Influence of cross passages temperatures on the life-cycle cost of technical equipment in a railway tunnel

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Abstract. In order to achieve the climate goals, the implementation of sustainable construction is becoming more and more topical in the construction sector. Due to very long service lives especially in railway projects, the consideration of life-cycle aspects into the early design process is of great importance. Regarding the assessment of the economic pillar of sustainability, life-cycle costing has become an established method. This study presents the application of life-cycle cost analysis (LCCA) for decision aiding in railway construction. The two tunnel tubes of the project Koralmtunnel (KAT) are connected with approximately 70 cross-passages (CPs) at intervals of around 500 m. These CPs serve as escape-ways and additionally host utility rooms for technical equipment (telecommunication, power supply and remote control). First thermal simulations revealed indoor temperatures up to 80°C due to the heat release of the technical equipment without implementation of technical cooling systems in operation phase. This is caused by the limited heat transfer with the surrounding rock and with the adjacent running tubes. Therefore, the implementation of a cooling system is necessary. It is stated that higher indoor temperatures lead to reduced service lifes of the installed telecommunication systems. By the application of Arrhenius equation, the influence of several indoor target temperatures on the expected life time of the installed telecommunication systems has been determined. In order to meet target temperature requirements appropriate scenarios including different cooling scenarios have been designed. Finally, LCCA by application of the net-present value-method (NPV-method) was conducted in order to determine the most economical solution regarding CPs cooling systems based on selected target-temperatures.

1. Introduction
Large railway projects place manifold requirements on the design, the construction, the equipment, the commissioning as well as on the later operational management. In order to reconcile all these areas, which in some cases need to be assessed very differently, far-reaching considerations are required in advance. Long railway tunnel projects, increased demands on tunnel safety and the exploitation of existing technical possibilities are reasons why a massive increase in technical equipment can be observed. This trend needs to be monitored very carefully and critically so that it does not lead to increased maintenance cost, reductions in system availability, capacity constraints and quality of
operations management. Sustainable construction occupies a special place in the construction industry due to the centuries-long life-cycles of construction projects. Therefore, the construction sector plays a key role in this context and has enormous potential to reduce the human impact on our environment. From an economic perspective, private stakeholders often only focus on maximum profit and on short-term yielding. To implement sustainable construction, the three dimensions of sustainability (ecology, economy, sociality) must be considered throughout the lifecycle of a construction project. For the consideration of the economic pillar over the entire life span of construction projects LCCA represents a suitable instrument. Especially, public railway projects usually have very long lifetimes. Due to the long-term cost implications of operating cost and the maintenance of their technical equipment, a lifecycle-oriented approach is indispensable.

The so-called southern corridor (the Austrian part) is part of the Baltic Adriatic corridor of the Trans-European Network Transport (TENT-T) [1, 2, 3, 4]. Core of this southern corridor are the Semmering Base Tunnel (SBT) with a length of 28 km and the Koralmtunnel (KAT) with a length of 33 km.

The two railway projects SBT and KAT will be operated as high-speed track. According to the distance reduction between Graz and Klagenfurt (230 km to 130 km), the travel time will be reduced for more than 2 hours [3, 4]. Today the KAT is the sixth longest railway tunnel in the world. The KAT consists of 2 tunnel tubes, which are connected with approximately 70 CPs, every 500 m. The CPs (see figure 1) serve as escape-ways and as utility rooms which contain the technical equipment for operation.

![Figure 1. Schematic of a cross-passage - escape-way (left), utility rooms (right)](image)

Thinking the entire life-cycle in the construction phase leads to different implementation scenarios due to limited service life of telecommunication systems. Due to the limited possibilities of dissipating the heat through the rock or through the adjacent running tubes, utility room temperatures of up to 80°C occur during operation without cooling activities. These high temperatures mean that the telecommunication systems has to be replaced in shorter cycles. Based on the Arrhenius equation, the service life of the telecommunication systems can be determined as a function of the temperature. To increase the service life of the telecommunication systems, the utility room temperatures must be cooled. The cooling of the utility rooms requires additional construction cost of air-conditioning systems and/or ventilation systems in the construction phase as well as higher energy requirements for cooling in the use phase. On the other hand there are longer replacement cycles of the telecommunication systems in the use phase. In the sense of sustainable implementation, the decision-making problem arises for the investor between low initial construction cost with high usage cost or higher initial construction cost with lower usage cost.

2. Applied methodology
We illustrate how to use a NPV-method for decision-aiding in the design stage of railway projects under consideration of different thermal conditions.
2.1. Thermal conditions of long railway tunnels

The requirements for the thermal conditions inside a tunnel differ between construction phase and tunnel operation. During construction phase, the main constraint is the maximum allowable air temperature at the working areas, which must not be exceeded. While operation, the thermal conditions in the tunnel are important because tunnel air often is used for cooling technical equipment, which usually is located in utility rooms or zones within the CPs between the two tunnel tubes. To guarantee that the acceptable temperatures limits for the single utility rooms will be kept, a cooling process by the usage of tunnel air is required. Due to cost efficiency a simple mechanical ventilation system shall be installed in as many CPs as possible. In case this simple cooling process is not sufficient, air-conditioning systems are required.

As soon as outside air gets into the tunnel, the outside air temperature is one of the influencing parameters for the tunnel air temperature. For the current simulations the weather data (outside air temperature) from the region for the years 2010-2016 [5, 6] was processed. It turned out, that in 2013 summer short-term outside air temperatures, which represent the worst case for compliance with the temperature specifications, were maximum.

The rock temperature is one of the major parameters for the tunnel air temperature while construction and operation. The rock temperature curve was measured and monitored during the excavation phase and represents the start condition for the simulation of the time dependent evolution of tunnel-wall temperatures along the tunnel.

The most important heat sources during operation are the trains themselves. The impact of trains depends on the speed, the geometry of the trains as well as of the tubes. The piston effect of the trains generates an air flow in the tubes, which is essential for the thermal conditions along the tunnel. Hence the interval between the trains as well as their driving direction are further essential parameters. Depending on the slope of the track the convective heat release by breaks has to be considered too. The highpoint of the KAT is a few kilometers west from the emergency stop station. On both sides of the tunnel is a regular train station, so trains will have to stop and breaking energy will be released already in the tunnel.

In general, the fresh air-requirement is the major parameter for the tunnel air conditions. The higher the fresh air volume flow the bigger the influence of the outside air temperature.

Since tunnel air is used for cooling the utility rooms inside the CPs, the released heat from technical equipment such as the telecommunication units or the power supply units, have to be considered. In all of the 70 CPs technical equipment is installed. The released heat varies between 3 kW and 25 kW, depending on the type of equipment installed. A single CP would not have a big impact to the thermal conditions, but the sum of transported heat can lead to remarkable changes in thermal conditions within the tunnel. Due to redundancy reasons both cooling systems (ventilation and air-conditioning) are capable for re-cooling in both tubes. Depending on the tunnel air temperature in front of the CPs, re-cooling will take place in the tube with lower air temperature. If one tube is closed for maintenance, the second one is still in operation and due to the trains, an air flow and therefore a heat transport is granted. In the maintained tube the airflow depends on meteorology and if required on the maintenance ventilation. Simulations were performed, for identifying tunnel regions where tunnel air is cool enough to fulfill the thermal requirements. In figure 2 the simulation of thermal conditions within the utility rooms along the Koralmtunnel is shown.
Figure 2. Simulation of thermal conditions within the utility rooms along the Koralmtunnel

The technical equipment includes power units for low voltage, medium voltage, transformer systems and telecommunication systems. Due to the high temperature sensitivity of the telecommunication systems and its effects on their service lifes, only utility rooms with located telecommunication systems are considered. The increased room temperature in the CPs in figure 2 is the result of the installed telecommunications systems with base stations, which produce increased waste heat.

2.2. Service life of telecommunication systems - Arrhenius equation

The Arrhenius equation, named after Svante Arrhenius (1859 - 1927), describes approximately a quantitative temperature dependence in physical and chemical processes in which an activation energy has to be overcome at the molecular level [7, 8]. The Arrhenius equation is related to the Eyring equation, which represents a connection of the microscopic interpretation.

\[ t_E = t_Q \cdot e^{\frac{E_A}{R} \left( \frac{1}{T_E} - \frac{1}{T_Q} \right)} \]  

where:

- \( t_E \) = qualified life at absolute operating temperature \( T_E \)
- \( t_Q \) = test or qualification duration at absolute test or qualification temperature \( T_Q \)
- \( E_A \) = activation energy (the aging reaction)
- \( R \) = gas constant

Based on the Arrhenius equation, the service life of the telecommunication systems were calculated as a function of the utility room temperatures. Table 1 shows the service life and the replacement cycles of the telecommunication systems over a 50 year period.
Table 1. Service life of telecommunication systems at different utility room temperatures

| Utility room temperature | Service life | Replacement cycle |
|--------------------------|--------------|-------------------|
| 22°C                     | 16 years     | 3                 |
| 25°C                     | 13 years     | 3                 |
| 30°C                     | 9 years      | 5                 |
| 35°C                     | 6 years      | 8                 |
| 40°C                     | 4 years      | 12                |
| 45°C                     | 3 years      | 16                |

2.3. Life-cycle cost analysis

The framework for assessing the economic performance of construction projects is defined on international level in ISO 15686-5 [9]. In the course of a life-cycle cost analysis, different cost types that occur during the life-cycle of a construction project can be taken into account. In addition to different cost types, different calculation methods can be used. In general, a distinction is made between static and dynamic methods [10]. This study uses the NPV-method for the life-cycle cost analysis. With the NPV method it is possible to estimate the difference between the present value of cash inflows and the present value of cash outflows over a period of time [11].

\[ NPV = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \]

where:

- \( R_t \) = net cash inflow-outflows during a single period \( t \)
- \( i \) = discount rate or return that could be earned in alternative investments
- \( t \) = number of time periods

In particular, the usage cost and the assumed calculation parameters are of great importance for the results of LCCA [10]. In addition due to the uncertainties in assumed calculation parameters, the uncertainty of LCCA results is increased with increasing reference study period. Dominance analyzes, sensitivity analyzes and risk analyzes were performed to estimate the uncertainty of results. Dominance analysis is an appropriate analytic technique to identify the relative importance of predictors of an outcome [13, 14].

According to the ISO 15686-5 sensitivity analysis is defined as the test of the outcome of an analysis by altering one or more parameters from initial value(s). A sensitivity analysis can reveal how precise the calculation is, and how it affects the calculation if the inputs were different. Sensitivity analysis helps to identify input data with the highest impact on the LCCA results and the robustness of the final decision. Finally, for evaluating the opportunity and risk potential of the results Monte-Carlo simulations are applied. Monte-Carlo simulation is a numerical method that runs simulation with random numbers. Within the Monte-Carlo simulation, it is possible to determine probability distribution functions based on defined calculation rules [15].

3. Case study - Koralmtunnel

In the course of LCCA, two calculation runs were carried out. In the first calculation run, the classification of CPs made at the beginning was compared with an extreme value scenario (cooling of all CPs with air-conditioning systems). It turned out that the high energy requirement for cooling to low target temperatures with air-conditioning systems was the driving cost factor. Based on the first results
the extreme value variant was excluded after the first calculation run. Furthermore, scenarios with target temperatures in the utility rooms above 35°C were excluded for reasons of occupational safety during maintenance and repair. The adapted classification of CPs (four scenarios) is shown in figure 3.

![Classification of CPs depending on different target temperatures](image)

**Figure 3.** Classification of CPs depending on different target temperatures

The darkgray areas represent the CPs with air-conditioning systems and the lightgray areas the CPs with ventilation system. In all target temperature scenarios the CPs without utility rooms for technical equipment (CP 31, CP 33, bypasses and fire brigade accesses) are not considered.

The required input parameter for the application of the LCCA is shown in table 2. The values were given on the basis of literature research and from the experience of the project partners.
Table 2. Initial input parameter LCCA - Scenario 3 (target temperature 30°C)

| Input parameter                                         | Value               |
|---------------------------------------------------------|---------------------|
| Reference year                                          | 2025                |
| Interest rate                                           | 4.0%                |
| Rate of price increase                                  | 2.5%                |
| Rate of energy price increase                           | 2.75%               |
| Energy price                                            | 0.125 €             |
| Initial construction cost air-conditioning systems      | 211377 €            |
| Initial construction cost ventilation system             | 89094 €             |
| Initial construction cost telecommunication systems for standard CPs | 178265 €          |
| Initial construction cost telecommunication systems for CPs with base station | 385516 €          |
| Adaption, refurbishment and repair cost air-conditioning systems | 3% of CC/year     |
| Adaption, refurbishment and repair cost ventilation system | 6% of CC/year     |
| Adaption, refurbishment and repair cost telecommunication systems for standard CPs | 11.3% of CC/year  |
| Adaption, refurbishment and repair cost telecommunication systems for CPs with base station | 11.3% of CC/year  |
| service life air-conditioning systems                   | 10 years            |
| service life ventilation systems                        | 20 years            |
| service life telecommunication systems for standard CPs | 9 years             |
| service life telecommunication systems for base station CPs | 9 years            |
| Operating hours air-conditioning systems                | 8760 h/a            |
| Operating load scenario air-conditioning systems (Year 1 to 4) | 25%                |
| Operating load scenario air-conditioning systems (Year 5 to 9) | 28%                |
| Operating load scenario air-conditioning systems (Year 10 to 24) | 29%                |
| Operating load scenario air-conditioning systems (Year 25) | 31%                |
| Operating load scenario air-conditioning systems (Year 26 to 44) | 31%                |
| Operating load scenario air-conditioning systems (Year 45 to 50) | 33%                |
| Operating hours ventilation systems (Year 1 to 4)        | 2600 h/a            |
| Operating hours ventilation systems (Year 5 to 9)        | 2700 h/a            |
| Operating hours ventilation systems (Year 10 to 24)       | 2750 h/a            |
| Operating hours ventilation systems (Year 25)             | 3200 h/a            |
| Operating hours ventilation systems (Year 26 to 44)       | 3256 h/a            |
| Operating hours ventilation systems (Year 45 to 50)       | 3500 h/a            |
| CPs with air-conditioning systems                        | 4                   |
| CPs with CS                                             | 61                  |
| Standard CPs                                            | 57                  |
| Base station CPs                                        | 8                   |

For the NPV-method, all input parameters were compounded to the reference year 2025. Dynamic energy consumptions were determined for a realistic picture of the temperature development due to climate change. This is why an increasing energy consumption is emerging in the cooling of the utility rooms over the years. As a result, higher operating hours of the ventilation systems and higher operating load scenarios of the air-conditioning systems are required.

4. Results
This section presents the decision aiding process based on the results of the LCCA. To deal with the uncertainties in the assumptions, the results of dominance analysis, sensitivity analysis and risk analysis are also presented.

4.1. Comparison of scenarios
In figure 4 the results of the four CPs classifications (S1, S2, S3 and S4) are shown.
As shown in the illustration, scenario 3 (dark green line) has the lowest life-cycle cost after 50 years. Based on this scenario, the course of jumps and slopes over the considered life-cycle are explained.

In the construction phase, the initial construction cost of air-conditioning systems, ventilation systems, and telecommunication systems are incurred. The initial construction cost for scenario 3 involves the cost of 4 air-conditioned CPs and 61 ventilated CPs. All 65 CPs will be equipped with telecommunication systems (8 of them with telecommunication systems for base stations). The slope up to the year 9 results from the annual cost for the energy consumption for the cooling as well as from the annual adaptation, refurbishment and repair cost for air-conditioning systems, ventilation systems, and telecommunication systems. The jump in year 9 results from the first replacement cycle of telecommunication systems. The next jump in year 10 results from the first replacement cycle of the air-conditioning systems. Based on dynamic energy consumption, the slope between jumps is always a bit steeper over the years. Further jumps occur in the years 18 (second replacement cycle of telecommunication systems), in the year 20 (second replacement cycle of the air-conditioning systems and first replacement cycle of ventilation systems), in the year 27 (third replacement cycle of telecommunication systems), in the year 30 (third replacement cycle of the air-conditioning systems), in year 36 (fourth replacement cycle of telecommunication systems), in year 40 (fourth replacement cycle of the air-conditioning systems and second replacement cycle of ventilation systems) and in year 45 (fifth replacement cycle of the telecommunication systems).

Compared with scenario 1 (black line in figure 4), which was adopted as a reference scenario (100% after 50 years), scenario 3 reduces life-cycle cost by up to 20%.

4.2. Dominance analysis

In the course of the dominance analysis, the most influencing factors on the overall result were identified. Figure 5 shows the influence of the different cost categories in a sankey diagram. The considered cost categories are assigned to the technical systems (air-conditioning systems, ventilation systems, and telecommunication systems) on the right side of the sankey diagram. Telecommunication systems of
standard CPs and telecommunication systems of CPs with base stations were merged in this illustration.

The life-cycle cost after 50 years are initially divided into approx. 86 % on usage cost and approx. 14 % on initial construction cost. A closer look at initial construction cost shows that the air-conditioning systems have a very small influence on the initial construction cost, followed by the initial construction cost of ventilation systems and telecommunication systems. The usage cost are divided into maintenance cost and operation cost. 73% of operation cost come from the energy consumption of the ventilation systems and 27 % from the energy consumption of the air-conditioning systems. The maintenance cost are divided according to ISO 15686-5 in adaption, refurbishment and repair cost and replacement cost. The adaption, refurbishment and repair cost has a share of 53 % and the replacement cost a share of 47 %. Most of the adaption, refurbishment and repair cost comes from the telecommunication systems. These make up the decisive contribution with a share of 88 %. The second largest share is the adaption, refurbishment and repair cost of ventilation systems with 9 %. The remaining 3 % is provided by adaption, refurbishment and repair cost of air-conditioning systems. Even in the replacement cost the decisive stem from replacements of the telecommunication systems (replacement cycle every 9 years) with 83 %. Followed by the replacements of the ventilation systems with 13 % and the replacements of the air-conditioning systems with 4 %. In the right part of the sankey diagram, all cost categories are transferred to the technical systems. It can be clearly seen that the telecommunication systems account for the largest share of life-cycle cost (80 %). The contribution of the ventilation system to the overall life-cycle cost is 17 %. Due to the low active cooled cross-passages (only 4 CPs with air-conditioning systems), the share of air-conditioning systems is only 3 %.

Figure 5. Sankey diagram for scenario 3 (target temperature 30°C)
4.3. Sensitivity analysis
In the first step of the sensitivity analysis, based on the assumed initial input parameters (table 2), the parameters are changed individually and the effect on the life-cycle cost after 50 years was analysed. This procedure identifies the most sensitive parameters for influencing the overall life-cycle cost after 50 years.

| Table 3. Sensitivity analysis for scenario 3 (target temperature 30°C) |
|--------------------------|----------------|----------------|
| Initial input parameter  | Minimum threshold | Input parameter | Maximum threshold |
| Interest rate            | 3.0%            | 4.0%            | 5.0%            |
| Rate of price increase   | 1.5%            | 2.5%            | 3.5%            |
| Rate of energy price increase | 1.75%     | 2.75%            | 3.75%            |
| Energy price             | 0.0625 €        | 0.125 €         | 0.1875 €        |
| ARRC ventilation systems | 0% of ICC/year  | 3% of ICC/year  | 8% of ICC/year  |
| ARRC air-conditioning systems | 1% of ICC/year | 6% of ICC/year | 11% of ICC/year |
| ARRC telecommunication systems | 6.3% of ICC/year | 11.3% of ICC/year | 16.3% of ICC/year |
| Service life ventilation systems | 15 years | 20 years | 25 years |
| Service life air-conditioning systems | 5 years | 10 years | 15 years |
| Service life telecommunication systems | 4 years | 9 years | 14 years |
| Operating hours air-conditioning systems | 3760 h/a | 8760 h/a | 13760 h/a |
| Operating load scenario air-conditioning systems | 11% | 31% | 51% |
| Operating hours ventilation systems | 1200 h/a | 3200 h/a | 5200 h/a |

1 Adaptation, refurbishment and repair cost
2 Initial construction cost

In figure 6 the fluctuation of the considered input parameters after 50 years is shown. Accordingly, the economically positive effects are shown with the dark gray bars (below 100 %) and the negative effects are shown with the light gray bars (more than 100 %). The 100 % line represents the life-cycle cost after 50 years with unchanged input parameters (initial input parameters in table 2). The most sensitive screw within the life-cycle cost analysis is the service life of the telecommunication systems. If this information differs by 5 years (from 9 years to 14 years), the total life-cycle cost would increase by more than 45 %. The second and third most important parameters are the interest rate and the rate of price increase. With a fluctuation of the interest rate and the rate of price increase by plus/minus 1 % the life-cycle cost would increase by more than 20 %.
As shown in figure 6, the adaption, refurbishment and repair cost of the telecommunication systems - increasing life-cycle cost by more than 15% at 5% higher adaption, refurbishment and repair cost of the telecommunication systems - and the adaption, refurbishment and repair cost of the ventilation systems - increasing life-cycle costs by more than 6% at 5% higher adaption, refurbishment and repair cost of the ventilation systems - are also decisive parameters.

4.4. Risk analysis

In the course of the risk analysis it is examined with which probability the economically best scenario (S3 - target temperature 30°C) with fluctuating input parameters also remains the best scenario. For this purpose, the input parameters (interest rate, rate of price increase, rate of energy price increase and energy price) are stored within their bandwidths (see table 3) with a probability of occurrence. For the calculations, it was assumed for the parameters considered that the probability of occurrence between the lower and upper thresholds was 68.27% (which corresponds to a standard deviation of sigma). Within these bandwidths random numbers were determined by Monte-Carlo simulation.
Figure 7 shows the range of life-cycle cost for scenario 3. As already mentioned, a large amount of uncertainty arises as the reference study period increases. In the year 50, due to fluctuations in the parameters, in best case up to 15% lower and, in worst case, up to 30% higher life-cycle cost could occur. A comparison of all 4 scenarios in a risk analysis is not required. A different fluctuation of the input parameters in different scenarios can not occur.

5. Discussion
The first calculation run has shown that the decisive input parameters are the required cooling energy for air-conditioning systems and ventilation systems. This required energy input is significantly influenced by the classification of the cross-passages (cooling with air-conditioning systems or ventilation systems). From these findings, the extreme value scenario (all CPs equipped with air-conditioning systems) was discarded after the first calculation run and the focus was placed on the reduction of the required energy demands. The most obvious optimization measure with regard to the reduction of the life-cycle cost was the change of the cross-passages classification. With higher target temperatures, it is possible to equip less cross-passages with air-conditioning systems and thus reduce the energy consumption.

After completion of the second calculation run, it was found that, the cross-passage classification for the target temperature 30°C (scenario 3) is the most economical scenario over a period of 50 years. Allowed target temperatures of 35°C (scenario 4) exceed the life-cycle cost of scenario 3. The reason for this is that at 35°C target temperatures the decisive parameter is the replacement cycle of the telecommunication systems (every 3 years). This huge cost factor can not be compensated with the reduced energy demand in scenario 4 (no CPs equipped with air-conditioning systems).

In the dominance analysis, it can be seen that the cost drivers for the most economic scenario are the maintenance cost of the telecommunication systems. This finding is also confirmed by the sensitivity analysis carried out. The uncertainties in the service life of the telecommunication systems would most affect the overall life-cycle cost. The final risk analysis repeatedly emphasizes that life-cycle cost analyzes are always subject to uncertainties. Future developments of interest rates or price increase rates can not be predicted and can therefore only be taken into account with scenario analyses.
6. Conclusion
In the course of the study, it has emerged that an accompanying life-cycle cost analysis has a medium to long-term economic advantage in the construction of railway projects. The life-cycle cost can be considerably reduced, if the results of the LCCA are incorporated into the planning of cross-passage classification iteratively. Due to the great influence of energy consumption, the location of technical equipment (power units for low voltage, medium voltage, transformer systems and telecommunication systems) should be determined early in order to calculate the resulting waste heat in detail. Therefore, the design of the utility rooms should be tailored to the technical equipment in an early design stage.

References
[1] The Koralm Railway - A part of the new Southern Railway Line. ÖBB-Infrastruktur AG. 2012
[2] Erfahrung und Erkenntnisse aus der Instandhaltung und der Störungsbewältigung aus fast zehn Jahren Betrieb des Lötschberg-Baseistunnel. Suter D. Rudin C.Luginbühl P. STUVA-Tagung. Dortmund: Forschung + Praxis 49; S. 335. 2015
[3] The Baltic Adriatic Axis, Element of the future European TEN-T Core Network. bmvit. 2010
[4] Durchbruch in die Zukunft - Der Koralmtunnel. ÖBB-Infrastruktur AG. 2012
[5] Kühlung von Technischen Rumen in Eisenbahntunneln zur Erhöhung der Standzeiten und Minimierung der Wartung: Möglichkeiten der Optimierung am Beispiel Koralmtunnel. Steiner H. Sturm P-J. Fruhwirt D. 2017
[6] Meteorological data for the Koralm region. Amt der Steiermärkischen Landesregierung
[7] Zeitschrift für Physikalische Chemie. S. 226 - 248. Arrhenius S. 1889
[8] A glossary of terms used in chemical kinetics, including reaction dynamics. UPAC Compendium of Chemical Terminology. 1996
[9] ISO 15686 Life-cycle costing: Buildings and constructed assets (2008).
[10] Immobilienökonomie: Band 1: Betriebswirtschaftliche Grundlagen. Schulte, K-W. 2004
[11] Anomalies in Net Present Value, Returns and Polynomials, and Regret Theory in Decision-Making. Nwogug M. 2016
[12] EN 15978 - Sustainability of construction works Assessment of environmental performance of buildings Calculation method. CEN/TC 350. 2011
[13] The Dominance Analysis Approach for Comparing Predictors in Multiple Regression. Psychological methods. 8. 129-48. Azen R. Budescu D. 2003
[14] Dominance Analysis: A New Approach to the Problem of Relative Importance of Predictors in Multiple Regression. Psychological Bulletin. 114. 542-551. Budescu D. 1993
[15] Monte Carlo simulation of background characteristics of low-level gamma-spectrometers. Journal of Radioanalytical and Nuclear Chemistry. Breier R. Povinec P. 2016