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Life cycle costs and asset management for protective structures against natural hazards

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Abstract

With increasing risks from natural hazards in alpine regions in Austria OEBB-Infra and Hoffmann-Consult have developed a consistent methodology for condition assessment, prediction, and life cycle optimization of protective structures. Based on a thorough assessment of the asset stock standardized life cycles for key structures like rockfall and avalanche protection structures have been derived. The developed life cycle models allow a generalized assessment of asset condition, residual service life, and remaining asset value. In contrast to typical transport assets, protective structures are both subject to natural aging processes and random events with a certain occurrence rate. Beyond standardized life cycles on network level an adjustment to project level is necessary to account for actual condition development and asset specific events. The paper provides an overview on the developed generic life cycle with application to rockfall protection structures with prices 2022 in Austria.

Keywords

Life cycle costs, protective structures, rockfall protection, unit costs, optimization

1 Introduction

The impact of climate change with increasing risks of natural hazards on land use and transport infrastructure can be observed by an increasing number of fatalities and costs. According to the European Environment Agency, between 1980 to 2020 climate-related events caused economic losses of 487 bn € in the EU-27 being equivalent to an average of 11,9 bn € per year. In alpine regions and vulnerable areas these effects are more frequent and severe. In Austria alone, the estimated losses in this time frame from 1980 to 2020 are 702 fatalities and total economic losses of 11.35 bn Euro (~380 million € per year).

With growing concerns on the increasing threats of climate change as well as natural hazards, adaption and mitigation strategies at all levels of government are becoming more and more important every year. A key element in understanding and managing exposed areas and critical infrastructure is the concept of vulnerability and resilience. According to [1] vulnerability is defined as a combination of exposure to specific risks, the sensitivity to these risks and the capacities to respond. In this regard, resilience is defined as the capacity to anticipate, prepare for, protect against, respond flexibly, recover quickly and learn from these events and their consequences.

High-level transport infrastructure such as highways and railways are linear structures being especially vulnerable to natural hazards as a single event can block or take out an entire route. Apart from the immediate consequences on human life, vehicles, and infrastructure assets further economic and ecologic damages to connected areas and their inhabitants can be expected. Infrastructure operators therefore try to minimize risks by avoiding critical areas with their routes as well as building structures such as enclosures, rockfall protection and avalanche barriers as a passive protection. Active measures such as rock removal or avalanche blasting, as well as early warning systems and response plans, are typical instruments of infrastructure operators in risk management of natural hazards.

Beyond more or less frequent events from natural hazards all transport infrastructure assets are subject to ageing and degradation. In order to cope with these challenges transport infrastructure operators, try to organize all activities in the life cycle of their structures in an infrastructure asset management. A typical asset management cycle consists of inventory and condition survey, condition prediction, measure impact and costs, investment optimization, budgeting, construction and maintenance as well as tendering and benchmarking [2]. Based on these principles and a thorough assessment of protective structures a consistent methodology for condition assessment, prediction, and life cycle optimization of protective structures is presented. The developed life cycle models allow an assessment of asset condition, residual life, remaining asset value and investment needs. The developed methods are suitable for both project and network level and are demonstrated on rockfall protection fences of OEBB-Infra.

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2 Rail transport infrastructure in Austria

2.1 Overview rail infrastructure assets

The railway transport infrastructure in Austria is owned, maintained, and operated mainly by OEBB-Infra ensuring an economic, efficient and non-discriminatory use on behalf of the Republic of Austria. Their rail network has a route length of 4.871 km and 1.038 passenger stops with more than 190 million passengers and 100 million tons of goods being transported every year. In 2021 OEBB-Infra reported a total income of 3,3 bn € from revenues (28%), capitalized work (10%), and increase of inventories (62%). With 18.444 employees the total income per employee of 180 k€ has remained constant. The total expenditures in 2021 have been 2,92 bn € with main shares for personnel (43%), depreciation (29,5%), and purchased services (13%) among others [3].

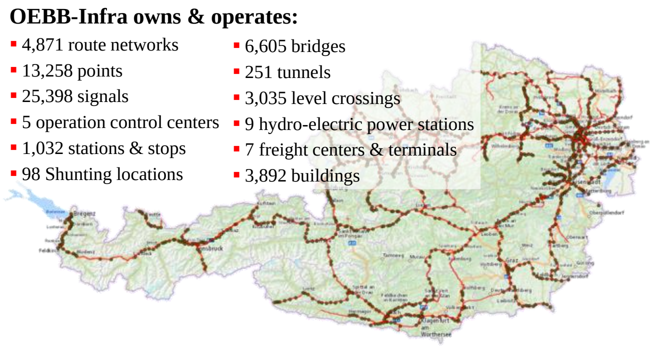

Figure 1 Overview of railway network, train stations and key assets of OEBB-Infra 12/2021 in Austria

2.2 Replacement costs and residual value

For transport infrastructure operators fixed assets include all assets that permanently serve the purpose of the operation and are not further processed. In accounting, these fixed assets are divided into property, plant and equipment (land, buildings, machinery, etc.), intangible assets (concessions, licenses, brands, etc.) and financial assets (securities, investments, shareholdings, etc.). A further distinction can be made between non-depreciable assets (e.g. land, securities) and depreciable fixed assets (e.g. civil structures, buildings, machinery). The valuation and depreciation of assets can be based on incurred validated acquisition costs (accounting) or current replacement costs (technical). Scheduled depreciation can be time-proportional (aging), substance-related (condition) and performance-related (traffic performance, operating hours). Unscheduled depreciation, on the other hand, is recognized immediately in case of extraordinary events [2].

As the railway infrastructure in Austria is of public importance and high economic value, OEBB-Infra publishes annual network status reports. These reports provide an overview on asset classes, age and replacement value, condition distribution, functionality, safety and quality, critical sections, investment backlogs, and budget needs. In the latest report of OEBB-Infra the technical replacement value corresponds to the value of the complete replacement of all assets according to the state of the art based on the current price basis [4]. *Table 1* provides an overview on the main asset types with quantity, age and service life. *Table 2* provides an estimation of the technical replacement value with price basis 2021 and 2022. According to this estimation, the total value of rail infrastructure assets is 52,9 bn € with the main shares being civil structures (31,7%), superstructure (27,7%), substructures and protective structures (12,4%), and electrical assets (10,7%). The replacement value of protective structures against natural hazards can be estimated with 450 million € (0,9%), representing a relatively small share with high importance for function and safety of the rail network.

Table 1 Asset types with quantity, age, and service life 01.01.2022

No.	Asset type	Unit	Quantity	Ø Age	Service life [a]
#1	Tracks core network (class a)	km	5 626	19	38 (16-60)
	Tracks supplementary	km	1 250	25	45 (25-60)
	Switches core network	pcs.	5 341	16	33 (18-50)
	Switches supplementary	pcs.	633	23	33 (27-50)
#2	Roofs	pcs.	3 472	24	55
	Bridges (incl. Culverts)	pcs.	8 775	50	100 (90-150)
	Tunnels	pcs.	251	44	142 (80-150)
#3	Houses	pcs.	2 043	56	92 (31-172)
#4	Interlockings	pcs.	653	25	39 (25-60)
	ETCS (Train Control System)	km	624	-	-
#5	Overhead	km	8 018	28	56 (40-60)
#6	Culverts	m2	99 305	54	80
	Retaining walls (Ø height 2,7 m)	m	786 845	72	100

Table 2 Asset classes with technical replacement value 01.01.2022

No.	Asset class	Share	Value 2021	Value 2022
#1	Superstructure (tracks)	27,74%	14,51	14,67
#2	Civil structures	31,65%	16,55	16,74
#3	Buildings	5,33%	2,79	2,82
#4	Control- & Safety	8,33%	4,36	4,41
#5	Electrical assets	10,70%	5,60	5,66
#6	Substructure & Protection	12,35%	6,46	6,53
#7	Telematics	2,39%	1,25	1,26
#8	Mechanical equipment	1,50%	0,78	0,79
	OEBB-Infra total	100,00%	52,30	52,89

Based on the financial statement for 31.12.2021 the value of non-current assets was 27,9 bn € and current assets of 1,0 bn € (accounting). The calculation of a technical residual value depends on available data and can be roughly estimated with 50% of replacement costs in case of continuous reinvestment and replacement of structures for extended periods (~52,9 × 0,5 ≈ 26,45 bn €). For a more specific estimation of residual value previous investments, actual condition distribution, and remaining life have to be taken into account. The network status reporting in OEBB-Infra considers the total asset condition based on the criteria #1 functionality, #2 safety, and #3 condition. As can be seen from *Figure 2* the condition of assets is in average good with a majority of assets in very good and good condition. Furthermore, there are almost no structures in very bad condition being the result of substantial investments with focus on the core rail network and critical assets [4].

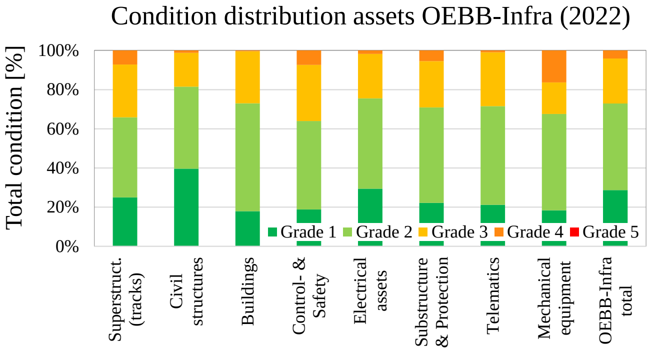

Figure 2 Railway network total condition for asset classes 01.01.2022

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2.3 Overview protective structures

The rail infrastructure operator OEBB-Infra protects the functionality and safety of all operations on their tracks against natural hazards with 8.500 protective structures. *Table 3* provides an overview on these protective structures with quantity, estimated average service life, and shares of assets with available condition data. For further analysis the asset stock of rockfall protection fences with 613 assets and a given service life of 40 years are highlighted. Although the condition survey procedures are currently being updated, for at least 64% of rockfall protection fences and 70% of protective structures condition data is available. As the survey interval is in average six years, the entire asset stock will soon have condition data based on these asset and element specific procedures.

Table 3 Overview protective structures OEBB-Infra (2020)

Protective asset type	Hazard type	Quantity	Service life*	Condition**
Snow rake Arlberg	Avalanche	1223	40	99%
Rockfall protection fence	**Rockfall**	**613**	**40**	**64%**
Rope barrier	Rockfall	650	40	66%
plank or sleeper wall	Rockfall	709	40	52%
Avalanche wall	Avalanche	590	80	75%
Avalanche wall - with facing wall	Avalanche	17	80	24%
Sliding snow protection - wooden tres	Avalanche	30	40	43%
Snow bridge	Avalanche	1418	60	79%
Snow net	Avalanche	210	40	17%
Underpinning	Various	1035	80	88%
Avalanche dam	Avalanche	7	80	57%
Rock anchor - single bar	Rockfall	136	80	46%
Rock anchor	Rockfall	14	80	0%
Rock nail	Rockfall	103	80	16%
anchor head or beam	Rockfall	508	80	81%
Rock cross-linking - light	Rockfall	64	40	70%
Rock cross-linking - heavy	Rockfall	85	40	69%
Rockfall protection dam	Rockfall	58	80	62%
Snow rake	Avalanche	77	40	86%
Steel wall	Various	252	80	52%
Avalanche deflection dam - concrete	Avalanche	77	80	86%
Avalanche deflection dam	Avalanche	38	80	58%
Shotcrete protection	Rockfall	100	40	64%
Bed-load retention barrier	Torrent control	23	80	65%
Wire ballast cage	Rockfall	45	40	9%
Slope protection	Rockfall	9	40	33%
Protection against drifting	Avalanche	12	60	0%
Gravel box	Various	7	40	14%
Other	Various	372	k.A.	3%
All protective assets	Various	8482	k.A.	70%

*Ø estimated service life **Share of assets with condition data

Protective structures are subject to ageing, natural hazards and subsequent degradation. The remaining life and actual condition are key factors for a determination and prediction of residual asset value and reinvestment needs. For roughly 61,5% of all assets respectively 46,3% of rockfall protection fences the data on asset age is available. As the data on asset age is highly censored and failed assets are mainly replaced, the median age of assets with condition data provides a first estimate on 50% of service life ("rule of halves"). As can be seen from the age distribution in *Figure 3* the median age of all assets is ~38 years and for rockfall protection fences the median is ~16 years.

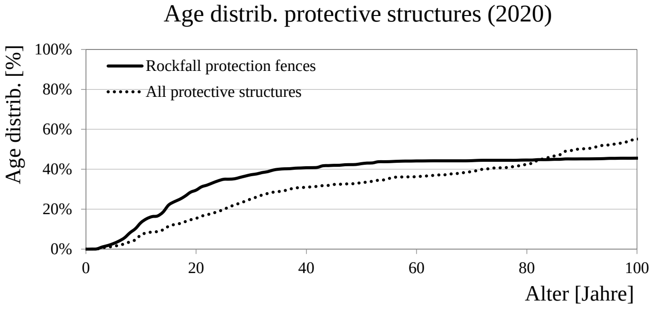

Figure 3 Age distribution rockfall protection fences (2020)

The estimation of protective asset service life of 2×38=76 years is rather high compared to the estimates from *Table 3*. The reason for this is over-ageing of some asset types with a share of roughly 20% of assets with an age between 80 to 120 years. In contrast, the comparatively shorter estimation of actual service life of 2×16=32 years of protection fences compared to previously used estimates of 40 years can be explained by event related failure and replacement of assets as well as changes in dimensioning requirements. Further analysis of condition data on surviving rockfall protection fences can be found in *Figure 4*. If the data is normalized, leaving out fences without age or condition data, an age-related degradation tendency becomes visible. However, age and condition data of protective assets are heavily censored. Therefore, reliable estimates are complex, requiring either a survival analysis on network level or a specific condition prediction for all assets with continuous updating as new data becomes available. In any case, the advantage of specific condition prediction with and without measures is the possibility to determine the development of the asset stock for decades ahead for any given investment strategy and budget.

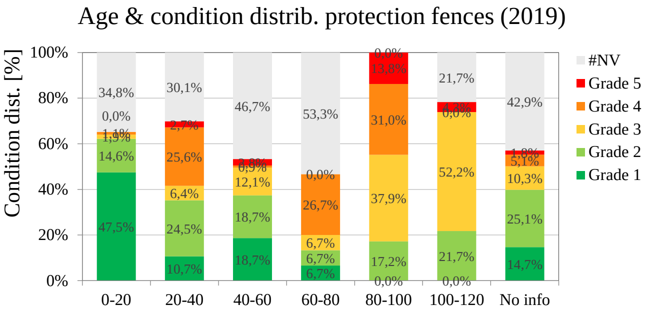

Figure 4 Age and condition of rockfall protection fences (2020)

Another important factor in asset management both for standardization of life cycles as well as cost estimates of maintenance, rehabilitation, and construction is the asset size. The size distribution of rockfall protection fences with a total of 120.000 m^2 of OEBB-Infra is provided in *Figure 5*. According to the statistical analysis 21% exhibit an area <100 m^2, 52% an area between 100 to 200 m^2, 12% an area between 200 to 300 m^2 and 8% between 300 to 400 m^2. The average for all protection fences is 195 m^2 (Median 160 m^2). With a typical height of fences between 3,5 to 4,0 m an average length of ~50 m for single fences and 32 km for all fences can be estimated. At a first glance this seems rather short for protecting a linear transport infrastructure such as the rail network in Austria with a route length of 4.871 km. However, as the critical sections in need of natural hazards or rockfall protection are limited and the number of functional interruptions is very low, the existing asset stock is largely adequate.

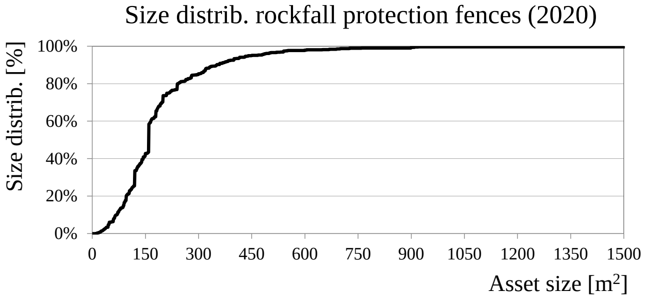

Figure 5 Size distribution rockfall protection fences (2020)

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2.4 Rockfall protection fences

Debris flows and rockfalls are mainly caused by rainfall events, thawing, storms, and erosion processes. In some areas deforestation and earthquakes may also result in these types of gravitational natural hazards. Based on a thorough identification and documentation of hazards and structures at risk a planning and adaption of active and passive measures becomes feasible. Passive measures for this kind of natural hazards try to avoid damage e.g. by adapted land use, and avoidance of critical areas. As this is not always possible, especially in case of transport infrastructures, active measures change the course of events or minimize damages being based on the following principles and resulting structures. Furthermore, systems for event detection and early warning combined with active and passive measures are of growing importance [5]:

- Diversion: Massive structures redirecting the flow away from critical areas and structures (e.g. dams)
- Retention: Holding back debris and rockfalls in flexible or rigid retaining structures and areas that need clearing after events (e.g. rockfall protection fence)
- Drainage: Draining and halting debris flows (e.g. debris-flow brakes, drained deposits)
- Passing: These measures guide the flow through critical areas in a controlled manner (e.g. channels)

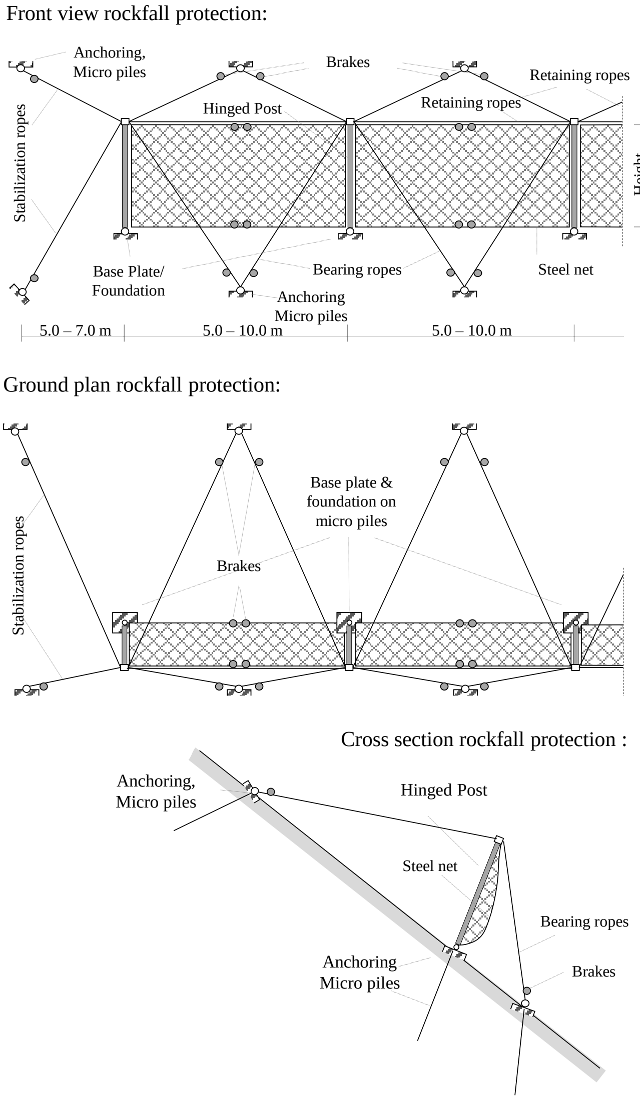

Figure 6 Schematic plan and key elements rockfall protection fence

As shown in *Figure 6* rockfall protection fences are flexible, lightweight structures to retain rockfalls, debris flows, driftwood, and snow. Typical fences consist of hinged anchored posts being held by retaining and stabilization ropes with flexible steel-mesh nets between them. All retaining and stabilization ropes are anchored on micropiles. In order to dampen the gravitational forces braking elements are used. Nowadays, rockfall protection fences are highly standardized and available in different sizes, safety ratings, and loading. In addition, rockfall fences need little space for installation, can be manufactured in almost any length and can be arranged as a single fence or in multiple rows depending on the situation. Together with their comparably low costs and applicability rockfall protection fences are therefore widely used along transport infrastructures like rail tracks (*Figure 7*).

Figure 7 Inspection rockfall protection fence Kastenreith (OEBB-Infra)

2.5 Construction, rehab and maintenance costs

The estimation of construction, rehabilitation and maintenance costs is a key task at every stage of the life cycle of civil structures. Prices for construction works exhibit systematic differences between regions and reference years as well as a wide variation between similar projects. The key to any meaningful estimation is therefore a systematic statistical analysis of adjusted projects costs for a given reference year and project size. As key findings the analysis of a sufficient number of projects yields reliable total cost and unit cost functions. Furthermore, most structures exhibit a distinctive economy of scale with significantly decreasing unit costs at increasing project size [2,6].

For the analysis of construction costs of rockfall fences eleven randomly chosen rockfall protection fence projects of OEBB-Infra have been analysed. As the projects have been completed between 2018 to 2021, all costs had to be adjusted to prices 2022 prior to the statistical analysis. The unit cost average is 347,5 €/m^2 with a standard deviation of 167,4 €/m^2 and a median of 295,3 €/m^2. Previous research has shown that power functions are a good choice for a cost model in terms of goodness of fit. Thereby, an exponent $\beta_2<0$ indicates decreasing unit costs with increasing project size (economy of scale). Although the number of analysis projects is limited, the provided cost functions from *Figure 8* allow a sufficient estimation. For a rockfall protection fence of 1.000 m^2 (e.g. 3,5 m height × 285 m length) average costs of 284 k€ (95% confidence 178 to 390 k€) with 284 €/m^2 can be estimated. For a systematic asset management and life cycle cost models a consistent cost analysis of construction and rehab projects is key and should be done on a regular basis.

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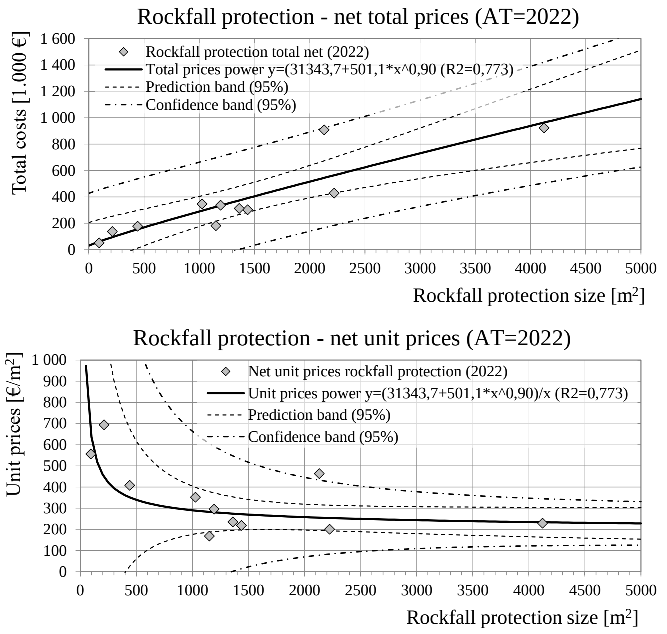

Figure 8 Rockfall protection fence total costs and unit costs

After initial construction the subsequent degradation due to ageing and hazard related events will lead to the question of a systematic condition assessment. The main goal of any periodic or event related condition survey is to provide a basis for the decision on timing, type and necessity of maintenance, rehabilitation or replacement measures. Therefore, surveys should always focus on the necessary information for decision making. This applies to small measures with limited impact on service life up to replacement measures resetting condition and service life of structures to the state of initial construction. Beyond empiric approaches towards measure selection, the crucial information of any measure is applicability to actual condition followed by costs and impact on condition development and service life. As shown in previous research it is possible to generalize measures on asset level or based on service specifications on element level. As the paper provides life cycle cost models on asset and element level, information on standardized measures are provided on the same levels (*Figure 9, Table 4*).

1 **Maintenance small**: Without special equipment with removal of fouling, small stones, retightening screws, checking for larger measures.
- Costs: fixed 500 €/case + variable: 1-2 €/m² of asset area
- Service life: Securing function, no impact on service life

2 **Maintenance big**: With special equipment, stone removal, vegetation, retightening, replacement of small parts, checking for larger measures.
- Costs: fixed 1.000 €/case + variable: 3-4 €/m² of asset area
- Service life: Securing function, little impact on service life

3 **Rehab small**: With special equipment, removal of stones, vegetation, retightening, replacement of nets, tendons, wires & braking elements.
- Costs: fixed 2.000 €/case + variable: 50-70 €/m² of asset area
- Service life: Effect on function & service life +5 years

4 **Rehab big**: As above with substantial replacement of nets, tendons, wires & braking elements as well as anchoring for damaged areas
- Costs: fixed 3.000 €/case + variable: 75-100 €/m² of asset area
- Service life: Effect on function & service life +10 years

5 **Replace partial**: As above with substantial replacement of nets, tendons, wires & braking elements + anchoring for damaged areas
- Costs: fixed 15.000 €/case + variable: 500 €/m² of affected area
- Service life: Effect on function & service life +15-20 years

6 **Replace full**: Removal of existing protective structures and replacement with constructing state of art rockfall protection nets
- Costs: fixed 30.000 €/case + variable: 300 €/m² of asset area
- Service life: Full function and service life +40 years

Figure 9 Standardized measures asset level (net prices AT=2022)

Table 4 Standard measures on element level (net prices AT=2022)

00 00	Expert Review (in case of need)	1.500 – 2.000,- €/Site
01.00	Site equipment (10-12% total)	40 – 45 €/m²
01.09	Directed & additional work (1-2% total)	2 – 4 €/m²
01 98	Directed work (manual)	50 €/h
02.00	Prepare site & earthworks (11-13% total)	50 – 60 €/m²
03.22	Drilling, Injection & Anchoring (30-35%)	100 – 110 €/m²
03.22.1	Micropiles (2x 4-5 m per foundation)	500 – 600 €/m
03.50	Foundation hinged posts	1.500 – 2.000 €/pc
04.52	Rockfall protection system (40-50%)	140 – 150 €/m²
	Discount (0-3%)	2 – 4 €/m²
∑	**Total net price (no VAT)**	**Ø 347,5 €/m²**
	Taxes (20% VAT)	Ø 69,5 €/m²
∑	**Total gross price (with VAT)**	**Ø 417,0 €/m²**

3 Standardized life cycle

3.1 Basic formulas and example

A life cycle cost analysis (LCCA) monetarizes all impacts of an investment during service life based on net present value and annual costs. The LCCA can be conducted from the perspective of asset owner, users and/or third parties as well as the environment. In the optimization the perspective and/or included impacts are a decisive factor for the results of the analysis. For rockfall protection fences the perspective of the owner with some modifications to account for events are a good start on network, asset, and element level. The presented formulas describe a basic deterministic life cycle with total costs (1), present value (2), annual costs (3), condition performance (4), remaining life (5), and residual value (6). For including uncertainty, the corresponding stochastic discrete and continuous LCCA models are found elsewhere [5].

$$\text{Total costs } V_k \rightarrow \text{total } C_k = \sum_{j=1}^{j=n} C_{e,j} \qquad (1)$$

$$\text{Present value } V_k \rightarrow \text{total } C_k = \sum_{j=1}^{j=n} C_{e,j} * (1+p)^{-t} \qquad (2)$$

$$\text{Annuity option } V_k \rightarrow C_{A,k} = \sum_{j=1}^{j=n} C_{e,k} * \frac{i * q^{x_a}}{(q^{x_a}-1)} \qquad (3)$$

$$\text{Performance function } V_k \rightarrow f_k(t) = \beta_0 + \beta_1 t^{\beta_2} \qquad (4)$$

$$\text{Remaining life } V_k \rightarrow t_{r,k} = \sum_{j=1}^{j=n} (x_{a,j} + x_{b,j}) - t \qquad (5)$$

$$\text{Residual value } V_k \rightarrow V_{t,k} = C_{e,j} \frac{t_{r,k}}{x_a} (1+p)^t \qquad (6)$$

with	$C_{e,j}$	*Construction and/or M&R costs*	*[€]*
	V_k…	*Investment options k=1…n*	*[-]*
	i…	*Interest rate with q=1+i*	*[%]*
	t…	*Time intervention/investment*	*[a]*
	x_a	*Service life*	*[a]*
	x_b	*M&R treatment life*	*[a]*
	$C_{e,k}$	*Present value costs option k*	*[€]*
	$C_{A,k}$	*Annuity life cycle option k*	*[€/a]*
	$t_{r,k}$	*Remaining life option k*	*[a]*
	$V_{t,k}$	*Remaining value option k*	*[€]*
	$Y_{t,k}$	*Condition option k at time t*	*[a]*
	β_i	*Parameters performance function f(t) → $y_{t,k}$*	*[-]*

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The provided example in *Figures 10 to 13* applies the afore mentioned formulas comparing a simple replacement cycle with a rehabilitation prior to failure of existing assets. For investment comparison based on present value the same analysis horizon and residual value at the end have to be considered. With the provided parameters the calculation shows that a rehabilitation is favourable, as the annual costs are lower. The calculated performance functions are highlighted, as the condition prediction with additional data regarding age, condition, and events will be further elaborated. In contrast to common approaches, the residual value is calculated based on remaining life. The main advantage in this case is that instead of just adding the rehab investment (accounting) the real functional value of assets is considered. With this approach, it can be proven, that in case a rehabilitation is economic, there can be no sunk costs as the residual value is "activated" as well.

with *service life x_a=20 years; β_0=0%; β_2=1 (linear); construction costs C_e=100 €; maintenance and rehab costs C_r=30 €; intervention y_c=75%; reset value y_d=0%; failure y_a=100%; interest i=0% - further assumptions – asset sample with same age, no risks*

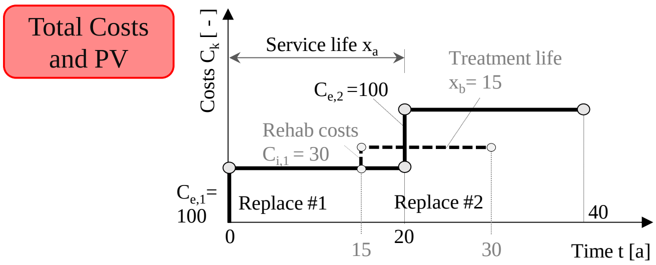

Figure 10 Total cost and present value calculation with example

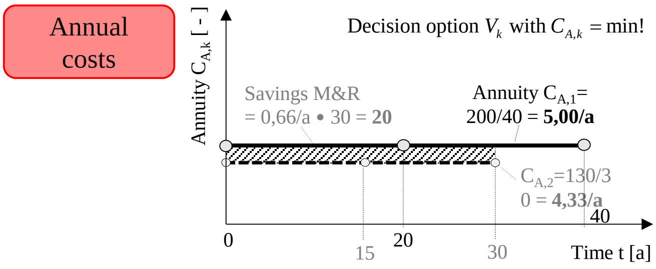

Figure 11 Annual cost calculation with example (interest i=0%)

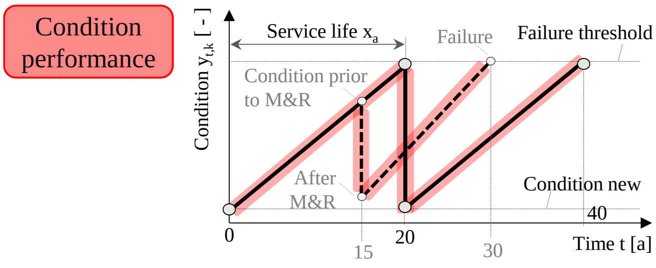

Figure 12 Deterministic condition performance with example (linear)

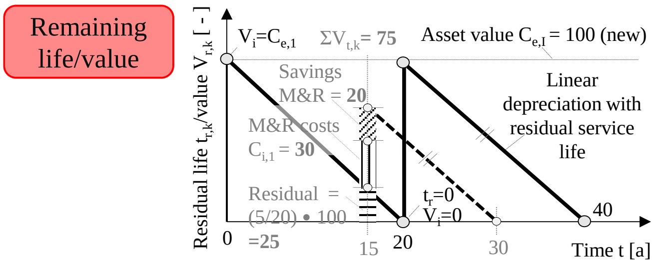

Figure 13 Remaining life/residual value calculation with example

3.2 Prediction with age/condition data

In contrast to a standardized LCCA with default values for costs and service life, individual assets may deviate substantially. Without adjustment to actual age and condition from surveys as well as current prices no meaningful analysis is possible. As shown, typical asset data is inhomogeneous with cases ranging from no age or condition data to assets with condition and age data down to element level. The developed LCCA model in this paper therefore accounts for all of these cases (*Figure 14*). With no age/condition data (A) the default performance function is used. With age, but no condition data the actual condition is derived by the standard performance (B). With condition and/or age data (C+D) the performance parameters are derived either by scaling (1 survey) or regression analysis (>1 survey). With additional data being available each year the standard performance function and predictions will become more and more accurate (adaption).

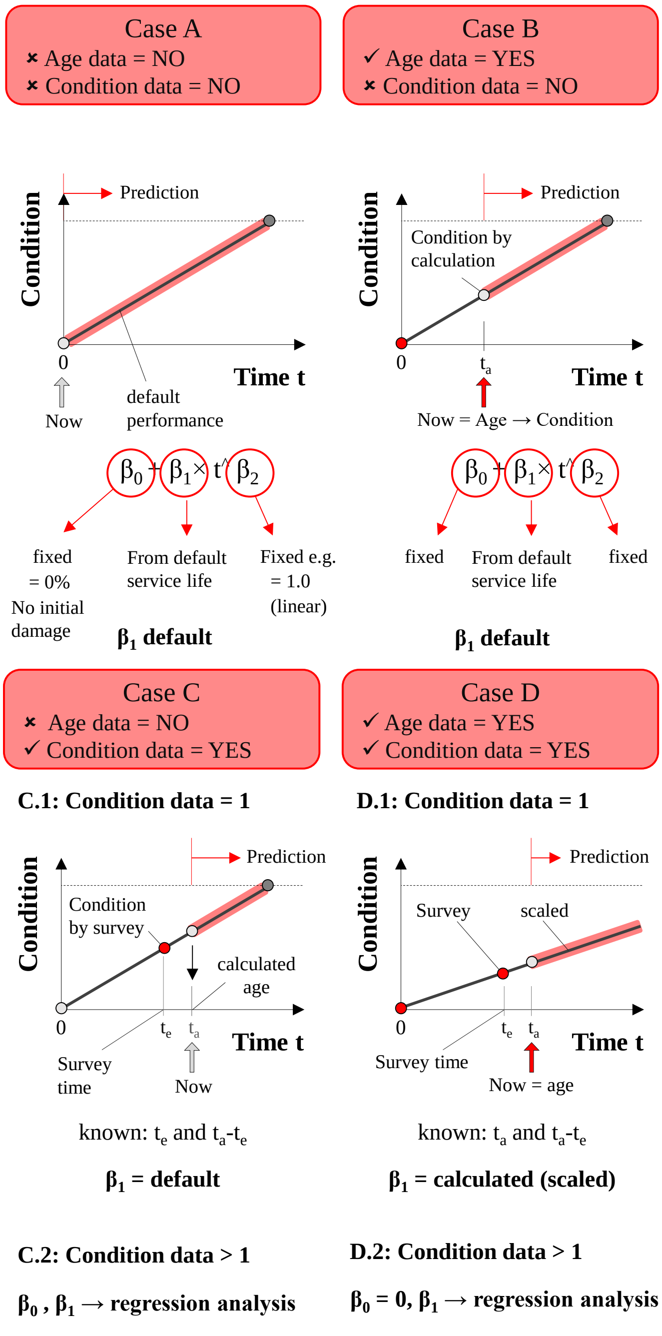

Figure 14 Asset condition prediction with/-out age/condition data

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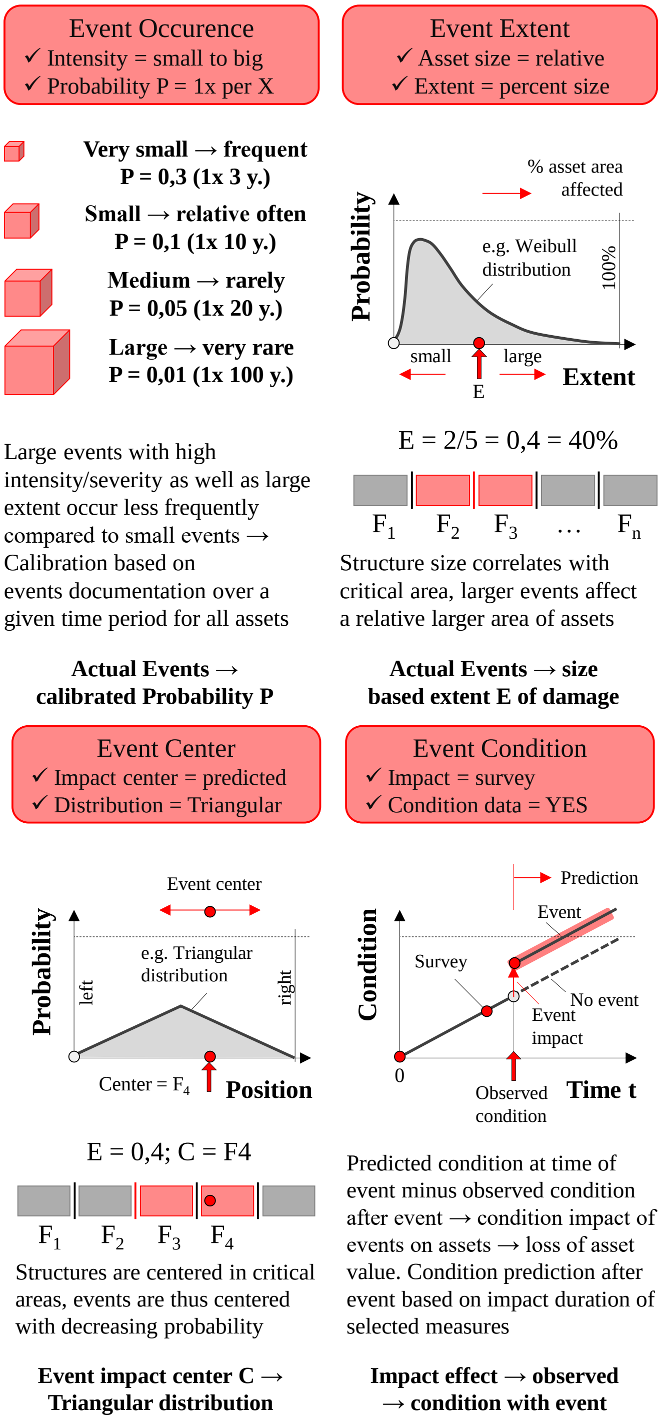
3.3 Prediction with events

Natural hazards like rockfalls may occur with a certain frequency decreasing with event size or intensity (event occurrence). Smaller events are more frequent resulting in a smaller extent of the affected protective structures (event extent). With protective structure placed centric in most critical areas a centric impact is more likely (event center). In case of an event all of these factors as well as the impact on asset condition can be observed (condition). With a consistent implementation and documentation, the presented models can be calibrated allowing an estimation of event volume on network level. Furthermore, the probability of events for single assets and elements can be predicted as well as the condition development after events based on an assessment of actual damages (*Figure 15*).



Large events with high intensity/severity as well as large extent occur less frequently compared to small events → Calibration based on events documentation over a given time period for all assets

Structure size correlates with critical area, larger events affect a relative larger area of assets

Actual Events → calibrated Probability P

Actual Events → size based extent E of damage

Structures are centered in critical areas, events are thus centered with decreasing probability

Predicted condition at time of event minus observed condition after event → condition impact of events on assets → loss of asset value. Condition prediction after event based on impact duration of selected measures

Event impact center C → Triangular distribution

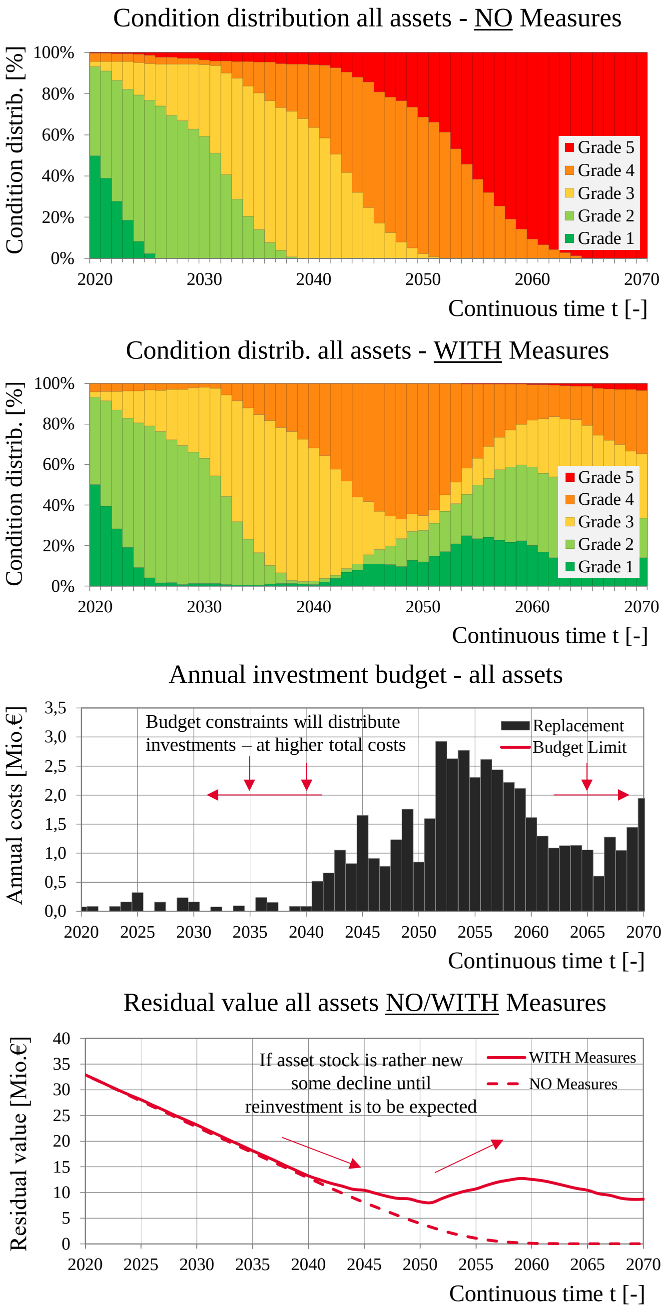
Impact effect → observed → condition with event

Figure 15 Asset/element condition prediction with/-out events

3.4 Simulation example network level

The LCC simulation on network level for rockfall protection nets is based on the generic simplified model on asset level. The simulation is applied for all rockfall protection assets with at least a condition information and/or age data (393/616 assets or 88,4% of total asset area). The simulation is based on an unlimited budget minimizing the total present value of investments in the analysis period of 50 years. The simulation results in *Figure 16* provide an overview on the condition distribution with NO/WITH measures as well as the annual investments budgets with residual value of the asset stock in the analysis period. With budget limits (constrained) the annual investments will be more evenly distributed at higher total cost, flattening the predicted reinvestment wave (NO Events).

with Asset type: Rockfall protection 393/616 assets (larger) Asset selection: with age or condition; Selected asset size = 68.073/76973 m2 (88,4%); Analysis year: 2020, Ø age selected assets = 9 years, interest rate 3%, NO Events



Budget constraints will distribute investments – at higher total costs

If asset stock is rather new some decline until reinvestment is to be expected

Figure 16 Network simulation results – 88,4% asset area, NO events

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3.5 Simulation example asset level

The LCC simulation on network level for rockfall protection nets with the generic simplified model is demonstrated on a selected asset comparing strategies from automated and manual treatment selection. *Figure 17* illustrates the measure timing and costs, present value, condition development, and residual value for both strategies. As rockfall events are not considered in the model (NO Events), the predicted budget needs and costs both on network and asset level will be considerably lower. However, the main advantage of the presented models is the automated updating based on available data and the possibility to include rockfalls based on actual events in any given year as well as predictions from calibrated probability distributions as shown in the next example.

with Asset type: Rockfall protection fence, ID 5091 (real asset); Total size = 900 m^2, no risks; Year of construction = 2016; Measures: Unit cost with extent based on condition Analysis year = 2020; Survey Grades: 2011 = 1; Interest rate: 3%; Natural hazards: NO events

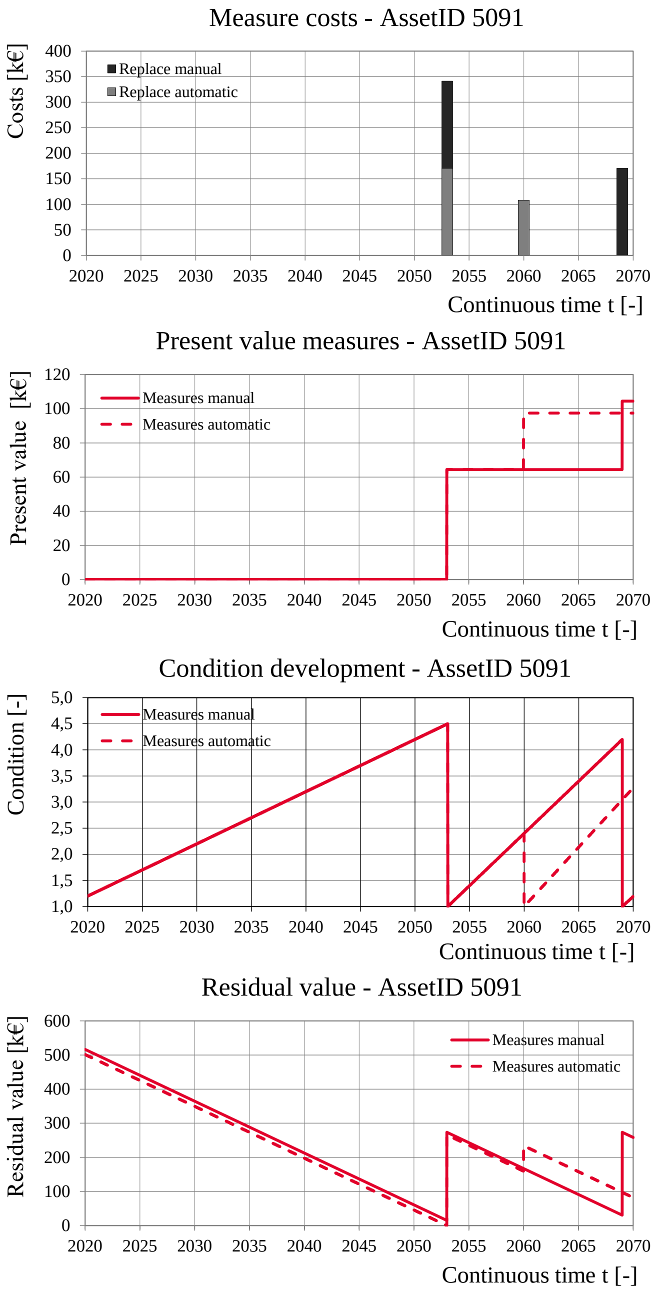

Figure 17 Asset simulation results - Asset ID5091 - NO events

3.6 Simulation example asset level

The simulation of rockfall protection fences on element level is based on highly standardized life cycle models with the four element types foundation, posts, steel nets, and anchoring. For the simulation the number of fields with height and width are given together with asset age, results of previous condition surveys, and year of analysis. Furthermore, the service lives and performance function for all elements can be defined as well as the afore mentioned costs for standardized measures on element level. The results for a typical rockfall protection fence example with an optimization of measures without (*Figure 18*) and with events (*Figure 19*) together with the resulting measures, condition development and residual value are provided below (NO/WITH events).

with *Asset type: Rockfall protection fence, Size: 10 fields, height = 3,5 m, length = 6 m; Total size = 10 × 3,5 × 6 = 210 m^2, no risks; Year of construction = 2000; Analysis year = 2022, Survey Grades: 2010 = 1; 2015 = 2; 2020 = 3; Interest rate: 3%; Natural hazards: NO/WITH events*

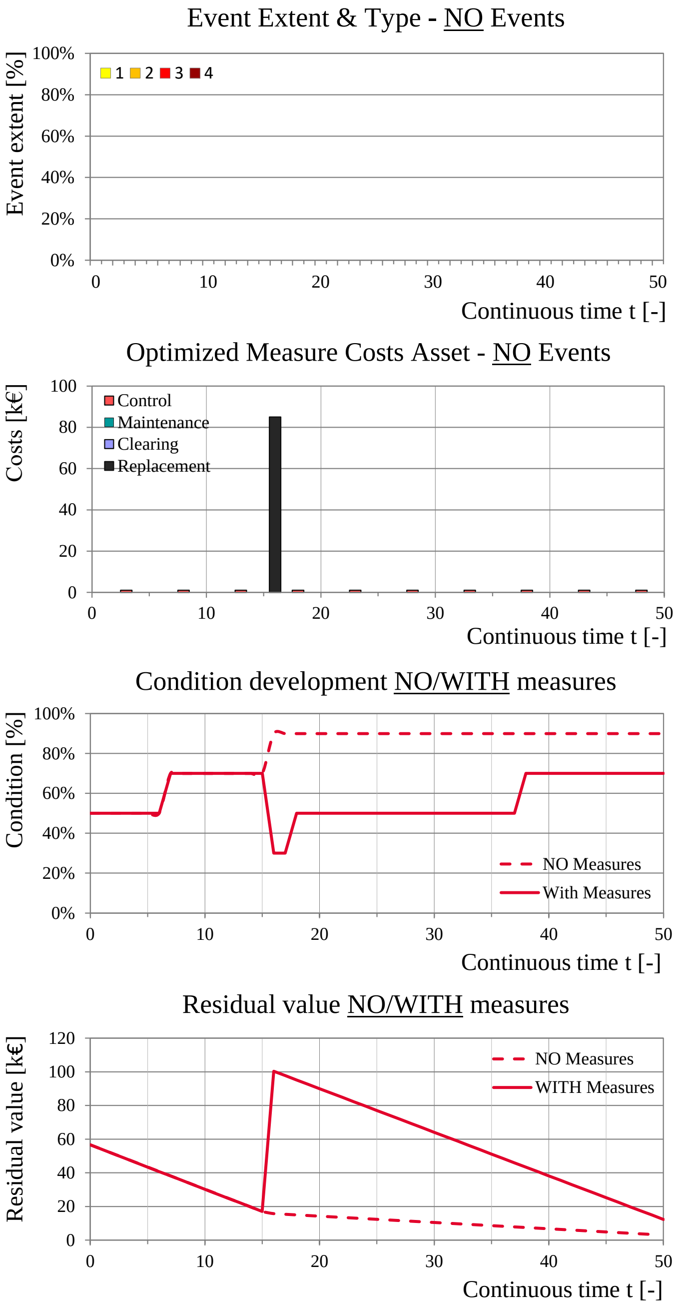

Figure 18 Asset element simulation results NO events

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As proof of example in simulations without events the measures are solely based on predicted condition development with ageing and an optimization of interventions leading to periodic controlling (e.g. 5 year interval) and a replacement in year 16. For the example with events the simulation predicts 11 very small events (clearing), 2 small events (clearing + maintenance), 3 medium events (condition loss with clearing + partial replacement), and no large events (full replacement). The resulting measures apart from control, maintenance, and clearing are partial replacements in the years 9/19/39 in the analysis period of 50 years. In practise, the simulation can be conducted for any starting year based on previous condition surveys and observed events. As future events can only be predicted based on calibrated occurrence probabilities a documentation based on severity, extent and affected assets is advised. Based on calibrated probabilities the simulation for all assets with and without events will provide specific insights into treatment selection, investment needs, asset stock condition and residual value as shown. Furthermore, the event probabilities and costs can be adapted to regional characteristics with sufficient data for calibration.

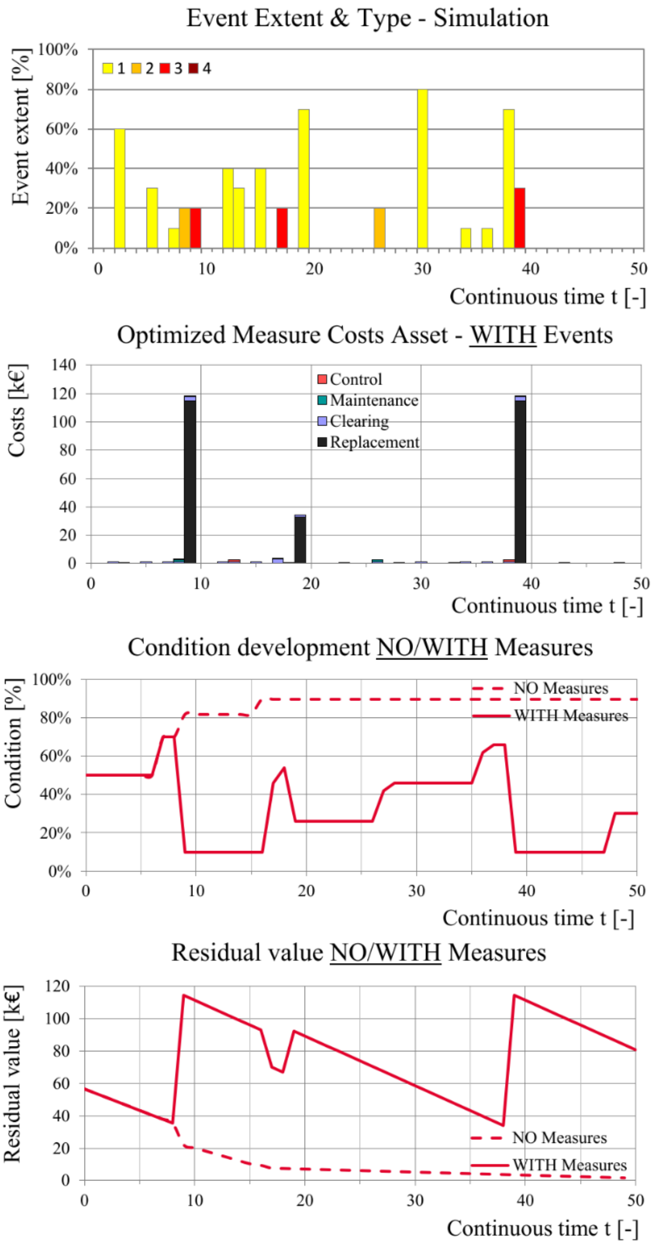

Figure 19 Asset element simulation results WITH events

4 Summary and Conclusions

Asset management in civil engineering can be defined as the systematic organization and optimization of all activities in the life cycle. The paper provides an overview on the railway asset stock in Austria with 8.500 protective structures against natural hazards. Based on a thorough assessment of construction projects of OEBB-Infra cost functions, measures and standardized life cycles for selected protective structure types have been derived. The developed and calibrated life cycle models allow a generalized assessment of asset condition, residual service life, and remaining asset value being subject to natural aging processes and random events. Depending on available data on these assets standardized calculations on network, asset and element level for the entire stock are feasible.

With application to rockfall protection fences the life cycle cost simulation on network level yields the condition distribution, asset stock residual value, and investment needs for any given budget constraint. On asset level the generalized life cycle allows a comparison of different measures and strategies for any given situation. The application of the simulation on asset element level allows the specific consideration of events and measures based on observed condition for any size of rockfall protection nets. Furthermore, the developed methods, models and results will be developed further and can be applied to other civil or protective structures.

Acknowledgement

The development of standardized life cycle cost models for protective structures against natural hazards with application on rockfall protection fences and other structures would not have been possible without the generous support and contributions of OEBB-Infrastructure AG from 2020 to 2022.

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