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Development of a methodology for studying tunnel climate in long railway tunnels and for optimizing the design process of cross-passage cooling systems

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ABSTRACT

When it comes into operation in 2026, the Koralmtunnel in Austria will be the worlds seventh longest railway tunnel. The installation of the power supply, telecommunications and electro-mechanical services is currently ongoing. Parts of these systems have to be protected from temperature and humidity variations and from the high dust loads which are characteristic of the tunnel atmosphere. In particular, cooling systems are required to counteract the significant amounts of heat released by some installations. Information on a large number of parameters (e.g. tunnel air temperatures) is required in the design process. However, such information is only partly available in the design stage. Hence, a prediction of tunnel air temperatures has to be made. Additionally, since hardly any information about the tunnel climate in long railway tunnels is available and in-situ measurements are not possible, as thermal conditions differ significantly between the construction/equipping phase and the operation phase, a novel methodology for the prediction of the tunnel climate had to be developed. This article presents a description of a new method comprising four main investigative steps and of its application to the Koralmtunnel as a selected case study. While steps 1 and 2 provide information about the actual cooling requirement and tunnel air temperatures for a period of 50 years, steps three and four of the investigation aim at the technical and economic optimization of cooling systems.

1. Introduction

Tunnel systems are an important part of the worlds transport infrastructure. Rail transport is considered one of the key factors in the sustainable transport of goods and people. For this reason, the European Union is now pushing for the expansion of the *trans*-European railway network (European Commission, 2022). This expansion drive includes four main railway routes crossing the Alpine region in a north–south direction. Fig. 1 (a) shows a scheme of the future railway network as it is aspired to today, as well as the Alpine railway routes from north to south.

Two of the routes depicted in (Fig. 1 (b)), the Scandinavian-Mediterranean route in the west and the Baltic-Adriatic axis in the east, pass through Austria (red ovals). The core sections on these routes comprise three, newly built, very long railway tunnels. Two of these, the Semmering basetunnel (Austrian Federal Railways, 2022a) and the Koralmtunnel (Austrian Federal Railways, 2022b), each over 27 km long, are on the Baltic-Adriatic axis.

Such long railway tunnels require many technical installations for power supply, telecommunications, remote control, etc. Many of these installations have to be mounted inside the tunnel tubes, with sensitive components having to be protected from the tunnel atmosphere. Such an atmosphere is usually characterised by daily and annual temperature fluctuations, and by fluctuations in humidity and dust pollution due to the emission and resuspension of particles from moving trains. Both thermal and dust loads result in an enormous maintenance effort for tunnel equipment (Ehrbar, 2017; Sturm et al., 2022). Thermal stress accelerates the aging process of electronic components (Hertl et al., 2009; Frivaldsky et al., 2017), and electrically conductive particles can cause malfunctions and damage to sensitive components (Zhang, 2007). In order to protect sensitive components (e.g. telecommunication systems) from the tunnel atmosphere, such components are usually housed

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in utility rooms.

In modern twin-tube single-track tunnels, these utility rooms are located in so-called cross passages that connect the tunnel tubes at intervals of 500 m maximum. The basic structure of such cross-passages is shown in Fig. 2. Basically, they can be divided into two structurally separate halves. While one half serves as an escape route in the event of a tunnel incident, the second half provides the possibility of setting up special utility rooms. In order to create favourable conditions for sensitive equipment in the utility rooms, specific requirements for room temperature, relative humidity and air quality are needed. In many cases, these requirements can only be met with the help of cooling systems.

The design process of cross-passage cooling systems requires valid data on the tunnel climate and/or on the expected tunnel air temperatures. As tunnel excavation is normally not complete during the planning phase of cooling systems, acquiring such data presents a major challenge. Gathering suitable data is further complicated by the fact that tunnel climates during construction and operation (i.e. with running rail traffic) differ considerably. In addition, during construction the tunnel may is just partially excavated. Hence, in-situ measurements are not possible or do not provide the required data about the temperatures during the operation phase.

A study of the relevant literature may help alleviate the data problem, but in practice information about the climate in long railway tunnels is still relatively rare, and even when available, for example, from geothermal studies carried out in Switzerland (Andreas, 1998), it is often not applicable. As tunnel climate strongly depends on local parameters such as the rock temperatures, which in turn are dependent on the geological conditions, each tunnel needs to be investigated separately.

The present study provides a detailed description of a newly developed methodology for predicting the tunnel climate in long railway tunnels during the design phase of cooling systems. Furthermore, the methodology aims at a technical and economic optimisation of the cooling systems. To better illustrate the steps involved, the procedure is applied and demonstrated in the form of a specific case study.

2. Methodology for tunnel climate investigations

The newly developed methodology comprises four main steps which need to be worked through in sequence. The individual work steps result from the necessary flow of information. In this context, the initial information required concerns that relating to tunnel cooling demand. If no cooling demand is identified, the investigation process can be stopped. However, in the case of long railway tunnels, the demand for cooling, and thus for cooling systems, is more or less a certainty. This leads to step two of the investigation procedure. This entails making a prediction of the tunnel climate in order to obtain relevant data for the design of appropriate cooling systems. Usually, the prediction of the tunnel climate needs to cover several replacement cycles in the cooling systems. Thus, a period of some decades often needs to be assessed. As soon as the results of the second investigative step are available, the design process for cooling systems can begin. From this point on, the remaining steps of the method are aimed at technical and economic optimization of the cooling systems. This includes the use of detailed 3D CFD simulations that provide information about the temperature distribution within utility rooms (step 3) and a life cycle cost analysis (step 4). Fig. 3 summarizes the methodology and shows the output of the investigative steps.

While well-established engineering tools may be used in order to achieve the stated investigative targets, they need to be adapted for application in long railway tunnels. The most important aspects of the individual investigative steps are therefore explained in more detail in the following sections.

2.1. Identification of cooling requirement

The first question to be answered is whether there is any cooling requirement in the cross-passages or whether the temperature requirements can be met through self-regulation. For this purpose, a model based on the first law of thermodynamics can be used. Care must be taken to ensure that all relevant thermal processes (heat fluxes) are considered in the model. Thus, every room that is characterized by a unique temperature requirement needs to be defined as a separate thermal zone. The heat transfer into and out of these thermal zones, as well as heat sources within the zones, ultimately define the temperature in the zones. In other words, a heat balance must be established for each individual thermal zone, taking account of interactions with the adjacent thermal zones. In addition, heat sources that represent heat release from technical installations also need to be taken into account. Eq. (1) shows the energy balance that needs to be established.

$$\dot{Q}_S + \sum_i \dot{Q}_{wall_i} + \dot{Q}_{rock} = 0 \tag{1}$$

Here, $\dot{Q}_S$ represents the heat sources, the heat transfer through walls is accounted for by the term $\dot{Q}_{wall}$. $\dot{Q}_{rock}$ accounts for the heat transfer between room air and rock layers. Both the heat transfer through walls (Eq. (2)) as well as the interaction with rock layers (Eq. (3)) are a function of the room air temperature. Thus, in a steady state calculation, the expected room air temperatures () can easily be expressed explicitly. The term t_{room_j} refers to the room air temperature in an adjacent utility room. While k denotes the thermal transmittance of a wall, α is the

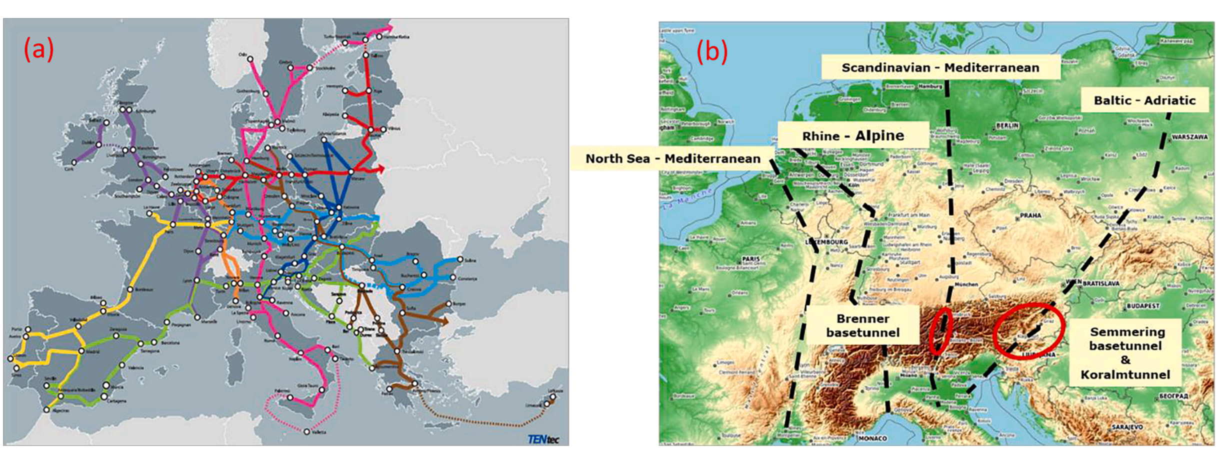

Fig. 1. European railway network, (a) – Trans-European Network Transport (TEN-T) (source: European Commission - Directorate-General for Mobility and Transport (2016)), (b) – selected trans-Alpine railway routes.

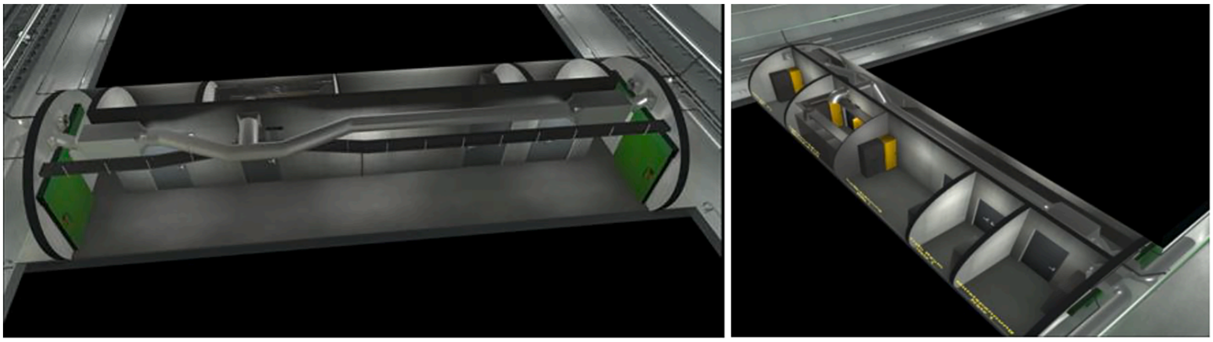

Fig. 2. Principle layout of cross-passages in a modern twin-tube single track tunnel (source: Austrian Federal Ministry of climate action, environment, energy, mobility, innovation and technology (2022)).

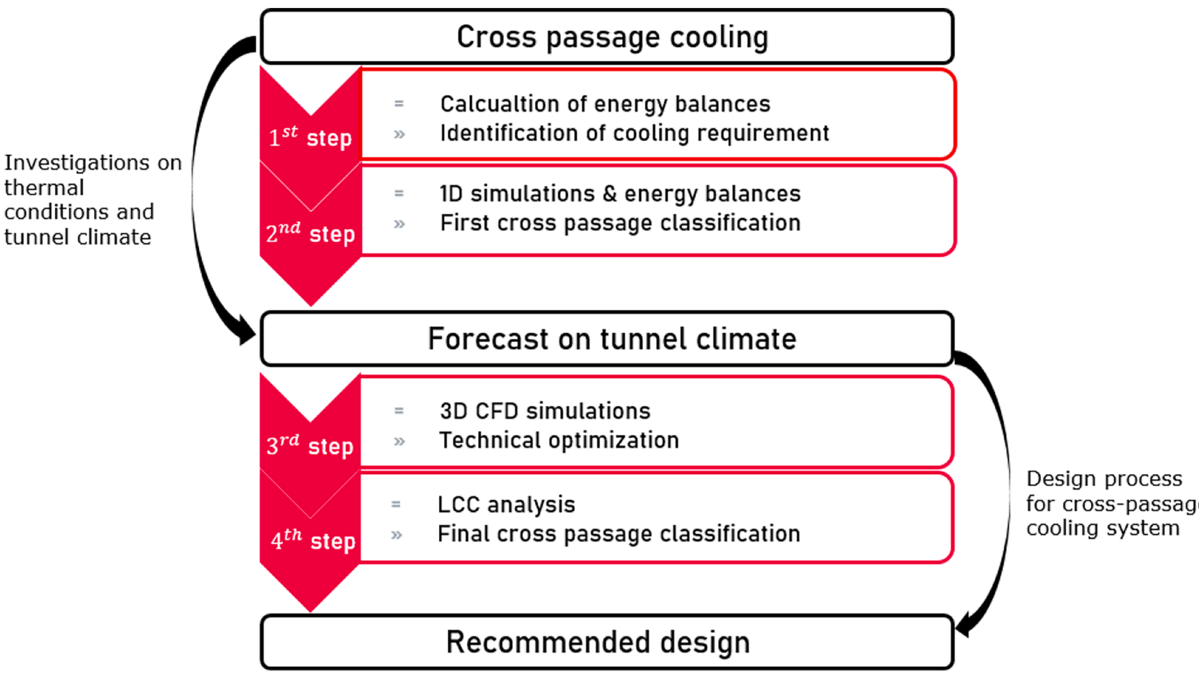

Fig. 3. Flowchart of the method developed for the investigation of tunnel climate in a long railway tunnel (Fruhwirt, 2021).

convective heat transfer coefficient.

$$\dot{Q}_{wall_i} = k^* A_{wall_i} {}^*(t_{room_i} - t_{room_j}) \quad (2)$$

$$\dot{Q}_{rock} = k_{rock} {}^* A_{wall} {}^*(t_{rock} - t_{room}) \quad (3)$$

A demand for cooling exists where the calculated room air temperatures exceed the target temperatures. Quantification of this cooling demand is made possible by simply setting the room air temperatures equal to the target values and adding the term $\dot{Q}_{cool}$ in the energy balance (see Eq. (4)).

$$\dot{Q}_S + \sum_i \dot{Q}_{wall_i} + \dot{Q}_{rock} + \dot{Q}_{cool} = 0 \quad (4)$$

2.2. Forecast on tunnel climate

Once a need for cooling has been identified, a cooling system has to be implemented. In the case of long railroad tunnels, two systems seem suitable. One is a ventilation system that uses tunnel air for cooling purposes and the other is an air conditioning system that uses either tunnel air or, if available, a continuous water supply for re-cooling. However, the design of both systems depends on the tunnel climate. Hence, the second investigative step entails forecasting the tunnel climate.

Only a few characteristic points of the forecasting process are dealt with here. A more detailed description is given in section 3, also showing the application to a selected case study.

The system design of cross-passage cooling systems usually assumes a service life of 10–25 years. However, the entire service life of a railway tunnel is roughly 150 years. Thus, the prediction of the tunnel climate needs to be projected over a long period in order to cover several replacement cycles of the cooling systems. Owing to the long time period and the large computational domain (long tunnel > 25 km), it is recommended that a 1D CFD approach or a model based on Bernoulli's equation and an energy balance be used for this investigative step.

Special attention must be paid to correct determination of initial conditions (e.g. rock temperatures). In the case of long railway tunnels, the planning of the cooling systems for the cross-cuts must be completed several years before the tunnel is commissioned. Usually this is done while excavation and lining work is still in progress. During this phase, a construction ventilation system is in operation in order to maintain proper air quality. This ventilation system has a considerable impact on the thermal conditions recorded during the design of cooling systems. Thus, in order to avoid bias, the initial conditions have to be determined in a pre-simulation that covers the entire excavation and equipping phase and provides a more realistic forecast of the thermal conditions at the beginning of the operation phase.

Another relevant aspect is the definition of boundary conditions. This includes thermal boundary conditions, as well as boundary conditions that are related to the railroad operation. The former category includes external air conditions (temperature and humidity) and the rock temperature. Train frequencies (train schedule) and train speed are considered to be the most important rail-related parameters. Due to the long period of time to be assessed, boundary-related variations over time need to be taken into account. In this context, the impact of climate change on the ambient air conditions is relevant. It is assumed that climate change will have a particularly significant effect on ambient air conditions in the Alpine region.

Despite the complexity entailed in forecasting tunnel climate in long railway tunnels, 1D CFD simulations provide sufficient data with respect to the required tunnel air temperature and relative humidity.

Such data can then be used to calculate the air temperatures achievable in tunnel utility rooms by means of a mechanical ventilation system. The cooling capacity of such a system is limited as it depends on the temperature gradient between target room air temperature and supply (tunnel) air temperature. In order to determine the achievable utility room air temperatures an additional energy balance needs to be established. Eq. (3) thus needs to be modified in order to consider the effect of a ventilation system. This modified energy balance can be expressed as shown per Eq. (5).

$$\dot{Q}_S + \sum_i \dot{Q}_{wall_i} + \dot{Q}_{rock} + \dot{Q}_{fan} + \dot{m}^*(h_{in} - h_{out}) = 0 \quad (5)$$

In this equation, $\dot{Q}_{fan}$ expresses the heat release by the supply air fan engine. In many cases the latter is situated within the air duct. Data on the heat release of the engine must be requested from manufacturers or derived on the basis of experience. Assuming ideal gas behaviour and constant property values, the enthalpy difference of supply and return flow can be expressed as shown in Eq. (6).

$$h_{in} - h_{out} = c_p{}^*(t_{in} - t_{out}) \quad (6)$$

While t_{in} is defined by the tunnel air temperatures determined in the previous 1D CFD simulation, t_{out} is equal to the utility room air temperature, and the expected room air temperatures are now determined. It has to be noted that these values represent average room air temperatures (1D approach). Thus, no three-dimensional effects in the room air temperature are taken into account.

2.3. Utility room air temperatures

The calculation of utility room air temperatures based on energy balances in step 2 provides a simplified figure for average room air temperature based on the assumption of homogeneity homogenous mixture. In reality temperature stratification is to be expected within the utility rooms. In order to gain information about such 3D effects, detailed 3D CFD simulations need to be performed.

The resulting computational model needs to take into account all relevant processes. On the one hand, this includes the impact of a supply air flow, and on the other hand, the heat sources represented by the heat release from technical installations (e.g. telecommunication systems). If the rock temperature is higher than the target utility room air temperature, the heat transfer to or from rock layers has to be taken into account as well. However, the complexity of the numerical model can be kept to a moderate level, if it is assumed that only the temperature distribution is of interest. Any additional consideration of humidity and condensation increases the complexity of the model and requires a significantly higher computational effort. Whether the impact of condensation should be included or not has to be decided by the user and depends on the humidity requirements defined specifically for each tunnel project.

The results from 3D CFD simulations can be used to ascertain whether sensitive components in the utility room will be exposed to unacceptable temperatures or whether the temperature requirements can be met. Whether humidity criteria are satisfied can also be dealt with in a similar fashion.

Once this has been taken care of, one may proceed with selecting the system needed for cross-flow cooling. A mechanical ventilation system cannot be used if the temperature and/or humidity requirements are not met. Where application of a mechanical ventilation system is possible, 3D CFD simulations can again be used to analyse the various ventilation operation strategies, i.e. to assess whether an on/off operation regime, operation at two or more discrete fan speed levels, or operation with a speed-controlled fan (inverter) is preferable.

2.4. Economic considerations

In addition to questions of technical feasibility, economic considerations are always important in an infrastructure project. For this reason, the fourth investigative step includes a life cycle cost analysis. This Life cycle cost analysis covers all relevant equipment that needs to be cooled as well as the cooling systems themselves. Such Life cycle cost analysis is aimed at determining an optimal target temperature for the utility rooms and at providing the additional data needed for the final selection of the cross-passage cooling system.

Life cycle cost analysis can be based on a variety of approaches. However, a dynamic approach is recommended when assessing a longer time period. A dynamic method allows for the valuation of cash flows up to a specific date and can thus be used to rank or compare different investments. The net present value method (Allendorf, 2008) represents a dynamic approach, as it takes into account the period in which an investment is made and in which an inflow of funds occurs (Nwogugu, 2016).

Eq. (7) shows the definition for the net present value. It is defined as the sum of all net cash receipts divided by $(1+i)^\tau$, where i denotes the interest rate under consideration. The net cash received is defined as the difference between all cash inflows and cash outflows in a certain period of time τ (see Eq. (8)).

$$NPV = \sum_{\tau=0}^{n} \frac{i_\tau - o_\tau}{(1+i)^\tau} = \sum_{\tau=0}^{n} \frac{NCR}{(1+i)^\tau} \quad (7)$$

$$NCR = i_\tau - o_\tau \quad (8)$$

This makes it possible to determine the total life cycle cost of the systems assessed and thus allows for final selection of the cross-passage cooling systems.

2.5. Limitations

The method presented here can be understood as a novel tool for predicting the tunnel climate in long railway tunnels. However, users need to be aware of the limitations and sensitivity of the method. This is all the more important as validation using measurement data in real tunnels is not possible.

A forecast for a long period of time is always subject to uncertainties due to unforeseen events. In this context, the rapid development of, and increasing requirements in, telecommunication technologies (e.g., the increasing number of radio frequencies that have to be covered) need to be highlighted. It is thus advisable, in order to maintain the validity of results in the face of potential changes in parameters, that a conservative approach be adopted in model applications.

In addition, as the approach assumes the absence of temperature gradients, the results derived from the calculation procedure applied in steps 1 and 2 merely provide indicative results concerning utility room temperatures, and should not be treated as the basis for final system selection.

Furthermore, a holistic economic model requires consideration of supply chains, stock-holding, etc. In other words, the user has to decide which cost elements have to be included in the economic model. This decision is likely to vary depending on the changing relevance of the various cost elements in different projects.

3. Application to a selected case study

In order to demonstrate its practicality, the new method was applied to the Koralm railway tunnel (Austrian Federal Railways, 2022a) in Austria. The Koralm railway tunnel is a twin-tube single-track tunnel with a total length of 32.9 km, having 70 cross-passages spaced 500 m apart. To meet the safety requirements of the TSI ((European Railway Agency, 2008)), there is an emergency stop in the centre of the tunnel. In addition, two ventilation stations with vertical supply airshafts are located some kilometres from the portals. The ventilation system is designed for emergency events like a tunnel fire and for operation during maintenance. The maximum overburden of the tunnel is 1200 m, which is the main reason why the ventilation shafts had to be located quite close to both portals. Fig. 4 shows a longitudinal section of the Koralm railway tunnel.

There are five utility rooms within each cross-passage, one for telecommunication systems and four rooms housing the equipment for power supply (low and medium voltage components). The temperature requirements were defined individually for each of the utility rooms. Table 1 shows a list of the target temperatures of the Koralm railway tunnel utility rooms. T_{target} is the target temperature range at which the room air temperature must be maintained. T_{min} and $T_{extreme}$ values are acceptable only for a short period of time (3 h).

The key here is the target temperature range for the telecommunication room, which is defined as 15–22 °C. Keeping the room air temperature within this temperature range is quite a challenge as the telecommunication equipment produces a significant amount of heat. For standard telecommunication equipment, the heat release rate is about 6 kW and for telecommunication base-stations, this increases to as much as 26 kW. These base stations are arranged in pairs and are located in six cross-passages distributed at regular intervals throughout the tunnel.

Table 1
Target temperature ranges for the utility rooms in the Koralm tunnel (Fruhwirt, 2021).

Utility room	T_{min} [°C]	T_{target} [°C]	$T_{extreme}$ [°C]
Low voltage room 1	−5	0–30	40
Telecommunication room	10	15–22	30
Low voltage room 2	−5	0–30	40
Transformer room	−25	0–35	70
Medium voltage room	−5	0–30	40

3.1. *Cooling requirement in Koralm railway tunnel utility rooms*

The first step of the investigation requires accurate definition of the thermodynamic system. In the case of the Koralm railway tunnel, this thermodynamic system covered an entire cross-passage and adjacent tunnel sections. Each of the utility rooms, as well as the escape route and the tunnel sections was modelled as an individual thermal zone. Fig. 5 shows a scheme of this thermodynamic system.

For these systems, the energy balance, in accordance with Eq. (1), was applied to determine the room air temperatures. Thus, the expected room air temperature was determined for each utility room in the tunnel. Fig. 6 shows the room temperatures in the telecommunication and low-voltage rooms in the Koralm railway tunnel, which can be achieved by self-regulation without active cooling (Steiner et al., 2017). In addition, the target temperatures of both rooms are added as horizontal lines in order to enable a comparison of predicted and target values. This comparison shows that there is a need for cooling in all telecommunication rooms and in numerous low-voltage rooms. No need for cooling was identified for the remaining utility rooms (e.g. low-voltage room 1).

In order to quantify the actual cooling demand for every utility room, Eq. (4) was employed to calculate the energy balances for every cross-passage. It turned out that the cooling demand varies strongly from cross-passage to cross-passage, and lies in the range of 1.6–36 kW.

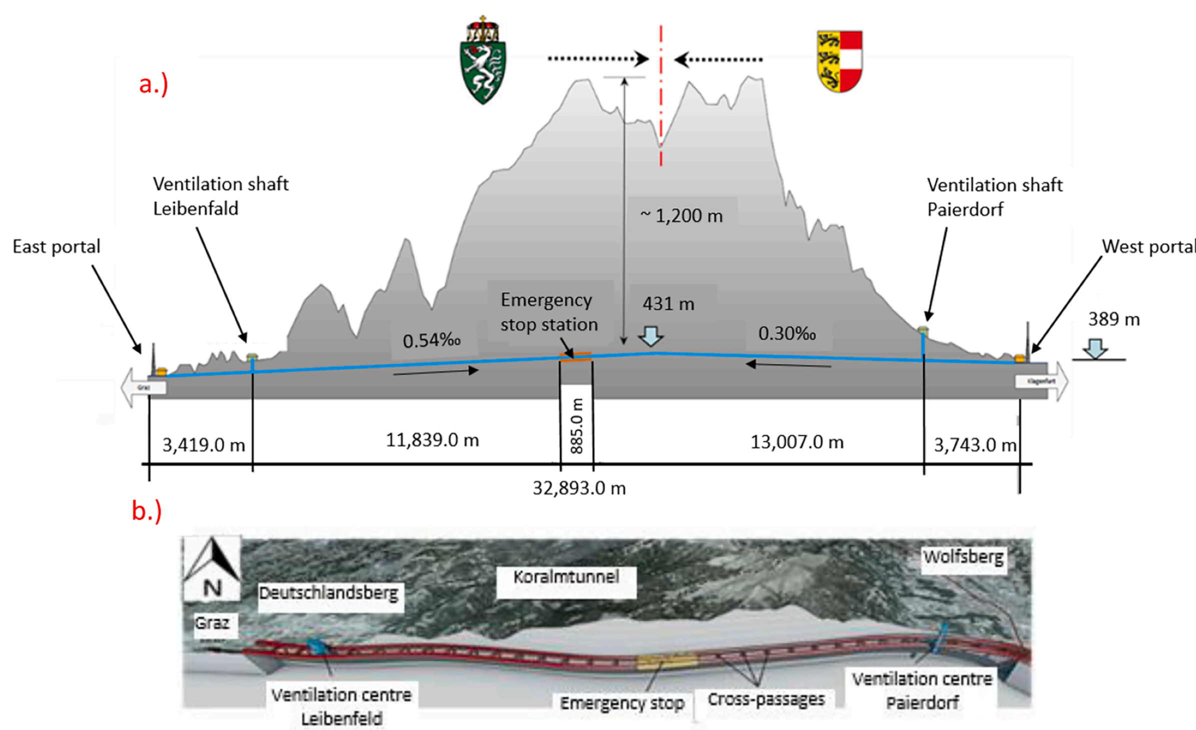

Fig. 4. System of the Koralm railway tunnel – a.) longitudinal section, b.) map excerpt(Steiner et al., 2017) published in (Richter et al., 2017).

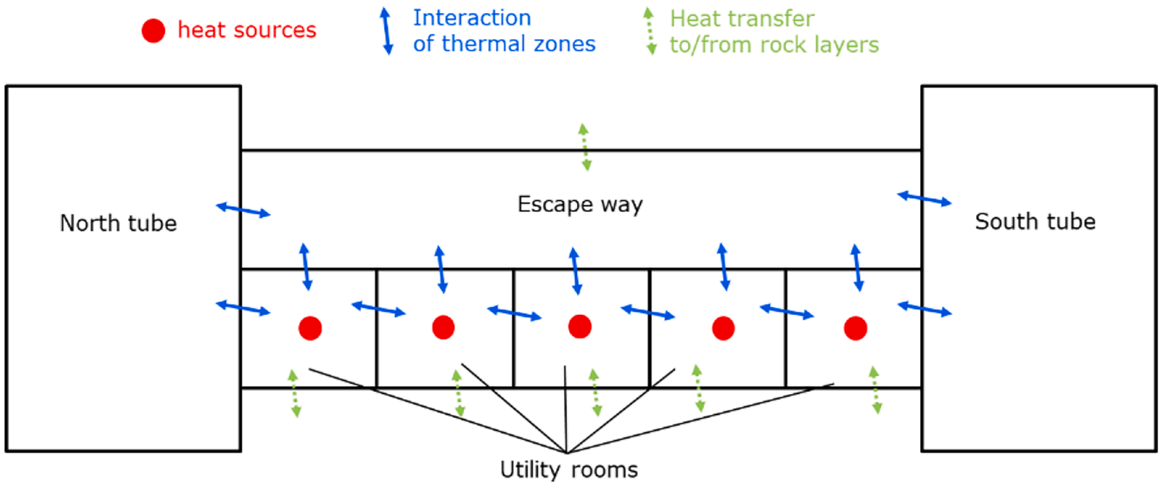

Fig. 5. System configuration for the determination of the expected utility room air temperatures. (Fruhwirt, 2021).

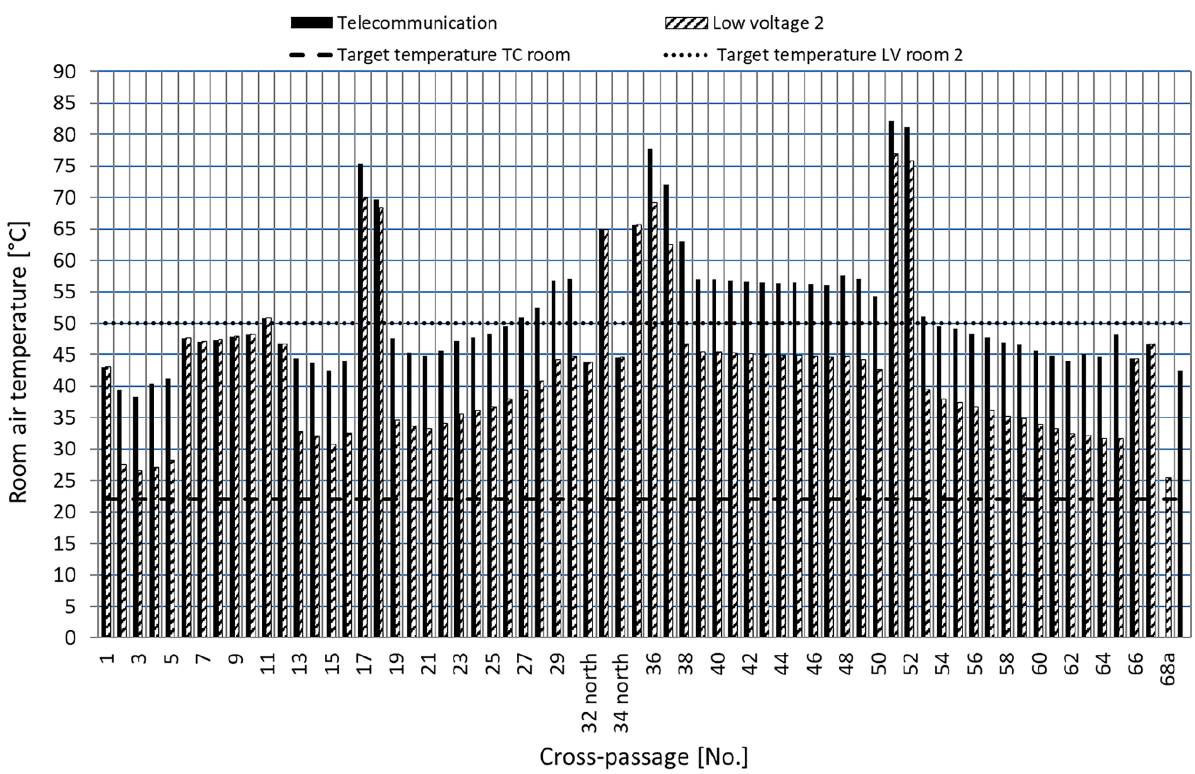

Fig. 6. Expected utility room air temperatures without active cooling systems.

3.2. Forecast on the Koralm tunnel climate

Following identification of cooling needs, information about the climate in the Koralm railway tunnel is then required in order to enable proper design of cross-passage cooling systems. For this reason, 1D tunnel climate simulations were performed. These simulations represent the second step of the model presented here.

IDA tunnel (Equa Sweden, 2020) was used to solve the Bernoulli and the energy equation needed for predicting the Koralm railway tunnel climate. It is a commercial solver and is a tool widely used in the design process of tunnel ventilation systems. In order to be able to carry out the tunnel climate simulations, it is necessary to define the specifications required for the calculation model and the simulation parameters. One of these specifications is the period to be assessed, which was set at 50 years. In the following, only the most relevant specifications are discussed. For a detailed explanation of the entire model the reader is referred to (Fruhwirt, 2021).

3.2.1. Heat transfer

To give an accurate prediction of the tunnel climate the heat transfer between the solid tunnel walls and the tunnel air must be modelled with sufficient accuracy. In this context, the most important heat transfer mechanism is heat convection. In IDA tunnel, the convective heat transfer is calculated according to Eq. (3). The convective heat transfer coefficient is determined as a function of the Nusselt number.

In contrast, the heat transfer in solid layers works through heat conduction. Thus, the rock temperature in a certain rock layer (e.g. $k+1$) between the thermal boundary t_{rock} and the wall surface can be determined as per Eq. (9). In this equation, λ denotes the thermal conductivity defined as a material property value, s represents the layer thickness, and k is the running variable that defines the layer number.

$$t_{rock_{k+1}} = t_{rock_k} + \frac{\dot{Q}_{rock}}{A_{wall}} * \frac{s}{\lambda} \tag{9}$$

The wall construction considered in the IDA tunnel simulation comprised three solid layers. These are concrete, shotcrete and rock material. In tunnel sections close to the portals, rock material is replaced by soil material. The property values of all solids are given in Table 2. It has to be noted that these property values of soil and rock represent average values. In practice, they normally vary depending on the water content.

While the layer thickness of concrete and shotcrete was set as constant, the thickness of rock/soil layers varied depending on the local overburden. In tunnel sections with high overburden, it was set to the maximum of 285 m. The radial resolution of the solids included 25 layers.

3.2.2. Initial conditions

As mentioned earlier, the initial conditions must be carefully defined in order to obtain accurate results. For this reason, a pre-simulation of the construction and equipment phase of the Koralm railway tunnel was carried out in order to take the impact of the construction ventilation into account. This is necessary, because the construction ventilation system is to remain in operation till 2025, and will thus cause significant changes in the Koralm railway tunnel climate. In this context, it is important to have detailed information about the ventilation system as well as about the work processes (heat sources). In the Koralm railway tunnel, a U-shaped ventilation regime is applied during the construction phases. Hence, the tunnel is divided into two halves. In each of them, one tunnel tube serves as the supply air tube and the other as the return air tube. The impact of the construction ventilation system can be illustrated by the wall surface temperature curves at selected points of time during the construction phase (see Fig. 7). This diagram shows the tunnel air temperatures along the south tube of the Koralm railway tunnel as a function of the tunnel position. Two aspects are particularly worth mentioning here. Firstly, the offset in the tunnel air temperature curves in the centre of the tunnel, which is a caused by the applied construction ventilation system. Secondly, the dependency on the outside air temperatures, which is very pronounced in the portal areas. The seasonal temperature variations (+1 to +19.5 °C) require knowledge of the time schedule for construction and of the equipping works in order to accurately define the initial conditions employed in simulation of the tunnel climate (operation phase). In the test case, the rock temperatures at the end of the second year (December 02 in Fig. 7) were used as initial conditions in the tunnel climate simulations.

3.2.3. Boundary conditions

The thermodynamic system of a long railway tunnel depends on a large number of parameters. The most important are the local rock temperature, the ambient air conditions and the train frequency. But many other parameters (e.g. train speed, water content in solid layers, etc.) must also be taken into account when predicting the tunnel climate. Accurate prediction of tunnel climate requires that the totality of parameters be studied in all their complexity. However, at the present point, and for purposes of simplification, only the most relevant boundary conditions are explained. A more holistic description of the IDA model is available in (Fruhwirt, 2021).

Table 2
Property values of solid materials.

Quantity	Rock material	Soil	Shotcrete	Concrete
Thickness [m]	<285	<50	0.5	0.3
Specific heat [kJ/kgK]	724	1000	900	960
Conductive heat transfer coefficient [W/mK]	3.38	2*	1	2.3
Density [kg/m^3]	2876	1700	2000	2400

*According to DIN EN ISO 13,370 [2018–03]

3.2.3.1. Rock temperature:. The rock temperatures represent an important boundary condition, as they strongly influence the temperature level in the tunnel sections of a long railway tunnel. For this reason, it is recommended that the variation of rock temperatures along a tunnel be taken into account. In the case of the Koralm railway tunnel, the undisturbed rock temperature (solid curve in Fig. 7) varies from 10 °C, in tunnel sections close to the portals, to 32 °C in the tunnel centre. In order to be able to define the thermal boundary condition accurately, in the IDA model the Koralm railway tunnel was divided into a series of tunnel sections, thus, enabling an approximation of the rock temperature curve with a resolution of 500 m. The values of the undisturbed rock temperature were applied at the edge of the solid layers (see thickness of solid layers as explained in Section 3.3.1).

3.2.3.2. Outside air temperature. The second crucial parameter strongly influencing the tunnel climate is the outside air temperature. In order to have accurate data for this boundary condition, long-term measurements taken from a meteorological station near the east portal (Federal State of Styria, 2022) served as a basis. Hourly mean values of outside air temperature and relative humidity were used. It has to be noted that daily or monthly average values are not applicable, as short-term variations of the temperature have an influence on the thermal conditions in portal regions. An evaluation of these data showed that the summer of the year 2012 was characterized by a high average temperature level while the summer of 2013 reported high peak temperatures up to 39 °C. For this reason, it was decided to use data from both years for the prediction of the tunnel climate.

Due to the extended period of time to be assessed in the tunnel climate simulations, long term effects may be relevant. In this context, the impact of climate change was taken into account. For this reason, an expert statement from the Austrian meteorological office ZAMG (Zentralanstalt für Meteorologie und Geodynamik, 2022) provided information about the expected temperature rise in the project area and served as a basis for calculation. Based on this statement, the expected temperature rise in the region of the Koralm is as shown in Table 3. There, monthly average values of a 30-year period in the past (No. 1), as well as the expected value for the period up to 2070 (No. 2) are listed. In addition, the difference between expected values and the values of the past (No. 3) is specified. The latter values represent the expected increase of monthly average temperatures in the project area.

The expected increase of monthly average temperatures by 2070 (No.3 in Table 3) is assumed to differ between the winter and summer period. However, the average temperature increase is expected to be roughly 2.25 °C. Obviously, the prediction of the temperature increase in a 50-year period cannot be based on hourly average values (as is normally required for such a simulation). However, in order to consider the effect of climate change, the individual monthly averaged temperature increase was applied to the hourly average temperatures of 2012 and 2013. With respect to projection years between the period from 2012 to 2070 the ambient temperature was approximated by a linear function.

3.2.3.3. Train frequency. The passage of trains strongly influences the tunnel airflow. Thus, heat transfer inside the tunnel and the tunnel climate strongly depend on this parameter. In addition, trains represent thermal masses and are themselves a source of heat. While the latter effect can be accounted for, i.e., by defining train surface areas and temperatures (e.g. brake temperature), the train frequency has to be modelled based on a train schedule. However, as the latter is not usually known at the design stage of tunnel installation, this presents quite a big challenge. In addressing this problem, two scenarios for train

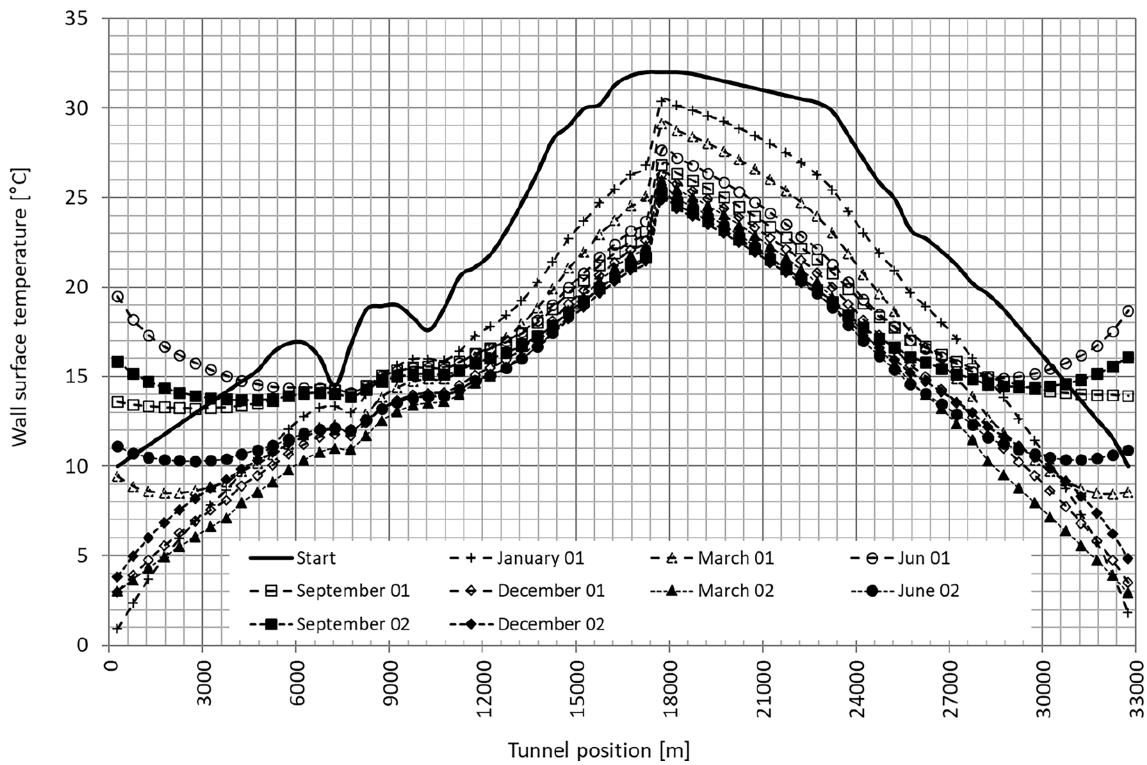

Fig. 7. Wall surface temperature curves along the south tube of the Koralm railway tunnel at selected points of time in the equipping phase (Fruhwirt et al., 2018).

Table 3
Monthly average temperatures of the past and expected values for the period from 2050 to 2070 for the area of Deutschlandsberg (Koralm railway tunnel - East portal) (Fruhwirt, 2021).

No.	Type	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
1	1971–2000	−3.1	−0.5	4.2	8.5	13.8	16.9	18.6	18.1	13.7	8.4	2.3	−1.8
2	Expected value	−0.6	1.9	6.5	10.7	15.9	19.0	20.6	20.2	15.9	10.6	4.6	0.6
3	Δ no.2 – no.1	2.5	2.4	2.3	2.2	2.1	2.1	2.0	2.1	2.2	2.2	2.3	2.4

frequencies were thus investigated, i.e., one high traffic scenario representing maximum capacity of the railway track (6 trains per hour and direction), and one low traffic scenario with only two trains per hour and direction.

3.2.4. Results from tunnel climate simulations

The climate simulations were conducted for both traffic scenarios. It was found that a higher train frequency accelerated the thermal effects inside the tunnel and led to a higher temperature level in most tunnel sections. For this reason, the remaining investigative steps were based on the results of the high traffic simulation run. These results can be expressed as hourly average temperatures along a tunnel tube (see Fig. 8). Here, the maximum, minimum and average air temperature in July of the first year of operation are shown as a function of the tunnel position. Two important aspects need to be emphasized in this context: the homogeneous temperature curve at a high temperature level in regions close to the tunnel centre, and the strong influence of the outside air conditions in portal areas. The latter effect leads to a large variation of the temperature at the portal sites, as these follow the daily variations of the outside temperatures. This underlines the importance of the usage of hourly average temperatures in tunnel climate simulations.

The results of the 1D simulations provide a solid basis for the design of the cross-passage cooling systems. However, at this point no statement can yet be made as to whether a ventilation system is sufficient to keep the utility room air temperature within the target range. Thus, an energy balance is used once more to predict the utility room air temperature. The prediction of utility room temperatures achievable by mechanical ventilation was performed in accordance with Eq. (5). Here, the results of the IDA simulation were adopted in defining the supply air temperature. Furthermore, the maximum supply air volume flow is usually limited by the capacity of the filters needed to meet the air quality requirements. Although this limit varies depending on the filter type, on the basis of operational and technical considerations, it was set to 1.0 m^3/s at 1.2 kg/m^3 reference density.

As the strictest temperature criterion applies for the telecommunications room, the energy balances initially were calculated for the telecommunication rooms. Fig. 9 depicts a scheme of the thermodynamic system used to determine the expected temperatures in the telecommunications rooms.

This calculation step provides values for the hourly average room air temperatures. This can additionally be expressed as the number of hours in which the target temperature is exceeded. Fig. 10 shows this quantity for selected cross-passages along the Koralm railway tunnel as a function of time in operation. Based on these results we can state the following:

- The tunnel climate is subject to large variations depending on the tunnel position.
- Low rock temperatures in portal regions may provide the possibility to install a ventilation system.
- The temperatures in cross-passages close to the tunnel centre are permanently above the target temperature of the telecommunications room.

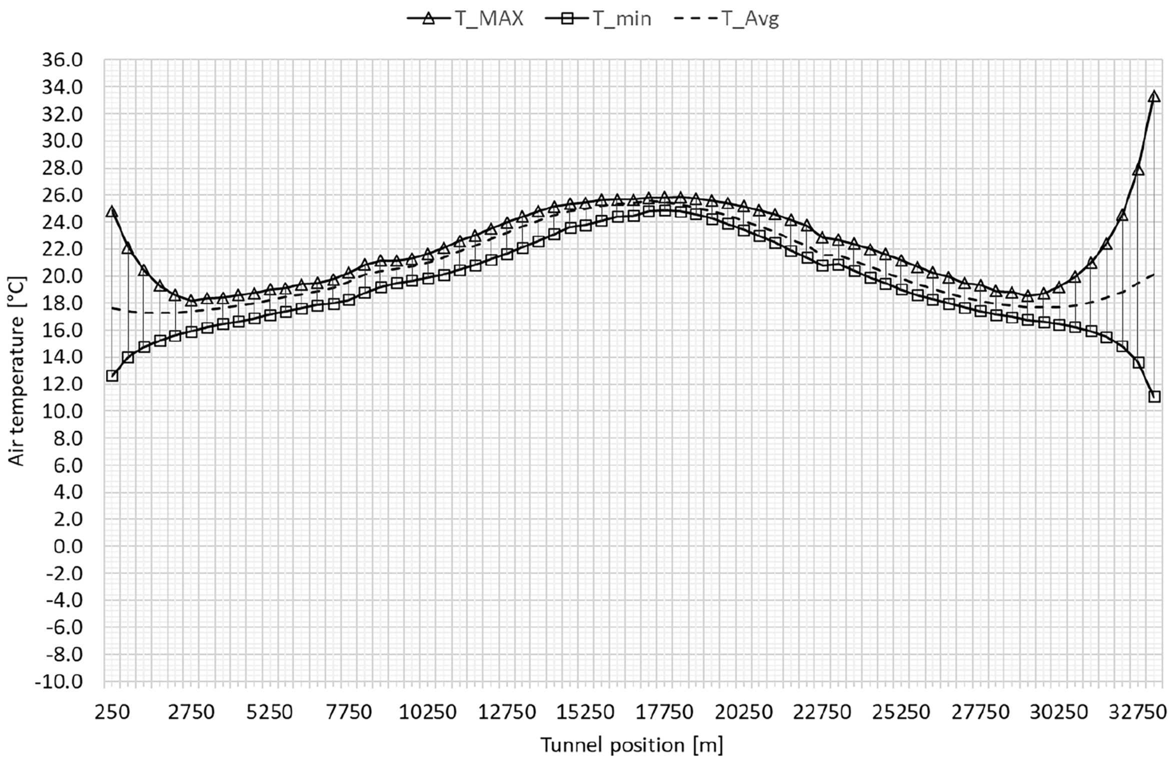

Fig. 8. Tunnel air temperature curve in Koralm railway tunnel south tube – July (1st year of operation) (Fruhwirt, 2021).

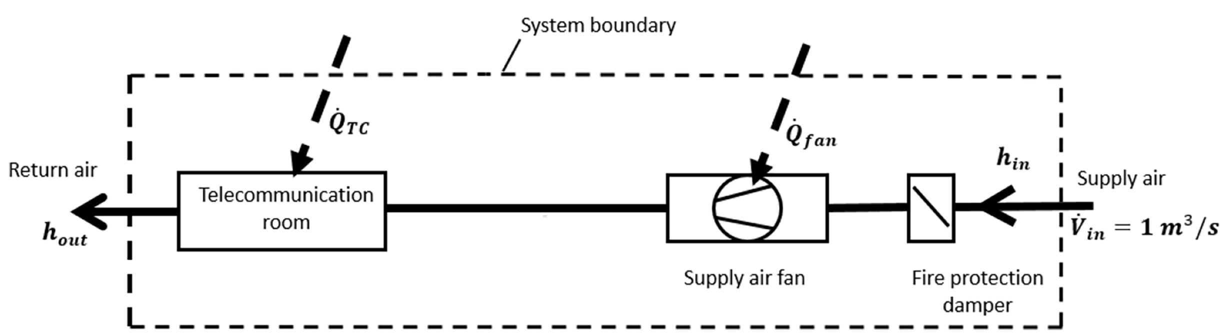

Fig. 9. Thermodynamic system for the determination of the utility room air temperature.

- The running traffic leads to a reduction of the temperature level in the tunnel centre.
- The effect of climate change causes a significant increase of temperatures close to the portals.

Strict interpretation of the results shows that there is no cross-passage in which the temperature in the telecommunications room can be kept permanently within the target temperature range. Consequently, every cross-passage requires the installation of an air conditioning system. However, the approaches used so far have not yet taken account of 3D effects such as temperature stratification.

3.2.5. Utility room cooling concepts

The results of the 1D simulations in the second step of the investigation have shown that a cross-passage cooling system is needed within every cross-passage of the Koralm railway tunnel. In practice, the actual amount of cooling needed varies significantly. For this reason, and also due to the fact that tunnel air is the only available medium for cooling, two different cooling systems were designed. One is a mechanical ventilation system that directly uses the cooling effect of tunnel air, and the second system is an air conditioning system that uses tunnel air for re-cooling. Both systems are redundantly designed in order to enable (re-) cooling via both tunnel tubes, thus, improving the flexibility of the system.

3.2.5.1. Mechanical ventilation systems. Fig. 11 shows a schematic of a cross passage equipped with a mechanical ventilation system. The main advantage of such a ventilation system is its simplicity, as it only consists of a supply air fan, dampers at the boundary to the tunnel tubes, piping and fittings. This means that the maintenance effort and energy consumption can be kept at a moderate level. The main disadvantage, on the other hand, arises from the air quality requirements in the operating rooms, which require appropriate treatment of the supply air (particle filters) (Sturm et al., 2022).

3.2.5.2. Air conditioning systems. In cross-passages characterized by a high cooling demand, one that cannot be met by a mechanical ventilation system, an air conditioning system is installed. Such a system is depicted in Fig. 12, and includes a refrigerant cycle, a water cycle and an air cycle. The necessity of a water cycle results primarily from safety regulations on the maximum permissible amount of refrigerant mass in an escape route (Federal Ministry of Social Administration; Federal

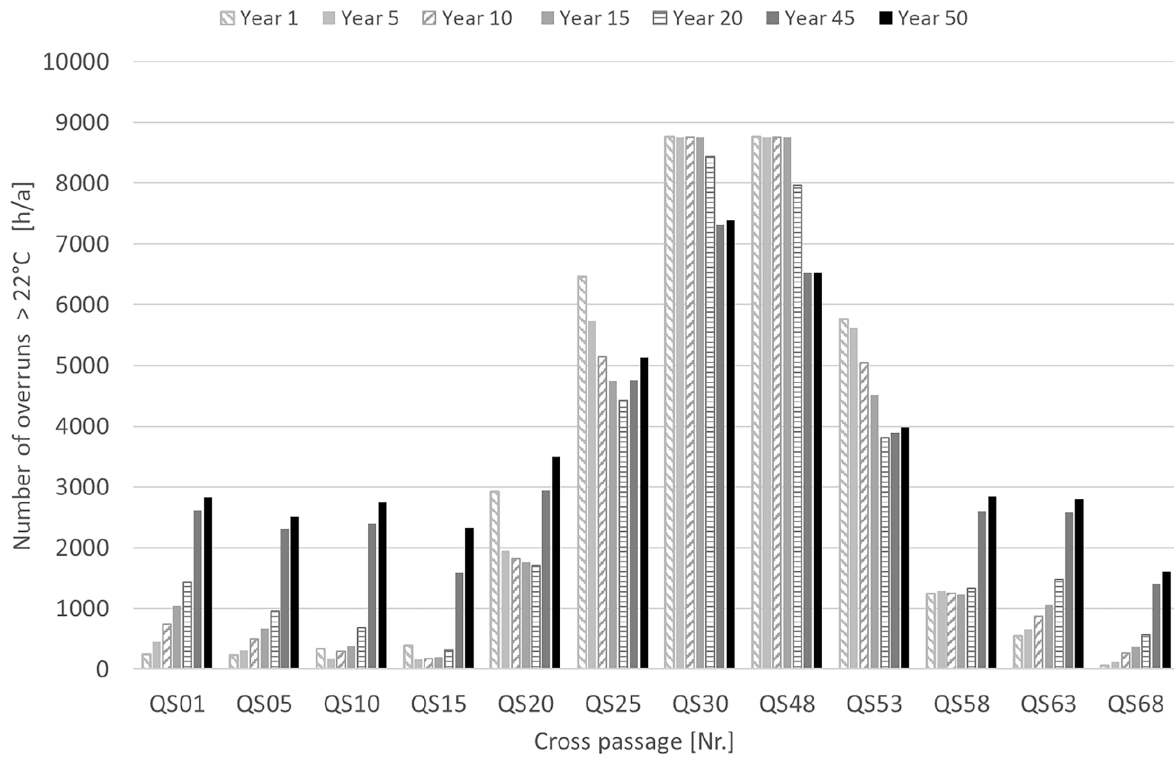

Fig. 10. Expected room air temperatures in the telecommunication room of selected cross-passages along the Koralm railway tunnel (Fruhwirt, 2021).

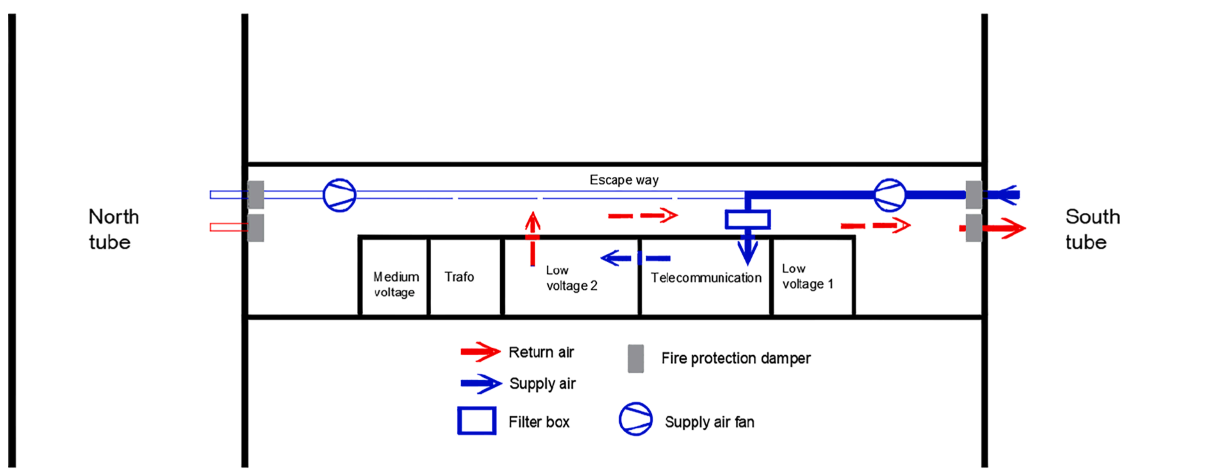

Fig. 11. Principle layout of the ventilation systems in the Koralm Tunnel (Fruhwirt, 2021).

Ministry of Trade, Commerce and Industry; Refrigeration Plant Ordinance; Federal Republic of Austria, 2020). Obviously, the complexity of an air conditioning system is higher compared to that of a mechanical ventilation system. However, the resulting cooling capacity allows for precise control of the utility room air temperatures.

The system selection for cross-passage cooling can be made on the basis of the results obtained in the second investigative step. However, these results do not take into account three-dimensional effects such as temperature stratification. In order to gain more detailed information about the temperature distribution, 3D CFD simulations were carried out in the third step of the method presented here.

3.3. *3D effects on utility room air temperature distribution*

The 3D simulations of the temperature distribution within a Koralm railway tunnel cross-passage were carried out using Ansys Fluent as 3D CFD solver. The simulations were aimed at determining the 3D effects on the temperature distribution within the utility rooms. Thus, the computational domain covered those utility rooms characterized by a specific cooling demand, i.e. telecommunications and low voltage room 2, the escape route and the ventilation system, as depicted in Fig. 11. As their influence on short-term effects is expected to be marginal, utility rooms with no need of cooling were neglected in the 3D CFD simulations.

Two simulation runs were carried out. The first simulation run was a steady-state calculation to find out whether the target temperatures could be achieved with the help of mechanical ventilation. In contrast, the second simulation run aimed at the optimization of supply air fan operation.

3.3.1. *Solver setup and mesh generation*

In the numerical model, a transient Reynolds-averaged Navier Stokes

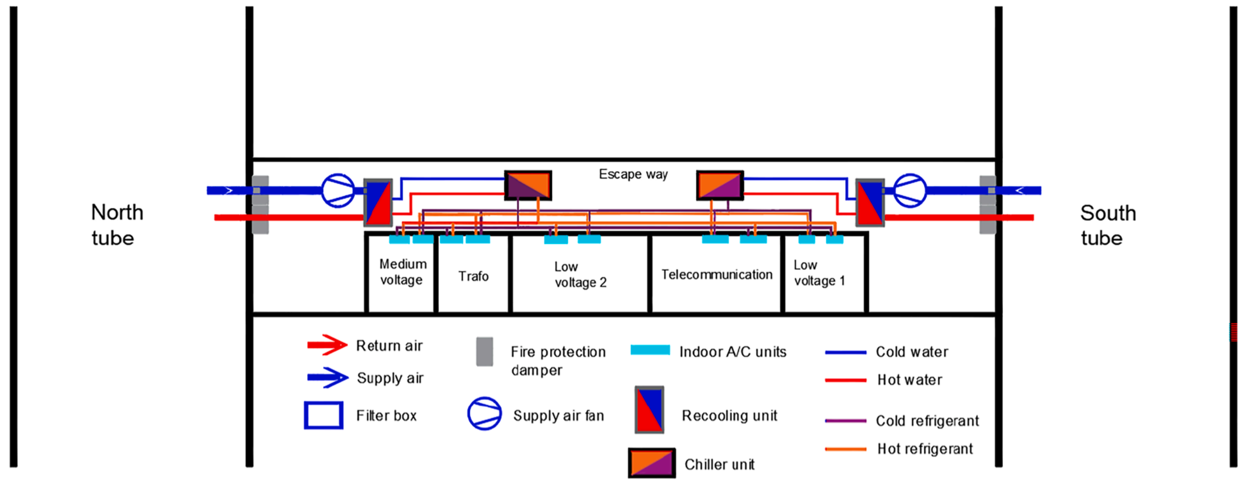

Fig. 12. Principle layout of the air conditioning systems in the Koralm Tunnel (Fruhwirt, 2021).

equations (RANS) approach was used. To model the turbulent flow, the realizable k-ε model was employed in combination with the enhanced wall function for the near wall treatment. The pressure–velocity coupling was done using the Pressure-Implicit with Splitting of Operators algorithm (PISO) algorithm. To model the heat transfer, the energy equation was activated, but heat radiation was neglected.

The mesh was generated using tetrahedrons with a maximum cell size of 0.16 m, and 0.04 m within the supply air duct. The requirement for the dimensionless distance from wall $y^+ < 300$ was met. This required the generation of inflation layers on the walls. The generated mesh comprised 3.5 million cells and was used in both simulation runs (steady state and transient).

3.3.2. Boundary conditions

In the steady state simulation, a constant supply air volume flow of 1 m^3/s was considered as an inlet boundary at the entrance of the ventilation duct (0.4 m diameter). In the subsequent transient simulation this value was kept the same, but an on/off regime following a defined time schedule was employed in order to simulate fan activation and deactivation.

In both cases, the supply air temperature was set to 20 °C, which represents the maximum temperature that allows for a cooling of the telecommunications room by a mechanical ventilation system (energy balances according to Eq. (5)). The heat emission from telecommunications equipment was modelled by a total heat flux of 6 kW, which was assigned to the tops of two control cabinets in the telecommunication room. This is due to the fact that the sensitive components are housed in special cabinets equipped with a cooling system.

3.3.3. Results from 3D CFD simulations

The first simulation run determined the temperature field in the telecommunication room with an active ventilation system, the second simulation run helped in optimizing fan control. The results of the 3D CFD simulations are shown in Fig. 13. Here, the temperature contours are shown on a vertical plane through the telecommunication room. The exact position of the vertical plane is depicted in the image on the right

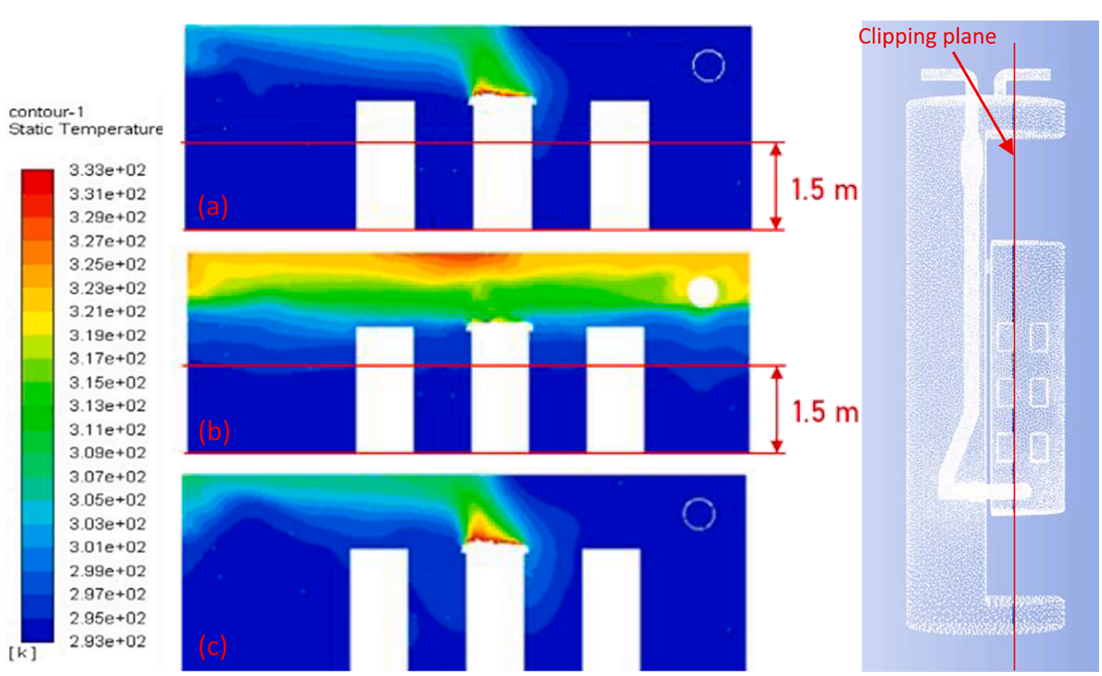

Fig. 13. Results from 3D CFD simulations (a) steady state, (b) 75 sec after fan deactivation, (c) 65 sec after fan-reactivation, temperature values in [K] (Fruhwirt, 2021).

side of Fig. 13. Image (a.) shows the results of the first simulation run in which a steady state simulation was performed. These temperature contours provide the information needed to assess the feasibility of a mechanical ventilation system in meeting temperature requirements. Images (b.) and (c.) show the temperature contours 75 s after deactivation of the supply air fan and 65 s after reactivation of the fan.

Basically, three important aspects have to be noted when interpreting these results. The first is the well-defined temperature stratification within the telecommunication room. While the volume above the cabinets acts as some kind of thermal buffer with temperatures up to 45 °C, the cabinets themselves are not exposed to unacceptable temperatures. In contrast to this result, the results from the earlier step 2 of the investigation indicate an average room temperature of 24.8 °C, and thus reveal a clear need for air conditioning in the cross-passage.

The second aspect is the asymmetric temperature distribution resulting from the inlet momentum of the supply air. Cabinets located near the supply air inlet are permanently exposed to the low supply air temperature.

Third, additional important information can be derived from the results of the transient simulation. The deactivation of the supply air fan leads to a temperature distribution as shown in figure (b). According to this, the control cabinets are exposed to temperatures above the target temperature (22 °C) within 75 s after deactivation, so that the supply air fan is switched on again. After another 65 s, the warm telecommunication room air is removed and the original temperature distribution is reached once again (see image (c) in Fig. 13).

Based on the results of the 3D CFD simulations, the temperature criterion in the telecommunications room was further refined. While the target temperature is still set at 22 °C, it now has to be achieved at a height of 1.5 m above floor lever. This is possible, as the internal cooling of the control cabinets extracts room air at a height of 0.1–0.2 m. The temperatures prevailing here are below the target temperature. Furthermore, the results of the transient simulation show that on/off control of the ventilation system cannot be recommended for application in the Koralm railway tunnel. This is due to the very short time period which elapses between on/off changes in fan operation. However, a control regime based on two or more discrete fan speed levels seems to be feasible.

Since the results of the 1D and 3D approaches differ, the 3D results needed to be verified. To do this, in-situ measurements were performed in the escape tunnel of an Austrian railway tunnel. Within this escape tunnel, a dedicated test room with characteristics similar to those of the Koralm railway tunnel utility rooms was erected and several test scenarios, with variations of supply air temperature and heat release rate, were performed (Institute of internal combustion engines and thermodynamics, 2020). The general outcome of these investigations confirmed the results of the 3D CFD simulations. The test scenario revealed well-defined temperature stratification and showed that the integrated control cabinets were not exposed to temperatures above the target temperature. For a detailed description of these tests the reader is referred to (Fruhwirt, 2021).

Based on the findings from the 3D CFD simulations, it can thus be concluded that 3D effects in the temperature distribution indicate that there is still some room for optimization. It should be noted that while the results of the 3D CFD simulations will vary if the arrangement of the cabinets is changed, the basic conclusions may still be considered valid.

3.4. Life cycle cost analysis

In the last step of the investigation, a Life cycle cost analysis was carried out for the cross-passage cooling systems and the telecommunication systems. Basically, the cost development for both systems is driven by initial construction and operating costs. The latter are dominant in the evaluation of the total life cycle cost of cross-passage cooling systems and telecommunication systems. Considerable accuracy is required in estimating all relevant cost elements. This includes the approximation of the expected service lifetime as well as the estimation of the required maintenance effort.

Here, service life was set at 20 years for ventilation systems, and at 10 years for air conditioning. These values represent empirical values and are derived from previous tunnel projects. In contrast, the service life of telecommunication systems was assumed to be a function of the room air temperature. To account for this, an Arrhenius approach was applied to the Eyring equation (Eyring, 1935), which is commonly used to approximate ageing processes on chips and sensors due to thermal stresses. This results in a formulation as shown in Eq. (10).

$$\tau_E = \tau_Q {}^* e^{\frac{E_a}{R} {}^* \left(\frac{1}{T_E} - \frac{1}{T_Q}\right)} \tag{10}$$

Employing this equation, the service life of the telecommunication systems could be determined for selected telecommunication room air temperatures in the range of 22–60 °C. The results of this calculation are shown in Table 4, and reveal that a temperature range of 22–35 °C appears to be suitable. Any further increase of the room air temperature reduces the expected service life to <6 years and this would result in a significant reduction in track availability.

In addition to the expected service life, the effort required in maintenance also has a strong influence on the cost development. Annual cooling system maintenance costs were approximated by applying constant percentages (1% for ventilation and 6% for air conditioning) to the initial construction costs. In contrast, the annual maintenance costs for telecommunication systems I_m were approximated as a function of temperature. In order to do this, the formulation shown in Eq. (11) was used. Here I_0 denotes the initial construction costs for telecommunication systems and $\frac{\tau_{22^\circ C}}{\tau_T}$ is the quotient of expected service life at 22 °C and the service life at the assessed temperature T. This quotient takes into account the increase in costs with increasing room air temperature.

$$I_m = I_0 {}^* 0.0638 {}^* \frac{\tau_{22^\circ C}}{\tau_T} \tag{11}$$

Within the temperature range of 22–35 °C, four temperature scenarios were defined and evaluated in the Life cycle cost analysis. For each temperature scenario, cross-passage classification was made in terms of whether the cross-passage could be equipped with a mechanical ventilation system (low cooling demand) or an air conditioning system (enhanced cooling requirement). This cross-passage classification was made based on the results of the energy balances derived in accordance with Eq. (5). Table 5 shows the cross-passage classification for each of the temperature scenarios.

Once service life and maintenance effort were estimated, and cross-passage classification was completed, the net present value method (see Section 2) was applied. As a first step, a comparison of two different scenarios, both characterized by a target temperature of 22 °C, was carried out. These scenarios differed in terms of cross-passage classification. While for the first scenario, cross-passage classification was based on Table 5 (22 °C), the second scenario assumed that every cross-passage was equipped with an air conditioning system. The comparison of the cost developments in both scenarios is depicted in Fig. 14. A few points have to be highlighted here. The offset at 0 years is due to differences in initial construction cost. During the assessed period of 50 years, both the cooling systems as well as telecommunication systems have to be replaced several times. The cost of replacing these systems can be seen as changes of gradients in the cost trend curves. These gradient changes are indicated separately in Fig. 14.

It turned out that, from an economic perspective, a combination of air conditioning and ventilation was advantageous over air conditioning in each cross-passage. At the end of a 50-year period, a deviation in total life cycle costs of 30% was found. In addition, the costs in the second scenario (air conditioning only) are permanently higher than those in the scenario with a combination of ventilation and air conditioning. Thus, the economic advantage of scenario 1 (combined cooling system)

Table 4
Approximation of the telecommunications system service life as a function of the utility room air temperature (Fruhwirt, 2021).

Operation temperature	22 °C	25 °C	30 °C	35 °C	40 °C	45 °C	50 °C	55 °C	60 °C
Service life [years]	16	12	9	6	4	3	2.1	1.5	1.2

Table 5
Cross passage classification related to the system selection for cooling purposes for various target temperature scenarios. (Fruhwirt, 2021).

Target temperature	Number of ventilation systems	Number of air conditioning systems
22 °C	10	57
25 °C	34	33
30 °C	63	4
35 °C	67	0

is given regardless of when the systems are replaced.

Based on this result, the remaining temperature scenarios were evaluated in a further simulation run. Fig. 15 shows the anonymized Life cycle cost of all temperature scenarios, where the Life cycle cost of the 22 °C scenario (first classification) is defined as reference (100%).

The general trend can be described as decreasing cost with increasing target temperature. This trend continues until a target temperature of 30 °C is reached. A further increase of the target temperature to 35 °C directly leads to the highest Life cycle cost (107%). This is the result of a significant decrease in the telecommunication system service life, accompanied by only few financial benefits, as the number of mechanical ventilation systems increases just slightly from the 30 °C to the 35 °C scenario. At the end of the 50-year period, the difference between the reference costs and the lowest Life cycle cost in the 30 °C scenario is about 21%. Compared to this, the financial benefit is 13% when the target temperature is increased to 25 °C.

The validity of these results was tested by means of additional dominance analysis and sensitivity analysis. The dominance analysis provided information about the cost elements and their impact on the total life cycle cost. Such an analysis was performed for each temperature scenario. It turned out that operating costs (86% of total life cycle costs) dominate over initial construction cost (14%). When examining the total cost of the individual systems, it can be seen that the costs for telecommunication systems (79.6 %) are significantly higher than the costs for cooling systems. Within the latter category, the respective shares for ventilation and air conditioning were 15.8 % and 4.6 %.

From an economic point of view, 30 °C seems to be the optimal target temperature for the Koralm railway tunnel telecommunication rooms. Nevertheless, the 25 °C target temperature scenario is recommended for the Koralm railway tunnel with a cross-passage classification according to Table 5. This is because small financial losses (~8% in Life cycle cost) enable an increase of telecommunication service life by 3 years (25%). Ultimately, this leads to higher track/tunnel availability and has positive effects on the Life cycle cost. Such impacts were neglected in the objective Life cycle cost analysis.

4. Conclusions

The operation of long rail tunnels requires numerous electromechanical installations. Such installations are quite sensitive to high temperatures and dust loads. For this reason, such components are usually housed in dedicated utility rooms within the tunnels cross-passages. In addition, the definition of temperature requirements for utility room air is intended to guarantee a minimum service life for sensitive systems. In order to meet these requirements, in many cases cross-passage cooling systems are needed. The design of such cooling systems requires information about the tunnel climate or tunnel air temperatures. Due to the low number of very long (>25 km) railway tunnels in the world, information on tunnel climate in very long railway

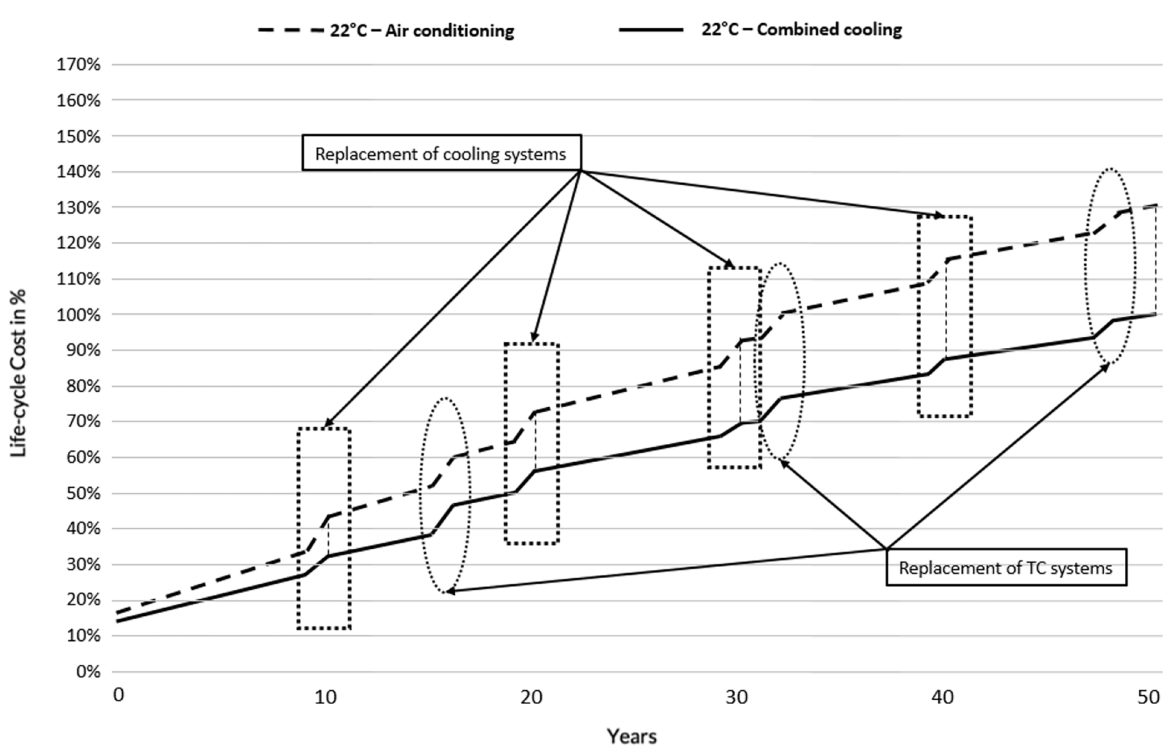

Fig. 14. Comparison of life cycle cost for a combination of ventilation and air conditioning and for full equipment with air conditioning (active cooling) units ((Fruhwirt, 2021), data originally published in (Scherz et al., 2019)).

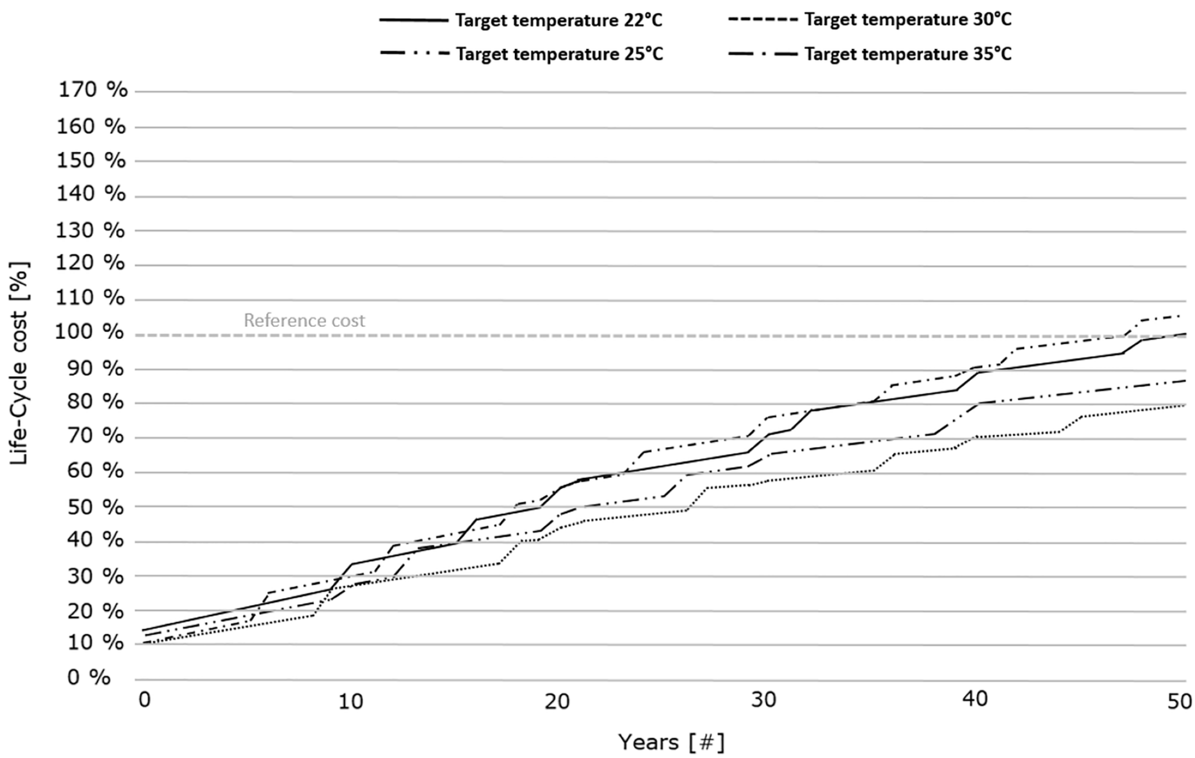

Fig. 15. Life-Cycle cost in four selected target temperature scenarios (Scherz et al., 2019).

tunnels is still quite rare. Additionally, tunnel climate depends strongly on the local geology, ambient air conditions and train-related parameters, i.e., train schedule. For this reason, a novel methodology was developed to aid prediction of tunnel air temperatures and to support the design process of cross-passage cooling systems. This methodology comprises four main steps, and makes use of well-known engineering tools employed in tunnel climate investigations. The four steps are as follows:

- Identification of cooling demand based on the first law of thermodynamics.
- Forecast of the tunnel climate using a one-dimensional approach.
- 3D CFD simulations for the determination of 3D effects in the temperature distribution within utility rooms.
- Life cycle cost analysis of relevant systems to provide economic data for a final selection of cross-passage cooling systems.

This set of investigative steps represents a systematic approach that can be applied to every tunnel project. The present article shows how the new method was applied to the Koralm tunnel (Koralm railway tunnel).

Energy balances based on the first law of thermodynamics were established as part of the first step in the investigation. This indicated the presence of a need for cooling in every cross-passage in the Koralm railway tunnel, as the room air temperature in the telecommunication room and the adjacent low-voltage rooms exceeded the target temperature. For this reason, in the second step of the investigation, a prediction of the tunnel climate was made using IDA tunnel as a solver for Bernoullís equation and for the energy conservation equation. The results of this simulation showed a strong dependency on ambient air in tunnel sections close to the portals, as tunnel air temperatures follow the daily variations in outside air temperatures. In contrast, the tunnel air temperature in tunnel sections close to the tunnel centre is mainly dependent on the local rock temperatures. The tunnel air temperatures obtained were then taken as input data in the subsequent 3D CFD simulations in order to determine the temperature distribution within the utility rooms. For the performance of the 3D CFD simulations ANSYS Fluent was employed in order to show whether a simple mechanical ventilation system was able to provide sufficient cooling capacity. These 3D simulations (carried out in step 3 of the investigation), revealed that a well-defined temperature stratification is to be expected within the utility rooms. While the maximum temperature at the ceiling reached 45 °C, the sensitive components were never exposed to unacceptable temperatures. However, in cross-passages that are characterized by very high heat release from technical systems, a ventilation system is not sufficient. In such situations, an air conditioning system is required. With the aim of providing data for final system selection in every cross-passage, a life cycle cost analysis was then carried out in the fourth step of the investigation. It turned out that a target temperature of 30 °C represents the economic optimum for cross-passage cooling. However, after taking account of some items neglected in the life cycle cost analysis (e.g. the impact of track availability), a cross-passage classification based on a target temperature of 25 °C is finally recommended for the Koralm railway tunnel.

As a final conclusion it can be stated that a novel methodology has been developed in order to investigate the tunnel climate of long railway tunnels. This new method includes investigations with a high level of detail that have not been carried out and/or documented before. In addition, the explanation of the method also includes information on the experience gained in applying the method to a specific tunnel project.

CRediT authorship contribution statement

D. Fruhwirt: Conceptualization, Investigation, Methodology. **P. Sturm:** Supervision. **H. Steiner:** Supervision. **R. Borchiellini:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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