COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

PROACTIVE OR REACTIVE? PROBABILISTIC DYNAMIC LIFE CYCLE ASSESSMENT FOR THE EVALUATION OF ADAPTATION STRATEGIES IN CRITICAL INFRASTRUCTURE UNDER NATURAL HAZARD

Roberta Di Bari[1], **Dimitrios V. Bilionis**[2], **Korbinian Czirwitzky**[3], **David Borschewski**[3] **and Stergios A. Mitoulis**[2]

[1] University of Birmingham, Department of Civil Engineering
Edgbaston, B29 TT2 Birmingham
e-mail: {r.dibari, s.a.mitoulis}@bham.ac.uk

[2] Environmental Reliability and Risk Analysis (ERRA)
11745, Athens, Greece
{d.bilionis}@erra.gr

[3] University of Stuttgart, Department of Life Cycle Engineering (GaBi)
70569, Stuttgart, Germany
{korbinian.czirwitzky, david.borschewski}@iabp.uni-stuttgart.de

---

Abstract

Construction is one of the industries that significantly contributes to climate change and is making efforts to reduce carbon emissions. At the same time, natural disasters already impact construction timelines and budgets, causing delays in projects worldwide. It is, therefore, necessary to direct decisions towards renovation strategies with low environmental impacts and implement them before natural disasters intensify, leading to unbearable consequences. Traditional Life Cycle Assessment analyses do not account for unexpected extreme events' environmental consequences. To overcome this gap, enhanced approaches integrating Risk Assessment utilising probabilistic and dynamic approaches can be used. As a first step, damage scenarios are derived based on vulnerability assessments and fragility curves. Hazard functions are afterwards modelled to characterise the selected uncertainty. Variabilities, due to, e.g., decarbonisation trends in the construction industry are also considered. This enables the compilation of the life cycle inventory and the assessment of the life cycle's environmental impacts. Unlike existing methodologies, the developed approach considers the dynamic performance of building systems, which may improve with retrofitting or deteriorate over time due to ageing. This work uses the methodology to evaluate and compare reactive, proactive, and hybrid strategies that combine proactive and reactive measures. During the analysis of a strategy, it is possible to evaluate and compare adaptation options based on their sustainability performance. The methodology is applied to a transmission tower subjected to different climate scenarios of extreme icing and wind gusts.

Keywords: environmental sustainability, LCA, natural hazard, LCA uncertainty.

---

1 INTRODUCTION

Decarbonising the building sector by 2050 is critical in delivering emissions and resource cuts globally, but it is also in the interest of the whole construction industry. Among all industries and sectors, construction is one with the highest contributions to greenhouse gas (GHG) emissions and, therefore, is particularly called for immediate action, investment, and policies [1]. On the other hand, unpredictable extreme weather events already affect construction timelines and budgets by delaying construction projects worldwide (estimated 45%), costing project owners and contractors billions of dollars in additional expenses and lost revenue each year [2]. As GHG emissions continue to climb, climate change progresses more rapidly than expected, exacerbating natural disasters such as floods, hurricanes, and wildfires. Drastic changes and more sustainable practices for a resilient built environment are needed [3].

The assessment of environmental life cycle impacts can be provided by Life Cycle Assessment (LCA), whose framework and calculation rules are established by international standards ISO 14040 [4] and ISO 14044 [5]. In the construction sectors, such standards are specified further by EN 15804 [6], EN 15798 [7], and EN 15643 [8].

The underlying model, data uncertainties, and variabilities, as the occurrence of natural disasters, are the main barriers to a robust early life cycle impact assessment [9]. Therefore, for current LCA applications, variable and uncertain information is mostly solved using assumptions. In the case of natural disasters, their occurrence is generally neglected in traditional LCA. As a result, such analyses are called into doubt since such assumptions might not reflect the long-life cycle of building and infrastructure assets [10]. Recent research in the field of LCA underscores the need for novel future-oriented approaches addressing uncertainties and variations to avoid shortsighted interpretations of results that might mislead decisions towards strategies that will be deemed ineffective and disadvantageous in the long term [11].

This work addresses this challenge and presents a novel methodology for future-oriented LCA analyses in uncertain circumstances dictated by natural disasters. The developed approach allows the *exploration* of different design alternatives (i.e. it is an explorative approach). Moreover, the approach allows for dynamic and probabilistic approaches to handle data uncertainties and variabilities. The novelty of the work is the consideration of the evolutionary performance of buildings and infrastructure assets, which is currently lacking in the state-of-the-art approaches. With regard to this, Section 2 of this work provides fundamentals for understanding dynamic and probabilistic approaches and a review of state-of-the-art approaches. Section 3 presents the methodology and highlights how this overcomes the identified research gaps. The methodology is applied to a transmission tower subjected to extreme icing and wind gusts (Section 4). Based on such an application, conclusions and future outlooks are outlined (Section 5).

2 STATE OF THE ART

2.1 Life Cycle Assessment (LCA) and future-oriented approaches

Life Cycle Assessment (LCA) is a method to describe the potential environmental impacts of a product or service throughout its life cycle. A product's life cycle from "cradle to grave" includes the phases from raw material extraction through manufacturing, use, end-of-life treatment, recycling, and disposal. An LCA study comprises four phases, which are: 1) goal and scope definition (G&S), 2) inventory analysis (Life Cycle Inventory – LCI), 3) impact assessment (Life Cycle Impact Assessment – LCIA) and 4) interpretation [4].

This work will refer to the computational structure for LCA analysis proposed by Heijungs [12], which describes mathematically the generation of LCA results through linear algebra and calculates the results of the analysis in the following Formula (1).

$$\boldsymbol{r} = \boldsymbol{Q} \times \boldsymbol{H} \times \boldsymbol{G}^{-1} \times \boldsymbol{u} \quad (1)$$

Bold characters indicate matrices and vectors, where:

- **r** is the vector of LCA results;
- **Q** is the matrix of characterisation factors (part of LCIA);
- **H** is the environmental intervention matrix of emissions per unit process (LCI);
- **G** is the technology matrix representing the inter-process flows (LCI);
- **u** is the external supply vector related to the functional unit (G&S). [12]

Based on the chosen approach, the provided formula and its matrices can be further characterised. Figure 1 provides the graphical illustration provided by Di Bari et al. [13] for a more immediate understanding of different approaches.

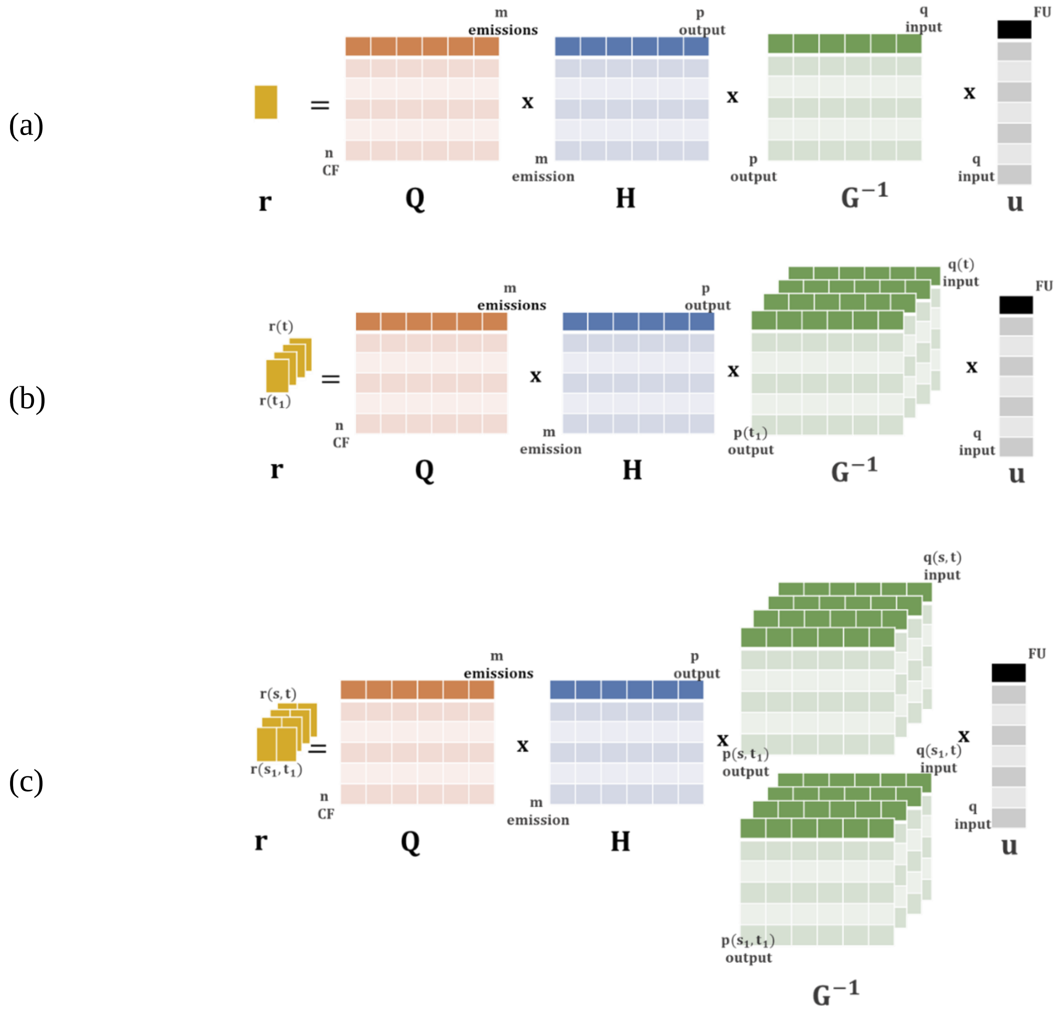


Figure 1: LCA approach influence on LCI and technology matrix G. Examples for: a) static, b) dynamic, c) dynamic + scenario LCA [13].

Traditional LCA approaches are static and non-explorative. Therefore, they provide a unique r result based on a unique set of data stemming from a specific system. Dynamic approaches consider meanwhile variations and extend the set of data. For instance, they can consider temporal variation of systems. In this sense, they are future-oriented approaches. For each point in time of the measurement (t) one result is generated (r(t)). In the presence of uncertainties, at each point in time of the measurements, different values can be recorded. Each measurement reflects a s-scenario. As a result, the r vector is a function of time t and scenario s. For each t, more results can be generated. The results can be represented as a range of values or a probability distribution.

2.2 LCA for assessment of effects due to uncertain natural disaster: research needed

In the presence of uncertainties, tools used for Risk Assessment can be integrated into LCA analyses for uncertainty propagation. When such uncertainties are stochastic, such as the ones describing natural disasters (e.g. earthquakes), tools for Probabilistic Risk Assessment can be integrated, and probabilistic LCA approaches can be defined [14]. Available methodologies for sustainability assessments with integration or RA are provided in the literature review of Di Bari et al. [15].

According to the outcomes of the recent review, existing frameworks rely on structural verification according to current design codes to verify the structural performance of constructions. These frameworks focus on limited economic and environmental metrics. Climate change and waste are prioritised as environmental issues. Economic analyses are limited to assessing Net Present Value and effects due to indirect costs. Most studies still prefer deterministic approaches and do not carry out uncertainty analyses. These frameworks assume, in fact, that built systems designed according to current design codes will present lower vulnerability to shock events caused by natural hazards. As an advantage, the use of deterministic approaches allows for measuring a broad set of environmental indicators, including diverse sustainability issues (e.g., Acidification Potential, Land Use, public investment, and fatalities) [15]. When the occurrence of natural disasters is integrated into life cycle analyses, this is considered a source of stochastic uncertainties. Thus, Monte Carlo Simulation is preferred for propagating stochastic uncertainties [15].

Besides the methodological disagreements, a significant lack can be highlighted. Existing frameworks do not consider that built systems change their performance over time (see Figure 2). Such performance variations are due to upgrades or downgrades of structural performance. Upgrades can result from structural retrofit, and other refurbishment measures, as defined in EN 15798 [7]. Downgrades are meanwhile related to corrosion, deterioration or overall structural ageing. The state of the art of LCA analyses considers a stationary performance. When a building system is subjected to a shock event, a repair measure is performed aimed at re-establishing the initial structural performance. This assumption might not be realistic and can restrict the range of alternatives stakeholders can evaluate during decision-making. For instance, stakeholders might be interested in knowing if it is more sustainable and effective to: a) carry out only reactive measures and re-establish the initial functionality several times, pursuing *reactive* strategies or b) be *proactive* and perform more ambitious interventions, improving the quality or functionality compared to the original construction. On the one hand, proactive strategies might also require high investments, but on the other hand, they improve the performance of buildings and reduce the risk of future losses.

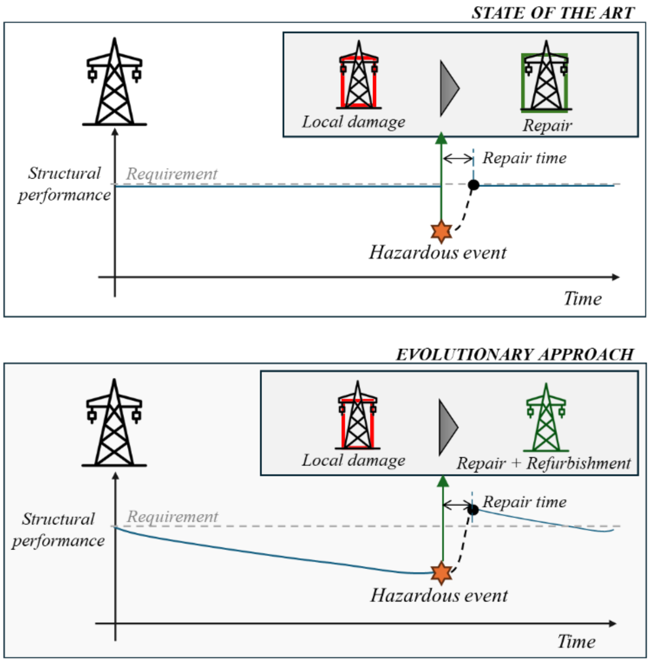


Figure 2. Structural performance variation after hazardous events in life cycle analyses. Comparison of state-of-the-art and proposed evolutionary approach.

3 METHOD

A novel methodology is presented here based on the research gaps outlined in Section 2.2. The developed approaches are based on the generalised procedure for Risk Assessment integration in LCA analyses presented by Sauve et al [14]. This procedure is enhanced to consider the evolutionary performance (in this case, structural performance).

Figure 3 provides an overview of the procedure and shows how the LCA analysis integrates Probabilistic Risk Assessment (PRA) for handling uncertainties. The original LCA framework is shown in the white rectangles, stages for a PRA in green, and stages of uncertainties analysis in grey. It can be noticed that this procedure integrates uncertainty analysis over the whole LCA framework: in this sense, it differentiates from the indications provided in the ISO 14040 standard, which addresses uncertainty analysis in the interpretation phase [4].

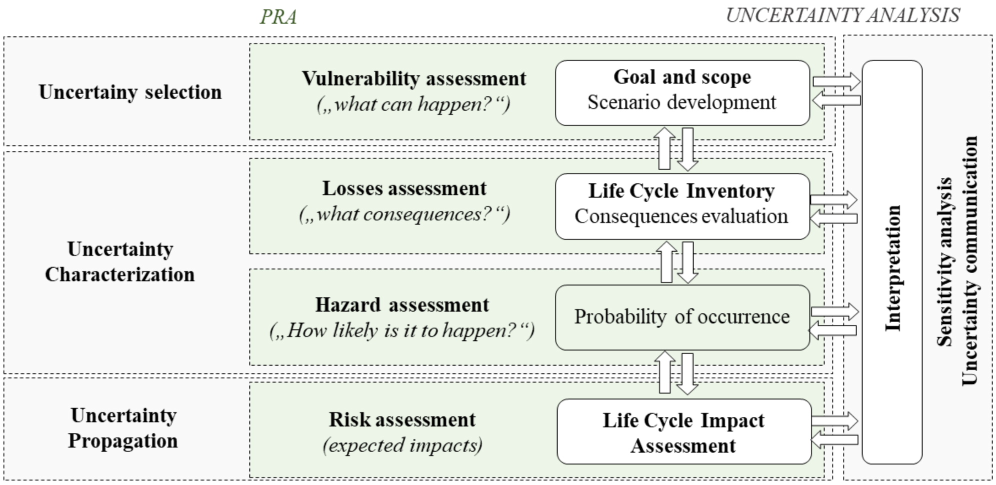


Figure 3: Probabilistic Risk Assessment integration in LCA. Procedure for Probabilistic LCA approaches for consideration of effects due to natural hazard.

3.1 Goal and Scope

The developed method adds two additional tasks to the ones usually carry out within the Goal and Scope of an LCA analysis.

Probable (also called "predictive" or "what-if" [16]) scenarios are selected within this stage. This overlaps the uncertainty selection stage of an uncertainty analysis [17]. The uncertainties, in this case, the natural disaster occurrence, are selected with the help of experts and designers. The hazard function λ(t) expresses the stochastic uncertainty of a parameter with a Probability Density Function (PDF) (Normal, Poisson, Gumbel distribution, etc.) or cumulative hazard function Λ(t) (CPD).

In the same stage, a vulnerability analysis of the system is performed to analyse possible damage scenarios. The derivation of fragility curves supports this task.

3.2 Life Cycle Inventory (LCI)

Following, the LCI is compiled. During this stage, the hazard and damage scenarios are analysed to derive necessary adaptation options. This overlaps the loss assessment foreseen in PRA.

Differently from state-of-the-art approaches, which use techniques like decision trees, in the developed methodology, a *matrix of measures* and the *evolution function* are established to perform the dynamic evolutionary assessment. The matrix of measures is a three-dimensional matrix that collects all possible combinations of measures, repair (RP), refurbishment (RF) and building new adaptation options (BN) that can be carried out after the occurrence of shock events (H(t)) depending on the structural performance level of the asset (P(t)) at that point in time (see Figure 4, left). Structural performance evolution can be established based on literature, simulations or experimental evidence. The number of combinations of measures equals the determined matrix's third dimension. Meanwhile, the number of hazardous events and the level of structural performance equals the number of rows and columns, respectively. The evolution function checks the time span and the structural performance before providing a measure. Depending on the evolution of the structural performance and the provided measures, the evolution function upgrades or downgrades the performance level.

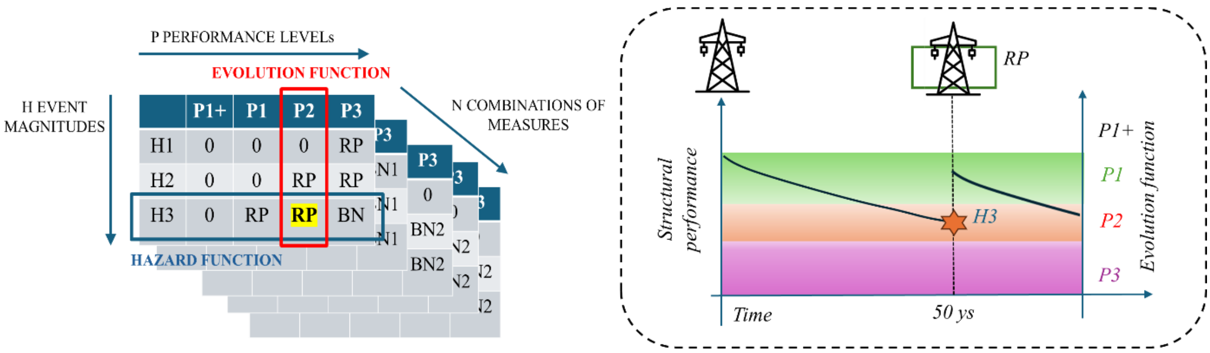


Figure 4. Matrix of measure and evolution function for dynamic evolutionary assessment.

3.3 Life Cycle Impact Assessment (LCIA) with Evolutionary Performance

After the loss assessment, the PDF or CDF are used to propagate uncertainties and generate results. The results (in this case, the life cycle environmental impacts and costs) are the combination of the likelihood of an uncertain event and its severity. Within this stage, a Monte Carlo Simulation can be performed, if the uncertainties can be classified as stochastic.

The Monte Carlo (MC) Simulation produces a random value (RV) for each time step consistent with the provided PDF or CDF and generates H_x shock events with different magnitudes.

Based on the event generated and the level of performance of the systems at time t, an adaptation options scenario (repair, replacement or refurbishment scenario) is selected from the decision matrix. For instance, in Figure 4, a transmission tower after 50 years undergoes a shock event (H3). The generated hazard event allows for a selection of a matrix row (marked with a blue line box in Figure 4). The evolution function selects a column for each combination (marked with a red line box in Figure 4). At this point in time, due to ongoing corrosion, the vulnerability class downgrades from P1 to P2. Therefore, according to the first combination of measures, a repair (RP, highlighted in yellow in Figure 4) is selected from the matrix of measures, and the original performance level (P1) is re-established.

The selected scenario is converted into emissions through the H intervention matrix and into impacts through the matrix of characterisation factors. H and Q matrices are created based on available environmental impact and cost datasets. Concluding, the result of the LCA analyses carried out through this methodology is a function of the point in time of the occurrence of shock events, the hazard function and the structural vulnerability.

$$\boldsymbol{r}(t, P(t), H_m) = \boldsymbol{Q} \times \boldsymbol{H} \times \boldsymbol{G}^{-1}(t, P(t), H_m) \times \boldsymbol{u} \quad (2)$$

3.4 Results processing, visualisation and interpretation

The r result vector, calculated with Formula (2) entails the results of every MC simulation run. To make informed decisions based on the results, the following statistical records can be extracted and communicated:

- The maximal r value: r_{max}
- The minimal r value: r_{min}
- The average r value: r_{mean}
- A standard deviation.

The difference between minimal and maximal values and the standard deviation can be utilised to evaluate the overall uncertainty of the results. Higher values indicate a higher uncertainty. The aggregation of the results vector can also be used to better grasp the results. Graphical representations of the results vector can help practitioners to establish a better understanding. Finally, sensitivity analyses are carried out for better communication of effects due to uncertainties.

4 APPLICATION

The methodology is applied to a power transmission tower located in eastern Finland. The tower belongs to a part of the 110 kV Kontiolahti – Uimaharju powerline with a length of approximately 8 km. The climatic data are collected and used for the uncertainty analysis. High winds and icing events were identified as relevant hazards, and their PDF and CDF were modelled.

4.1 Goal and Scope

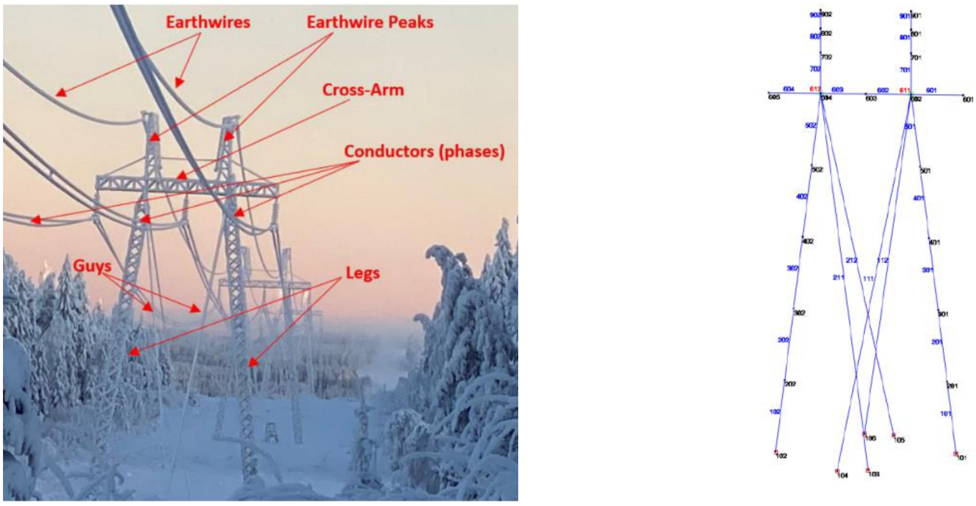


Figure 5: Photo typical tower (left) and tower FEM (right)

The tower is built from steel S355. The main members of the tower (Figure 5 (left)) include a cross-arm that supports the three phases, two legs that support the cross-arm, and two earth wire peaks that support the two earth wires. Furthermore, the whole tower is supported by four guys. The tower members are composed of steel angle profiles of various sizes. The lower tip of the cross-arm can be between 15 to 29 m above ground, while the cross-arm has a height of 0.65 m, and the earthwire peaks have a height of 3.55 m each.

In the scope of the study, the analysis aims to understand:

- *if* and *how* climate change affects economic and environmental impacts,
- *which strategy should be preferred*. Reactive strategies do not carry out any measure at t = 0; proactive strategies aim to strengthen the tower with renovation works at t = 0.
- *Which measure* in response to a tower collapse at t > 0 is preferable

In this study, Global Warming Potential - total (GWP-total) is calculated as an environmental indicator, as defined in EN 15804 +A2 [6]. The potential economic impacts stemming from the material and construction direct costs are also calculated based on verified publicly available data (e.g. Environmental Product Declaration or average datasets available in OKOBAUDAT [18]). The construction prices for steel are derived from Eurostat statistics on the production of manufactured goods [19]. For dynamic assessment, all impacts are adjusted with decarbonisation factors (1.4 %) [20]. Costs are meanwhile discounted with a factor of 3.0 % [21].

The considered life cycle stages include the manufacturing stage and assembly (modules A1-A3 + A5 [7]), the replacement or refurbishment with the adaptation option (B4-B5[7]), the deconstruction and end-of-life (EOL) stage (modules C1+C3-C4 [7]) as well as benefits and credits beyond the system boundary, which result from the reuse and/or recycling scenarios during the end-of-life (module D [7]). While in conventional LCA, a building product is commonly replaced with the same product, the developed approach allows for the exchange of different building products, e.g. the exchange of steel of the type S355 with high-strength steel (HSS) of the type S460. Therefore, modules B4-B5 comprise the current construction's EOL phase and the adaptation option's manufacturing stage.

The impacts are evaluated on the tower with a height of 18 m, the most common tower height in the investigated power line section (i.e. one tower of 18 m is the functional unit). The observation time of the analysis is 60 years, which equals the tower’s service life. Results are calculated on a yearly basis to analyse the point in time at which the environmental impacts can be allocated.

Measures and strategies definition

Three “as-is” scenarios are evaluated for the existing pilot. The scenarios consider the transmission tower with:

i. no corrosion
ii. corrosion depth of 0.5 mm on each side of the steel profiles
iii. corrosion depth of 1.0 mm on each side of the steel profiles.

Fibre-reinforced polymer (FRP) strips are investigated as an option to restore the corroded tower with a corrosion depth of 0.5 mm. These can be applied *proactively* at t=0. Two different FRP striping are evaluated:

1. **Single strengthening:** apply carbon FRP S512 (50 mm x 1.2 mm) plates only externally.
2. **Double strengthening:** apply carbon FRP S512 (50 mm x 1.2 mm) plates both externally & internally.

Transmission tower structures are characterised by limited overstrength. This means that hazard events usually lead to the total collapse of a tower. Therefore, the only probable (*reactive*) option after a hazard event is rebuilding the tower. The towers can either be rebuilt in the same way as the original with S355 or be rebuilt with HSS of type S460. The use of HSS potentially allows for new designs with less material. Demolition and rebuilding can also be carried out *proactively* at t=0. The following options are considered in case of reconstruction:

1. **Conventional:** The tower is rebuilt according to the initial design specifications.
2. **HSS Scenario 1:** All L70x7 angles of the initial tower are made by L65x6 angles, and all L60x6 angles with L50x5 angles.
3. **HSS Scenario 2:** All L70x7 angles of the initial tower are exchanged with L65x6 angles, all L60x6 angles with L50x5 angles and all L50x5 angles with L40x4 angles**.**
4. **HSS Scenario 3:** All L70x7 angles of the initial tower are exchanged with L55x5 angles, all L60x6 angles with L50x5 angles and all L50x5 angles with L40x4 angles.

Uncertainty Identification

The main natural hazards Finnish power transmission towers are exposed to are extreme winds, usually combined with icing. The occurrence of wind (f(u)) and icing events ($f(t_{ice})$) are uncertain parameters.

For the hazard analysis relevant data were provided by Finish Meteorological Institute (FMI) for various climate models over for historical and future periods. Based on those data the corresponding probability distributions of wind speed and ice thickness were specified assuming that they follow a Generalised Extreme Value (GEV) distribution. Moreover, a low root mean square error was derived between the bivariate (joint) empirical PDFand the product of the two marginal PDFs [22], allowing us to consider the two hazards as independent. Thus, the joint PDF of wind and icing can be calculated by multiplying the marginal PDFs of each variable as described in Equation (4):

$$f(u,t_{ice})=f(u) \times f(t_{ice}) \quad (4)$$

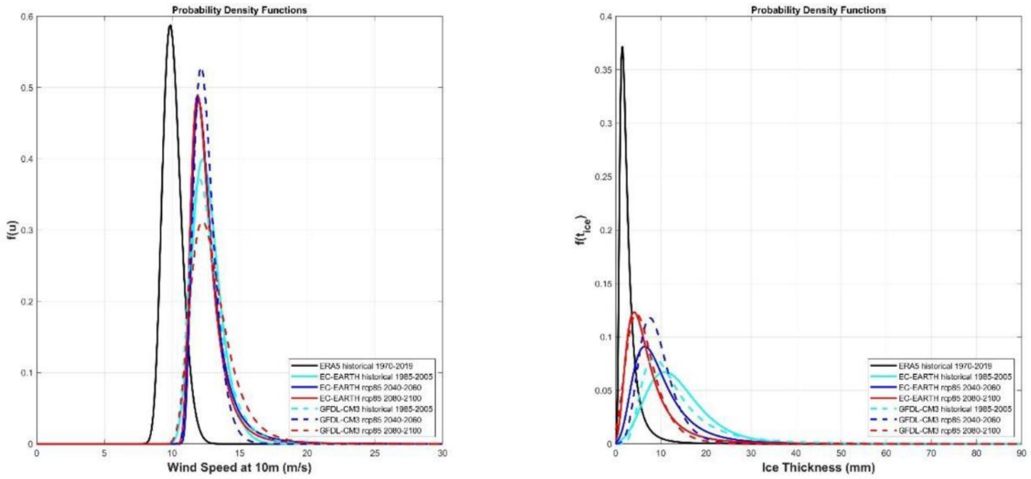
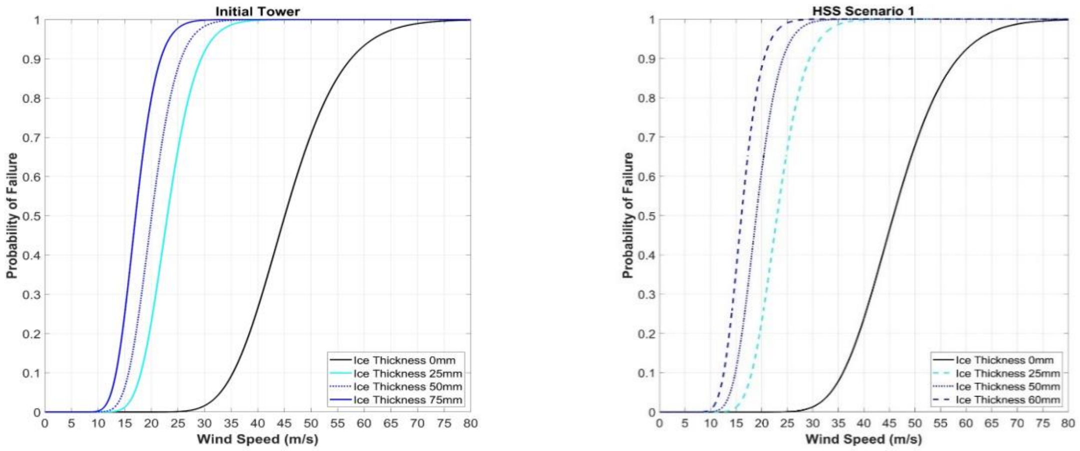


Figure 6: Probability Density Functions of wind speed (left) and ice thickness (right)

Fragility assessment

Along with the hazard function $f(u, t_{ice})$, the resistance of all probable structures against the combined hazards is evaluated. Two exemplary results of the evaluation are shown in Figure 7 in the form of fragility curves for the conventional “initial” tower and the adaptation option HSS Scenario 1. For each probable scenario, multiple fragility curves exist that describe the fragility under different icing thicknesses. Under a given icing thickness, each tower's cumulative probability of failure (PoF) depends only on wind speed [23].



(a) (b)

Figure 7: Fragility curves for the initial (i.e., “as-built”) tower (a) and the adaptation option HSS Scenario 1 (b)

The value of the fragility curves for a given windspeed u and ice thickness (t_{ice}) can be estimated by the lognormal CDF formula ϕ shown in Equation (5).

$$P(D>C|u,t_{ice})=\Phi\left(\frac{\ln(u/u_{50}(t_{ice}))}{\beta}\right) \quad (5)$$

With:

- u the wind speed in m/s
- $u_{50}(t_{ice})$ the median value windspeed in m/s under a given ice thickness, representing a probability of failure of 50 %
- β the dispersion of the probability distribution. Assumed to be 0.19 in all cases.

4.2 LCI and Matrix of measures

Life cycle models are created based on design information, and other life cycle models are developed with the help of fragility curves. The conventional power transmission tower is made by S355 steel with zinc coating to prevent corrosion. The corroded towers are assumed to be made of the same material. Moreover, to restore the tower with corrosion depths of 0.5 mm, FRP stripes can be applied at t = 0 of the analysis as a proactive strategy. Material quantities are documented in Table 2

Conventional Tower, Corroded Tower 0.5 mm, Corroded Tower 1.0 mm			
Building Product	**Quantity**	**Unit**	**Dataset [18]**
Steel S355	2619.03	[kg/tower]	microZINQ® hot-dip galvanized steel
Tower with 0.5 mm depth of corrosion and Single FRP striping			
Building Product	**Quantity**	**Unit**	**Dataset [18]**
Steel S355	2619.03	[kg/tower]	microZINQ® hot-dip galvanized
Single FRP Striping	24.58	[kg/tower]	solidian GRID and solidian REBAR
Tower with 0.5 mm depth of corrosion and Double FRP striping			
Building Product	**Quantity**	**Unit**	**Dataset [18]**
Steel S355	2619.03	[kg/tower]	microZINQ® hot-dip galvanized steel
Double FRP Striping	49.15	[kg/tower]	solidian GRID and solidian REBAR

Table 1. LCI. Bill of quantities and materials of measures associated to as-is scenarios.

Material flows for the adaption options in the case of failure of the tower (reactive strategies) are modelled and documented in Table 3.

HSS Tower Scenario 1			
Building Product	**Quantity**	**Unit**	**Dataset [18]**
Steel S460	2323.64	[kg/tower]	microZINQ® hot-dip galvanized steel
HSS Tower Scenario 2			
Building Product	**Quantity**	**Unit**	**Dataset [18]**
Steel S460	2192.24	[kg/tower]	microZINQ® hot-dip galvanized steel
HSS Tower Scenario 2			
Building Product	**Quantity**	**Unit**	**Dataset [18]**
Steel S460	2023.25	[kg/tower]	microZINQ® hot-dip galvanized steel

Table 2 Building masses and product specification of adaptation options in case of tower failure.

Table 4 shows one exemplary combination provided in the matrix of measures. A total of 20 combinations are considered.

Current Structure	**P1** **Conventional Tower**	**P2** **Enhanced after HSS**
H0	0	0
H1	Conv. Tower EOL + HSS Scenario 1 A1-A3	0
H2	Conv. Tower EOL + HSS Scenario 1 A1-A3	HSS Scenario 1 EOL + HSS Scenario 1 A1-A3

Table 3. Decision Matrix for Conventional Tower with no initial action and HSS Scenario 1 as a reactive adaptation option

4.3 LCIA and Results Interpretation

In Table 4 the impacts per kg (multiplication of Q x H matrices, see Formula (1)) of the products used in the various scenarios are presented. Due to its lower density, the impacts per kilogram of FRP striping significantly exceed those of steel. However, the mass required for FRP striping in the application is reduced by a factor of 100. The GWP values and costs are derived from [18-19].

Impact Category	GWP [kg CO_2-Eq./kg]		Cost [€/kg]	
	Construction (A1-A3)	EOL (C3, C4, D)	Construction (A1-A3)	EOL (C3, C4, D)
Steel S355	1.4	-0.38	7.16	-0.32
Steel S460	1.4	-0.38	7.30	-0.32
FRP Striping	23.3	0.01	218.54	0.00

Table 4 Environmental impacts and costs of used materials per reference unit based on available datasets.

After the LCI and all variability and uncertainty parameters are identified and quantified, the impact assessment is conducted, and uncertainty is propagated with an MC simulation. The calculations are performed through the adjusted version of the MATLAB script developed by Di Bari [13]. Results are presented mainly for climate scenarios EC-Earth rcp85 and GFDL rcp85 and the reference period between 2040 and 2060 as it matches the time span of the reference period of the study [21]. Additionally, the climate scenarios embody the scenario with the highest probability of failure for the tower.

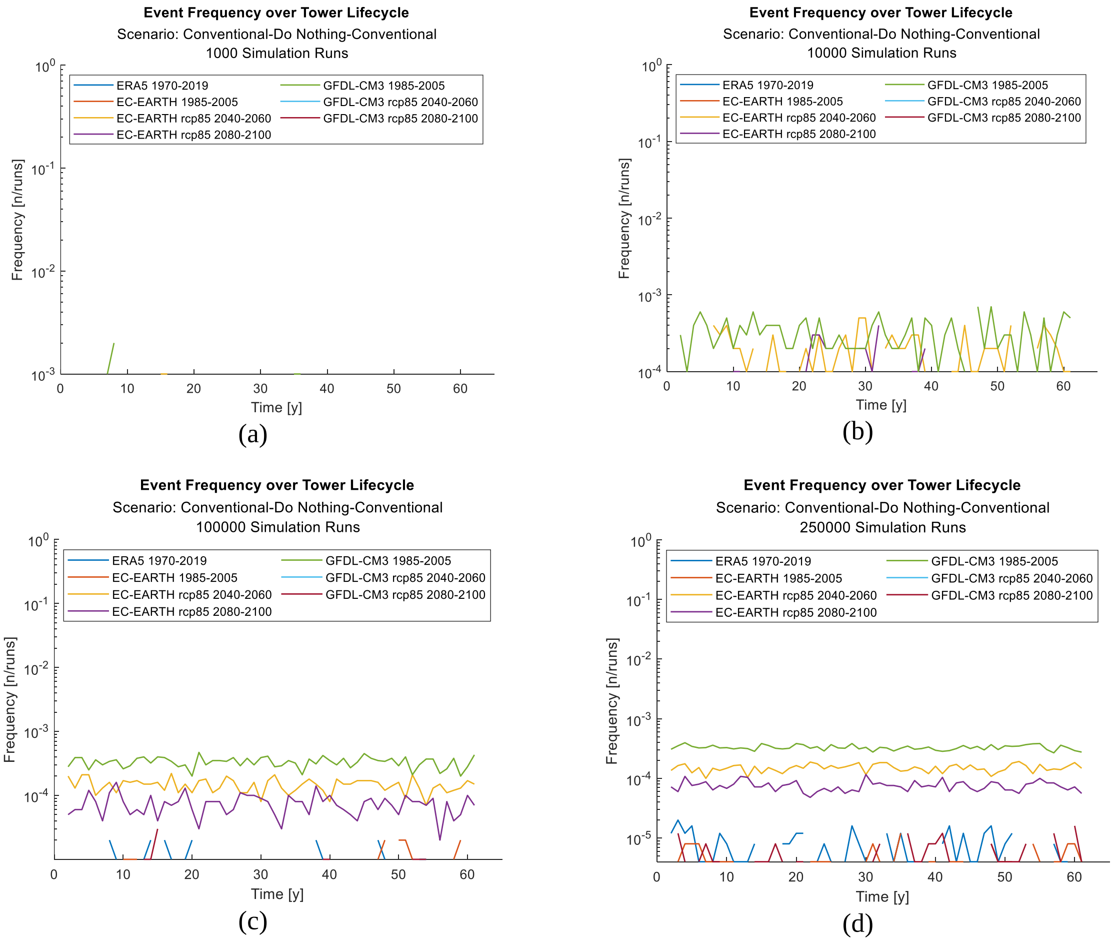


Figure 8: Event Frequency for different MC runs: (a)1,000, (b) 10,000, (c) 100,000, (d) 250,000 runs.

Figure 8 presents the frequency of hazard events per year for the different climate scenarios in the example of the scenario Conventional-Do Nothing-Conventional. The analysis is conducted for 1,000 runs (top-left), 10,000 runs (top-right), 100,000 runs (bottom-left), and 200,000 runs (bottom-right). In most climate scenarios no event is recorded when the number of Monte Carlo Simulations is run with 10,000 simulations or below. Based on this preliminary assessment, for this study, 100,000 runs are performed. These ensure a sufficient precision level of the simulations without high computational efforts.

Impact of Climate Scenarios on the results

In Figure 8 it is also possible to identify the influence of the different climate scenarios on the annual PoF. For the climate scenario GFDL-CM3 rcp85 in the reference period between 2040 and 2060, no failures are recorded regardless of the number of runs. On the other end, the highest event frequency can be observed for the climate scenario GFDL-CM3 with the reference period of 1985-2005. Both trends are also observable in the other scenarios. Figure 8 also highlights that there is a clear distinction between the climate scenarios when it comes to the frequency of events and especially the trends between the climate simulations. While the GFDL-CM3 rcp85 simulations project a lower event occurrence in future climate scenarios, the EC-EARTH rcp85 simulations project significantly higher event occurrences. The GFDL-CM3 rcp85 simulations show greater differences between the reference periods.

For further investigations, the GFDL-CM3 rcp85 and EC EARTH 2040-2060 rcp85 simulations are used, as their reference period falls within the reference period of the study, and it has been shown that the climate scenarios exhibit different trends.

Proactive vs. reactive strategies: adaptation option selection for 0.5 mm corroded tower

For the tower with an initial corrosion level of 0.5 mm, two different initial adaptation options with FRP striping are compared with a reactive strategy entailing the tower rebuilding as in the original state with S355. Figure 9 shows the mean GWP and costs over 60 years of observation time. For both GWP and costs, however, the reactive strategy Corroded 0.5 mm – Do Nothing – Conventional has the lowest values over the lifecycle.

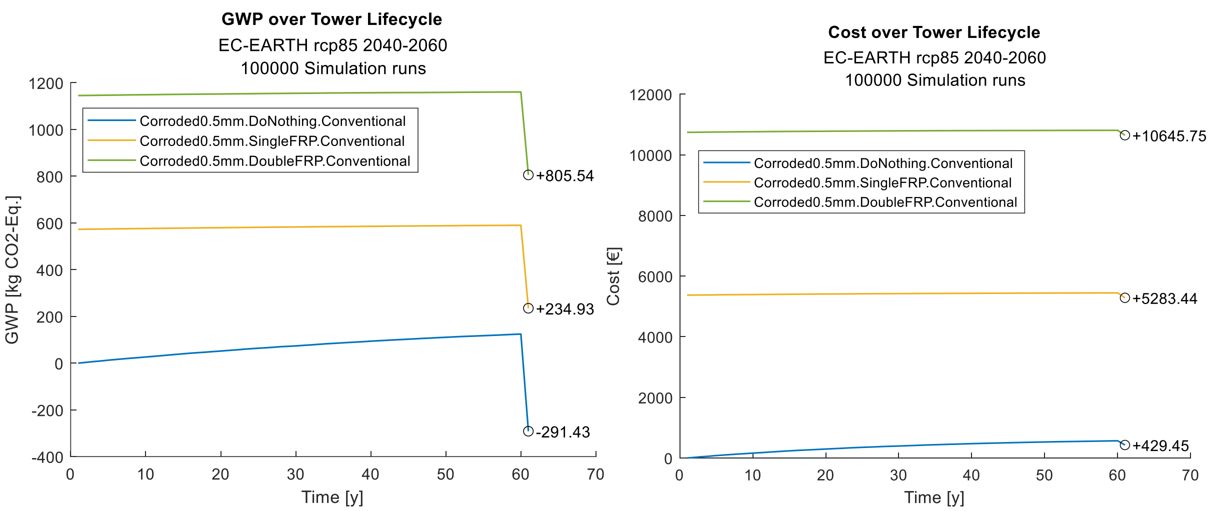


Figure 9: GWP (left) and costs (right) for the different initial adaptation options of the Corroded Tower with 0.5 mm corrosion with reactive or proactive adaptation option - climate scenario EC-EARTH rcp85 2040-2060.

Based on derived numerical results, there is a low chance of approximately 7 % that the corroded tower collapses during the reference period of the study. Only in approximately 5 % of the simulations the Corroded 0.5 mm – Do Nothing – Conventional performs worse from a cost perspective (approx. 7 % for GWP) than the mean expected impact of the tower initially refurbished with single FRP striping.

Figure 10 displays the same scenario in combination with a different climate scenario (GFDL-CM3 rcp85) for the reference period from 2040-2060. In this case, it is even more unlikely that the corroded tower will collapse if it is not restored initially, i.e. if proactive strategies are undertaken. Therefore, the Corroded 0.5 mm-Do Nothing-Conventional scenario has the lowest mean expected impacts and reactive strategies should be overall preferred. Based on numerical results, for both the Cost and GWP in more than 99.5 % of simulations, the lowest impact is recorded for reactive strategies.

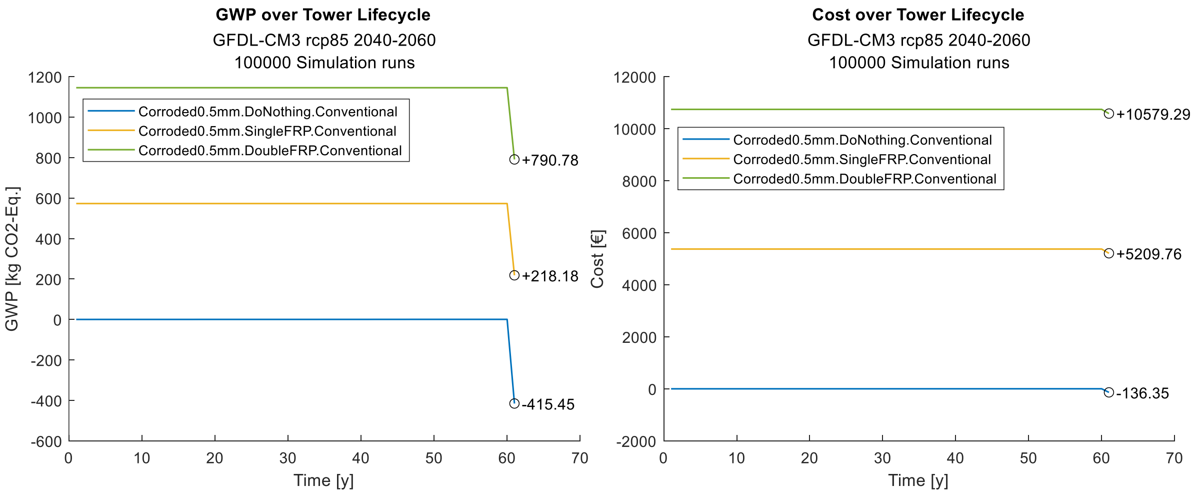


Figure 10: GWP (left) and costs (right) for the different initial adaptation options of the Corroded Tower with 0.5 mm corrosion with reactive or proactive adaptation option - climate scenario GFDL-CM3 rcp85 2040-2060.

Reactive strategy: adaptation option selection for conventional tower

Figure 11 shows the mean expected impacts for the climate scenario EC-EARTH rcp85 and the reference period 2040-2060 with a reactive strategy applied to the conventional tower without corrosion signs.

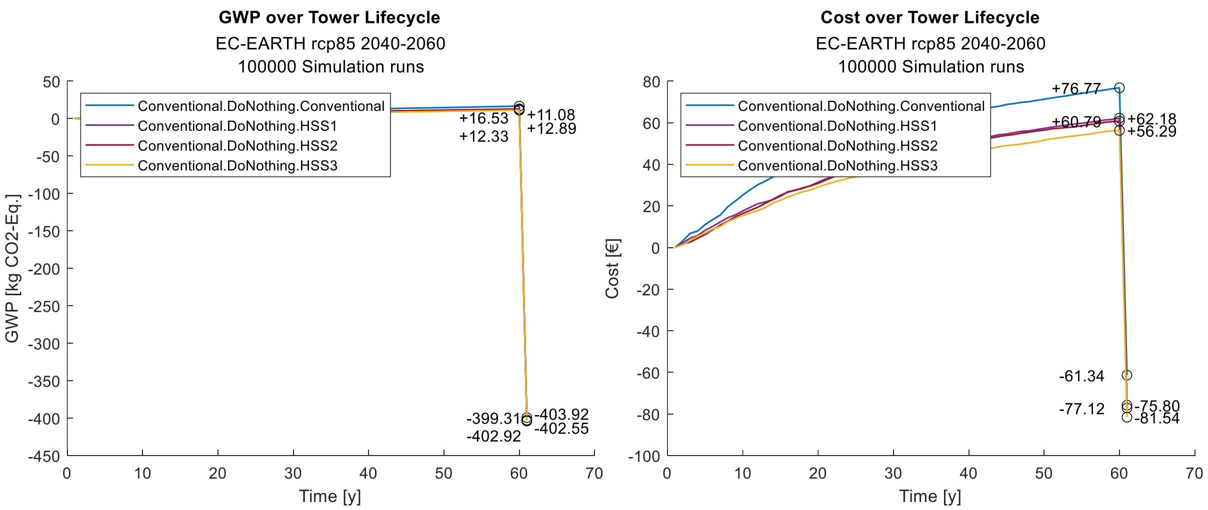


Figure 11: GWP (left) and costs (right) for the different initial adaptation options of the Conventional Tower without corrosion and reactive adaptation option - EC-EARTH rcp85 2040-2060

At t= 0, no measures are undertaken, and different adaption options are considered based on event occurrence and level of performance. The expected impacts over the complete life cycle are negative. This is because, the developed scenarios are investigating an already constructed tower with no initial action ("Do Nothing", reactive strategy). The final negative impacts are dictated by the environmental and economic benefits of module D after steel recycling. Due to the high recycling rates of steel, the benefits at the EOL outweigh the impacts of the low expected probability of a tower failure and a necessary restoration. Positive total impacts are recorded only for 0.9 % of the generated MC runs. With and without consideration of recycling benefits the reactive HSS 3 option presents higher economic advantages. Rebuilding the tower at its original design with conventional steel has meanwhile lower environmental and economic advantages. Low differences in terms of GWP can be reported.

Reactive strategy: adaptation option selection for 1.0 mm corroded tower

In the following, an analysis with a 1.0 mm corroded tower is presented. The analysis uses the climate scenario EC-EARTH rcp85 and the reference period 2040-2060 (Figure 12).

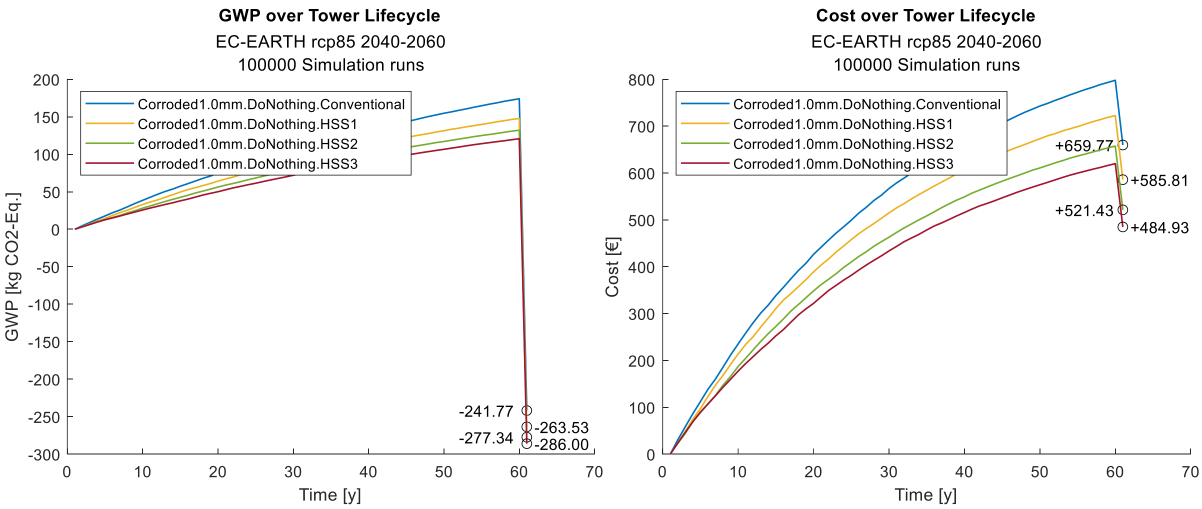


Figure 12: GWP (left) and costs (right) for the different initial adaptation options of the Corroded Tower with 1.0 mm corrosion with reactive adaptation option - EC-EARTH rcp85 2040-2060

It is apparent that the impacts shown in Figure 12 are higher in comparison with the previous case. However, in this case as well, the adaptation option HSS Scenario 3 records the lowest impacts among the studied adaptation options. It should be mentioned that the results may differ when assuming a longer lifetime of the tower, e.g. because it is unlikely that it is deconstructed after 60 years. Nevertheless, this outcome seems improbable considering the variability parameters, e.g., under an economic discounting factor of 0.03, an event anticipated 100 years from now will be discounted by 96.3 %.

5 CONCLUSIONS

The developed methodology defines a clear framework for the integration of uncertainty analyses and risk assessment consistent with the LCA computational structure. As a result, a powerful tool is realised for evaluating the viability of adaptation proactive and reactive strategies aimed at infrastructure assets, such as repairs and refurbishment, at any given point in time. By integrating probabilistic assessments of environmental and economic impacts, the methodology enables decision-makers to determine whether a proposed proactive or reactive intervention would be beneficial within the context of the assets' life cycle under uncertain circumstances dictated by possible natural shock events. This approach considers both the variability and uncertainty of key parameters, providing a comprehensive analysis of potential outcomes. As a novelty, the methodology allows for the consideration of an evolutionary performance of the asset. Additionally, the probabilistic method enables the simultaneous consideration of multiple variabilities and uncertainties. This makes it possible to reveal interactions between uncertainties, offering a more comprehensive understanding of system behaviour. As a result, it becomes possible to assess whether the environmental benefits, such as reduced resource consumption or emissions, and the economic advantages, like cost savings or extended service life, justify the adaptation effort. This capability ensures informed, sustainable decisions that align with long-term objectives.

The pilot study validated the capability of the framework to address the complexities of real-world scenarios. Based on the outcomes of the analyses, it is recommended to use a deterministic approach for scenarios with low Probability of Failure (PoF) rates (lower than 10^{-3}). This is because the required number of simulations to achieve meaningful results will increase significantly, while the variance in outcomes remains still minimal. However, when PoF rates increase in the range of 10^{-2} to 10^{-3}, probabilistic methods become more advantageous. Instead of obtaining a single deterministic value, this approach allows the representation of a range of possible outcomes. From this range, confidence levels can be determined, providing a significant transparency advantage compared to traditional deterministic practices that often report only single values. By integrating sensitivity analysis into the LCA methodology, uncertainties can be made more transparent, thereby offering a more robust decision-support system for policymakers and stakeholders.

In future works, the methodology will be applied to different infrastructure assets, such as bridges and under different natural and/or human-induced hazards. Moreover, future developments should focus on incorporating technical degradation into Monte Carlo simulations, which would further enhance the accuracy and reliability of the methodology. For cost analyses, indirect costs will be included (e.g., lost revenues due to a power outage). These advancements will be essential for ensuring that the proposed framework can provide meaningful insights and practical solutions for addressing the challenges posed by climate-resilient infrastructure. Finally, the framework will also be extended for the evaluation of other sustainability metrics (social, economic and environmental) and coupled with resilience analyses.

ACKNOWLEDGEMENTS

This work has received funding from the Horizon Europe Programme under (a) the GA no. 101093939) Asset Level Modelling of RISKs in the Face of Climate Induced Extreme Events and ADAPTtation (RISKADAPT); (b) the Marie Skłodowska-Curie Staff Exchanges Action (GA no. 101086413). Co-funded by the UK Research & Innovation, and the Swiss State Secretariat for Education, Research & Innovation.

REFERENCES

[1] European Commission, Buildings and construction (2023). Available online at https://single-market-economy.ec.europa.eu/industry/sustainability/buildings-and-construction_en

[2] S.J. Schuldt, M.R. Nicholson, Y.A. Adams, J.D. Delorit, Weather-Related Construction Delays in a Changing Climate: A Systematic State-of-the-Art Review (2021). https://www.mdpi.com/2071-1050/13/5/2861

[3] K. Abbass, M.Z. Qasim, H. Song, M. Murshed, H. Mahmood, I. Younis. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environ Sci Pollut Res Int. 2022 Jun;29(28):42539-42559 (2022). doi:10.1007/s11356-022-19718-6

[4] International Standardization Organization, Environmental management — Life Cycle Assessment — Principles and framework. ISO14040

[5] International Standardization Organization, Environmental management — Life Cycle Assessment — Requirements and guidelines ISO 14044

[6] European Committee for Standardization, Sustainability of construction works – Environmental product declarations: Core rules for the product category of construction products EN15804:2012+A2:2019.

[7] European Committee for Standardization, EN15978 Sustainability of construction works - Assessment of environmental performance of buildings: Calculation method EN15978:2023

[8] European Committee for Standardization, Sustainability of construction works – Framework for assessment of buildings and civil engineering works EN 15643:2021.

[9] R. Di Bari, O. Jorgji, R. Horn, J. Gantner, S. Ebertshäuser, Step-by-step implementation of BIM-LCA: A case study analysis associating defined construction phases with their respective environmental impacts, IOP Conf. Ser.: Earth Environ. Sci. 323 (2019) 12105. https://doi.org/10.1088/1755-1315/323/1/012105

[10] R. Di Bari, A. Belleri, A. Marini, R. Horn, J. Gantner. Probabilistic Life-Cycle Assessment of Service Life Extension on Renovated Buildings under Seismic Hazard. Buildings 10(3) (48), 1–22 (2020). https://doi.org/10.3390/buildings10030048

[11] M.-L. Pannier, P. Schalbart, B. Peuportier, Dealing with uncertainties in comparative building life cycle assessment, Building and Environment 242 (2023) 110543. https://doi.org/10.1016/j.buildenv.2023.110543

[12] R. Heijungs, The Computational Structure of Life Cycle Assessment, Springer, Dordrecht, (2002).

[13] R. Di Bari, Predictive Risk-Integrated Dynamic Environmental analyses and Integration in building design, PhD Thesis, University of Stuttgart (2025) (in press)

[14] G. Sauve, K. van Acker, Integrating Life Cycle Assessment (LCA) and Quantitative Risk Assessment (QRA) to address model uncertainties: defining a landfill reference case under varying environmental and engineering conditions, Int J LCA 26 (2021) 591-603. https://doi.org/10.1007/s11367-020-01848-z.

[15] R. Di Bari, R. Cucuzza, M. Domaneschi, S. A. Mitoulis. Integration of Risk Assessment in Life Cycle Analyses for Sustainable and Resilient Built Environment: A Review (2024)

in Proceedings of ICONREM 2024, edited by G.P. Cimellaro, Y. Zhou, A. Cardoni, F. Ansari (2024) (accepted, in press)

[16] E. Benetto, C. Dujet, P. Rousseaux, Integrating fuzzy multicriteria analysis and uncertainty evaluation in life cycle assessment, Environmental Modelling & Software 23 (2008) 1461-1467. https://doi.org/10.1016/j.envsoft.2008.04.008

[17] R. Heijungs, M.A.J. Huijbregts, A Review of Approaches to Treat Uncertainty in LCA, International Congress on Environmental (2004).

[18] BBSR, ÖKOBAUDAT Datenbank: Informationsportal Nachhaltiges Bauen, Bundesministerium für Wohnen, Stadtentwicklungen und Bauwesen, Berlin, (2023) Available online at https://www.oekobaudat.de/en.html

[19] Eurostat. Data Browser - Sold production, exports and imports - Iron or steel towers and lattice masts. Online data code: ds-056120 (2025) Available online at https://ec.europa.eu/eurostat/databrowser/view/ds-056120__custom_14911494/default/table?lang=en&page=time:2020

[20] Price Waterhouse Coopers, Net Zero Economy Index (2024). https://www.pwc.co.uk/services/sustainability-climate-change/insights/net-zero-economy-index.html.

[21] Eurostat. International trade of EU and non-EU countries since 2002 by HS2-4-6 - Import Finland Articles of carbon fibres, for non-electrical purposes. Online data code: ds-059341 (2025). Available online at https://ec.europa.eu/eurostat/databrowser/view/ds-059341__custom_15073689/default/table?lang=en

[22] M. Laine. RISKADAPT, D3.3 – Extreme value distributions for Europe – future climate (2024), available online at https://riskadapt.eu/wp-content/uploads/2024/12/RISKADAPT_D3.3_v1.2.pdf

[23] K. Czirwitzky, RISKADAPT, D4.2 – Structural resistance integration in lifecycle analyses (under review)