The life cycle environmental and financial consequences of those life extending repair actions were compared for these five scenarios, applied on the selected high-rise building.

For a short lifetime extension (5y) of the balconies, a patch repair is the most preferable option as the existing situation is restored with a minimum of intervention. When a service life extension up to 40 years is requested, different options (Conventional, GCP, ICCP) are found as sustainable performance options with regards to LCA and LCC. The most extensive scenario is the total replacement of the balconies (NEW) and involves the highest environmental and financial impact for the described FU's.

It must be highly stressed that the conclusions of this case study cannot be generalised, as the cost and environmental impact are case-dependant and influenced by the assumptions made for the reinforced structure, the selected materials and extend of the desired repair to achieve a particular service life extension for the specific situation. Several alternative scenarios were investigated in this study: the amount of removal of contaminated concrete, the cement concentration in repair mortar, the assumed life extension of patch repair, the effect of coating, the effect of the amount of zinc needed for sacrificial cathodic protection and even the uncertainty of the environmental impact of zinc in the end-of life scenario. The material choices (e.g. anode type in ICCP, type of coating), the extent of damage (e.g. volume of chloride contaminated concrete) influences the total impact of the repair method. Furthermore, material cost and labour prices variations are to be considered in the decision making process.

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