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METHODOLOGY FOR INVESTIGATIONS ON THE TUNNEL CLIMATE IN LONG RAILWAY TUNNELS -

OPTIMIZATION OF THE DESIGN PROCESS FOR CROSS-PASSAGE COOLING SYSTEMS

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ABSTRACT

The operation of long railway tunnels requires numerous technical installations. Parts of these installations react sensitively on thermal loads and dust loads and require protection from the tunnel atmosphere. In the case of modern twin-tube single track tunnels such components are often placed in utility rooms which are situated in cross-passages. In order to meet the temperature requirements of the utility rooms, cross-passage cooling systems have to be installed. Designing these cooling systems requires extensive investigations on the tunnel climate. This represents a big challenge, as information about the tunnel climate in long railway tunnels is rare. For this reason, a method to support the design process of cross-passage cooling systems had to be developed. The application of this method on a certain tunnel provided the required information for a data based system design of the cooling systems in the Koralmtunnel (AT). This includes both, details about the technical feasibility of ventilation and air conditioning systems as well as economic considerations.

Keywords: tunnel climate, cooling systems, CFD simulations, life cycle cost

1. INTRODUCTION

Tunnel systems are an important part of the world´s transport infrastructure. Wherever mountains have to be crossed or transit traffic needs to be diverted underground, tunnels are indispensable. Rail transport is considered one of the key factors for sustainable transport of goods and people. For this reason, the European Union forces the expansion of the trans-European railway network [3].

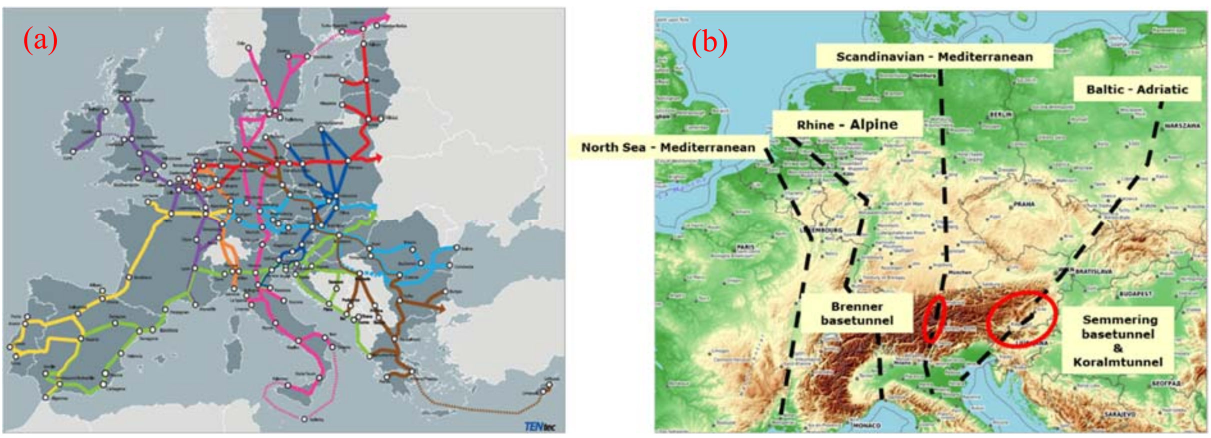

Figure 1: European railway network, (a) – Trans-European Network Transport (TEN-T) [2], (b) - selected trans-Alpine railway routes

This expansion includes the Alpine region that will be crossed by four main railway routes in north-south orientation. Figure 1 shows a scheme of the future railway network as it is aspired today. Two of the depicted routes (Figure 1) (b), the Scandinavian-Mediterranean route in the west and the Baltic-Adriatic axis in the east, are passing Austria. The core sections of these routes are three newly built very long railway tunnels. On the Scandinavian Mediterranean route the Brenner basetunnel is situated. It will be the world´s longest sub-surface railway track when it will be set in operation at the beginning of the next decade. In addition to that, there are two more very long railway tunnels on the Baltic-Adriatic axis, the Semmering basetunnel (28 km) and the Koralmtunnel (33 km).

Such long railway tunnels require a lot of technical installations for operation, such as power supply, telecommunication, remote control etc. Some components have to be installed inside the tunnel tubes, but sensitive ones have to be protected from the tunnel atmosphere. This tunnel atmosphere usually is characterized by high thermal loads or temperature variations and high dust loads, due to massive particulate matter emissions from railway operations. Both stresses result in an enormous maintenance effort for the tunnel equipment [17] [20]. While thermal stress accelerates the aging process of electronic components [10] [7], electrically conductive particles can cause malfunctions and damage to sensitive components [22].

In modern twin-tube single-track tunnels, such components usually are housed in so-called cross-passages. The basic structure of such cross-passages is shown in Figure 2. In general, they can be divided into two halves. While one half serves as an escape route in the event of a tunnel incident, the second half offers the possibility of setting up dedicated utility rooms. To create favourable conditions for sensitive systems in the utility rooms, there are certain requirements for room temperatures, relative humidity and air quality. The strictest requirement usually refers to the room air temperature [8].

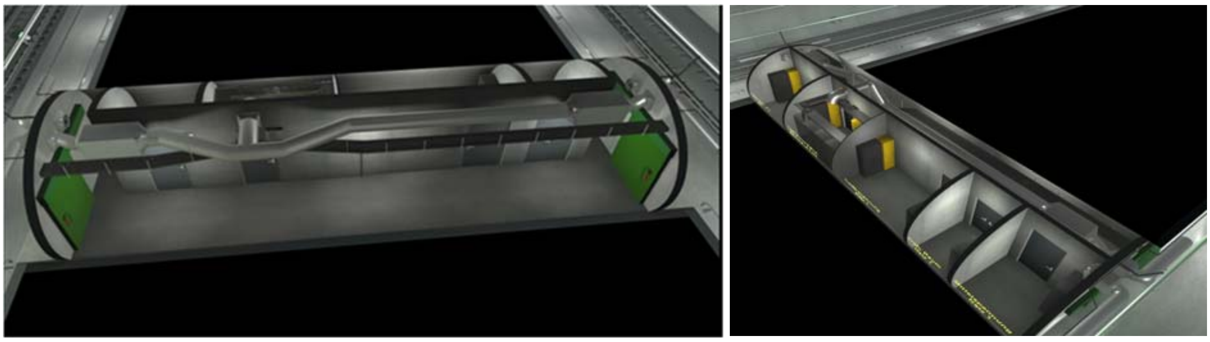

Figure 2: Principle layout of cross-passages in a modern twin-tube single track tunnel [14]

The design process of cross-passage cooling systems requires valid data about the tunnel climate or the expected tunnel air conditions respectively. Today only little information is available about the climate in very long railway tunnels. This is because the total number of railway tunnels longer than 25 km is low (four in Europe and seven in Asia). In addition, tunnel climate is strongly dependent on local parameters such as the rock temperatures. Hence, the tunnel climate needs to be investigated individually for every tunnel. Because information is rare and investigations of the tunnel climate are highly specific, a proper method that supports the design process of cooling systems and provides the required input data had to be developed.

2. METHODOLOGICAL APPROACH

Tunnel climate depends on many parameters, which vary from tunnel to tunnel, due to local environmental conditions and tunnel geometry. This fact makes the prediction of tunnel climate and the design of cooling systems in long railroad tunnels extremely complex. For this reason, a proper method had to be developed in order to be able to carry out systematic investigations of the tunnel climate and to support the design of cooling systems.

The developed investigation method comprises four main investigation steps including numerical simulations and economic considerations. Hence, both the technical as well as the economic perspective are taken into account. A flow chart summarizing the basic procedure of the method is shown in Figure 3

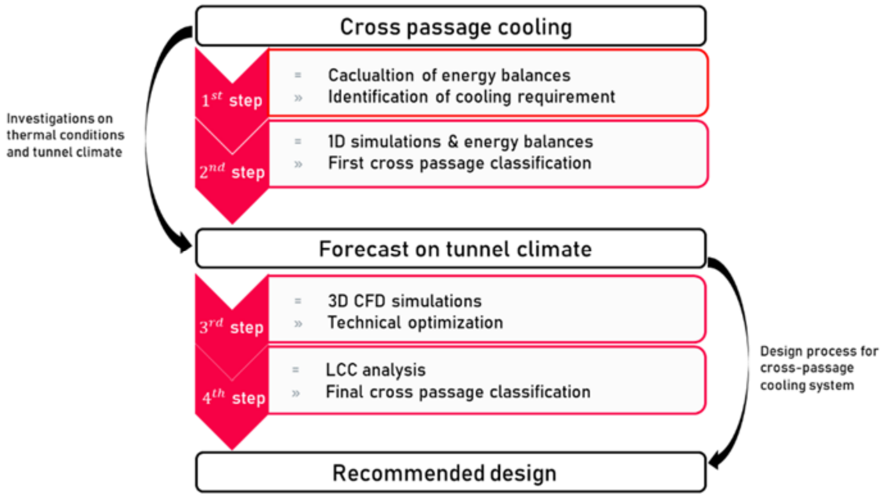

Figure 3: Flowchart of the developed method for the investigations on the tunnel climate of long railway tunnel (Fruhwirt Daniel, 2021)

The method developed is described in more detail below and applied to a specific case study.

2.1. Identification of cooling requirements

In order to identify the need for a cooling system, a model needs to be developed which is based at an energy balance between heat sources and heat sinks. Care must be taken to ensure that all relevant thermal processes (heat flows) are considered in the model and within certain system boundaries (i.e. individual rooms or so-called thermal zones). The temperature in a thermal zone is the result of all incoming and outgoing heat flows. Incoming heat flows are, for example, the waste heat from switch cabinets in the rooms or heat flows through walls from adjacent rooms or the surrounding rock.

In the end the energy balance of each individual zone can be expressed as shown in equation (1). There heat sources $\dot{Q}_S$, heat transfer through walls $\dot{Q}_{wall}$, the heat transfer between room air and rock layers $\dot{Q}_{rock}$ as well as the impact of cooling systems $\dot{Q}_{cool}$ as a sink are taken into account. Except the cooling term $\dot{Q}_{cool}$, all terms are a function of the room air temperature. Hence, the room air temperature can be explicitly expressed and calculated by the energy balance of the heat fluxes. In addition to that the undisturbed rock temperature has to be known in order to approximate $\dot{Q}_{rock}$ accurately.

In order to determine an equilibrium temperature that will be achieved through thermal self-regulation the term representing the cooling requirement is set zero in equation (1). This results in effective, averaged room temperatures which than can be compared with room target temperatures. If a cooling demand has been identified the calculation must be repeated with constant room temperatures corresponding to the target temperatures. This requires the consideration of the cooling term in the energy balances of the rooms characterized by a certain cooling demand. The final output of this second calculation run is the cooling demand of each individual thermal zone.

$$\dot{Q}_S + \sum_i \dot{Q}_{wall_i} + \dot{Q}_{rock} + \dot{Q}_{cool} = 0 \qquad (1)$$

2.2. Cooling concepts

If required to meet the room target temperature, a cooling system must 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. An air conditioning systems needs another medium for heat exchange, which could either be tunnel air or a continuous water supply. For the design of either of these systems the conditions of the climate inside the tunnel needs to be known.

2.3. Forecast on tunnel climate

As mentioned above, the knowledge of the tunnel climate is necessary for further design steps. In order to forecast tunnel climate, some specifications need to be made before. One of them is the projection time. Based on experience, the service life of cooling systems can be assumed by ten years for air conditioning and twenty years for ventilation systems. However, when performing a feasibility study any projection periods should cover several replacement cycles for system components. This leads to time spans of several decades. Extended projection periods as well as large computational domains result in general in long computational times. Hence, simple numerical models like 1D CFD or Bernoulli equation based models are recommended for this purpose.

Special attention has to be paid on the definition of the initial conditions and the boundary conditions. The former are strongly dependent on the rock temperatures as well as on the applied ventilation strategies during the tunnels construction and equipping phase. Because the utility room cooling systems are being designed at a time when tunnel construction is on-going for several months or even years, the initial conditions cannot be determined by measurements in the actual tunnel. This means that the initial conditions must be determined in a pre-simulation covering the entire period of time in which the tunnel climate changes from the last known state.

In a next step boundary conditions need to be defined. Basically, there are boundary conditions that depend on local parameters, while others are related to activities like the operation schedule. The former category includes outside air conditions (temperature and humidity) and the rock temperature, while the latter one concerns the train frequencies (train schedule) and the train speed as the most important rail-operation related parameters.

Due to the long period of time to be considered, long-term effects such as climate change must also be taken into account. Especially in the Alpine region, this can lead to a significant change in outside air conditions over the decades. In the end the application of a 1D CFD model or a Bernoulli based model respectively provides data about the tunnel air temperature and relative humidity as a function of the tunnel position and time. Based on this information, the design of cross-passage cooling systems can be carried out. This design process requires the determination of the utility room air temperatures that can be achieved by ventilation or air conditioning.

2.4. Forecast of utility room temperatures – cooling by ventilation

In order to determine the expected utility room air temperatures, once more the calculation of energy balances is required. If a ventilation system is considered, equation (1) has to be modified including the mass flow over the system boundaries (equation (2)). In this equation, $\dot{Q}_S$ denotes the heat sources represented by the waste heat of technical systems, $\dot{Q}_{fan}$ denotes the heat output of the supply air fan motor, and $\dot{m} * (h_{in} - h_{out})$ is the increase in supply air enthalpy h along the flow path. Assuming ideal gas behaviour and constant property values, this enthalpy increase can be determined as shown in equation (3).

$$\dot{Q}_S + \dot{Q}_{fan} + \dot{m} * (h_{in} - h_{out}) = 0 \quad \mathbf{(2)}$$

$$h_{in} - h_{out} = c_p * (t_{in} - t_{out}) \quad (3)$$

Based on this simple approach, the expected room air temperatures (t_{out}) that can be achieved by an active ventilation system are determined. It has to be noted that these values represent ideal ones that can be interpreted as an average room air temperature.

2.5. Forecast of 3D temperature distribution in the utility rooms

Because the actual temperature distribution can not be displayed by the simple calculation regime (energy balances) as described above, in a third investigation step detailed 3D CFD simulations have to be carried out to get more information about the impact of the inlet air flow and the temperature distribution within the utility rooms. This temperature stratification or temperature distribution respectively, depends on the general temperature level within the utility room, the heat sources, the arrangement of the cabinets, as well as of the momentum of the incoming cooling air.

To serve this purpose, standard 3D CFD models are employed. The geometric 3D model of the cross-passage has to cover all relevant components that have noticeable influence on the room air temperatures. If the rock temperature and the room air temperatures of adjacent utility rooms are lower than the room air temperature of the assessed utility room, the thermal interaction with rock layers and the adjacent rooms can be neglected if a conservative approach should be applied. If the temperature gradient from rock to air is negative, the impact of thermal interaction becomes relevant and should be taken into account.

The 3D model provides information about the temperature distribution in the room and thus also about the thermal load on the devices. If ventilation is not sufficient an air conditioning system must be installed. In addition to that, 3D CFD simulations can be used to analyze different operation modes of the ventilation system (e.g. variable speeds or on/off modus).

2.6. Economic consideration

In addition to technical feasibility, economic considerations are always important when planning an infrastructure project. For this reason, the fourth step in the methodological approach is a life cycle cost analysis (LCCA) that covers the relevant technical systems. In the case of cross-passage cooling systems, the analysis includes the cooling systems as well as all technical installations that are effected by the room air temperatures. Such a LCCA aims to determine an optimal target temperature for the utility rooms and provide additional data for the final system selection of the cross-passage cooling system.

There are several approaches to create an economic model. If a long period of time has to be assessed, it is recommended to use a dynamic approach, where each cash flow is valued at a specific date. This valuation is necessary to ensure comparability of investments. The net present value method [1] represents such a dynamic approach, as it takes into account the period in which an investment is made or an inflow of funds occurs [13]. In order to get a clear result, all cost relevant aspects like investment, maintenance, debugging services, operation and the replacement of systems need to be considered.

The net cash received (NCR) is defined as the difference between all cash inflows and cash outflows in a certain period of time τ (see equation (4)). Equation (5) shows the definition of the net present value (NPV) which is defined as the sum of all NCRs divided by $(1+i)^{\tau}$ where i denotes the interest rate under consideration.

$$\boldsymbol{NCR = i_{\tau} - o_{\tau}} \quad \textbf{(4)}$$

$$NPV = \sum_{\tau=0}^{n} \frac{i_{\tau} - o_{\tau}}{(1+i)^{\tau}} = \sum_{\tau=0}^{n} \frac{NCR}{(1+i)^{\tau}} \quad (5)$$

In the end, the total life cycle cost of the assessed systems can be determined. Based on this the final system selection of cross-passage cooling systems can be made.

3. CASE STUDY

The methodological approach as defined in section 2 is generally valid. However, any application needs input data which are of course site dependent. Such an application of the model has been performed in a case study for the 33 km long Koralm rail tunnel in Austria [14].

3.1. Project description

The Koralm Tunnel (KAT), where the technical equipment phase has recently started, is a twin-tube single-track tunnel with a total length of 32.9 km. It consists of the two tunnel tubes and 70 cross-passages spaced 500 m apart. In addition, there is an emergency stop station directly in the centre of the tunnel and two ventilation stations with vertical air supply shafts that are operated both in case of fire and during maintenance phases. The maximum overburden of the tunnel in the centre is about 1’200 m, which is the main reason for locating the ventilation shafts near the portals. Figure 4 shows a longitudinal section and schematic diagram of the KAT.

Most of the cross-passages host five utility rooms, one for the telecommunications systems and four rooms housing the equipment for the power supply (low and medium voltage components). Temperature requirements were defined by the client individually for each of the utility rooms dependent on the systems installed within the utility rooms (see Table 1).

Table 1: Target temperature ranges for the utility rooms in the Koralm tunnel [8]

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

(a)

(b)

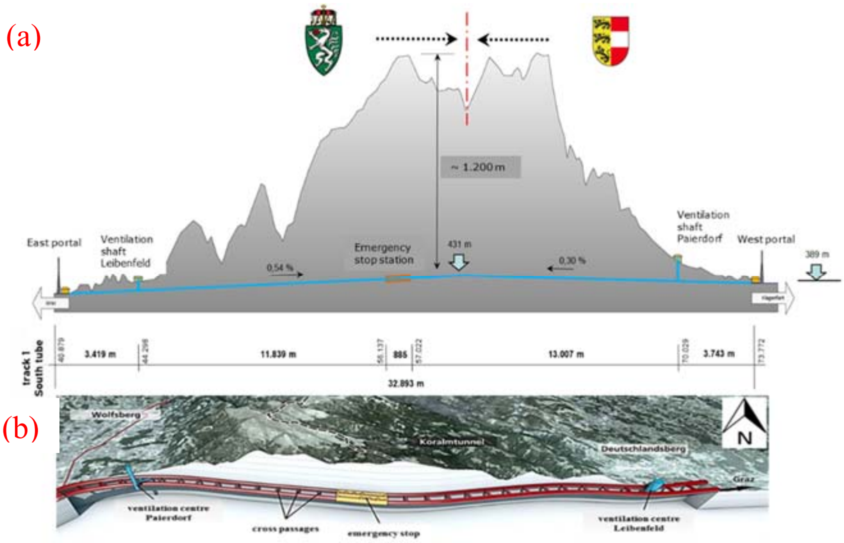

Figure 4: KAT tunnel system - (a) longitudinal section, (b) general scheme [16].

While the minimum and extreme values represent absolute boundary values, the third column (T_target) shows the target temperature ranges for normal operation. Accordingly, the target temperature range for the telecommunication rooms is defined as 15°C to 22°C. Keeping the room air temperature within this temperature range is quite a challenge because the telecommunication equipment produces significant waste heat. For standard telecommunication equipment, the heat dissipation is about 6 kW and for telecom base stations, this increases to as much as 26 kW. This high off-heat together with the rock temperatures in the tunnel (see section 3.3) requires room air cooling.

3.2. Identification of the actual cooling requirement

The first investigation step requires the definition of an accurate thermodynamic system. In the case of the KAT this thermodynamic system covers an entire cross-passage including five utility rooms, one for telecommunication systems (TC) and four rooms to house components for the power supply. Each of the utility rooms as well as the escape way were modelled as an individual thermal zone. Figure 5 shows a scheme of a cross-passage covering eight thermal zones (thermodynamic systems).

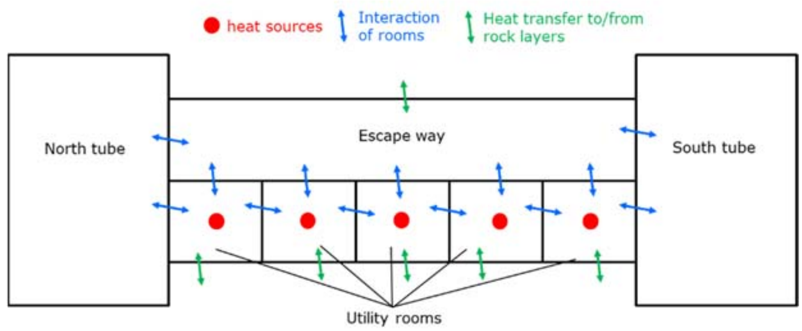

Figure 5: System configuration for the determination of the expected utility room air temperatures.

As illustrated in Figure 5 every utility room, the escape way and the adjacent tunnel sections are defined as separate but interconnected systems for which an energy balances are calculated.

The final outcome of this investigation step are the room temperatures reached in a steady state. It has to be noted that these values represent an averaged room air temperature, as an idealized, non-dimensional system (constant temperature in the entire utility room) is assumed. The energy balances applied to the thermal zones can be expressed as described in section 2.1.

Figure 6 shows the determined room air temperatures for every utility room in the Koralm tunnel in case of self-regulation (no active cooling system). It can be seen that the telecommunication room (TC), with a max. target temperature of 22°C and the adjacent low voltage room (target temperature 30°C) require an active cooling system.

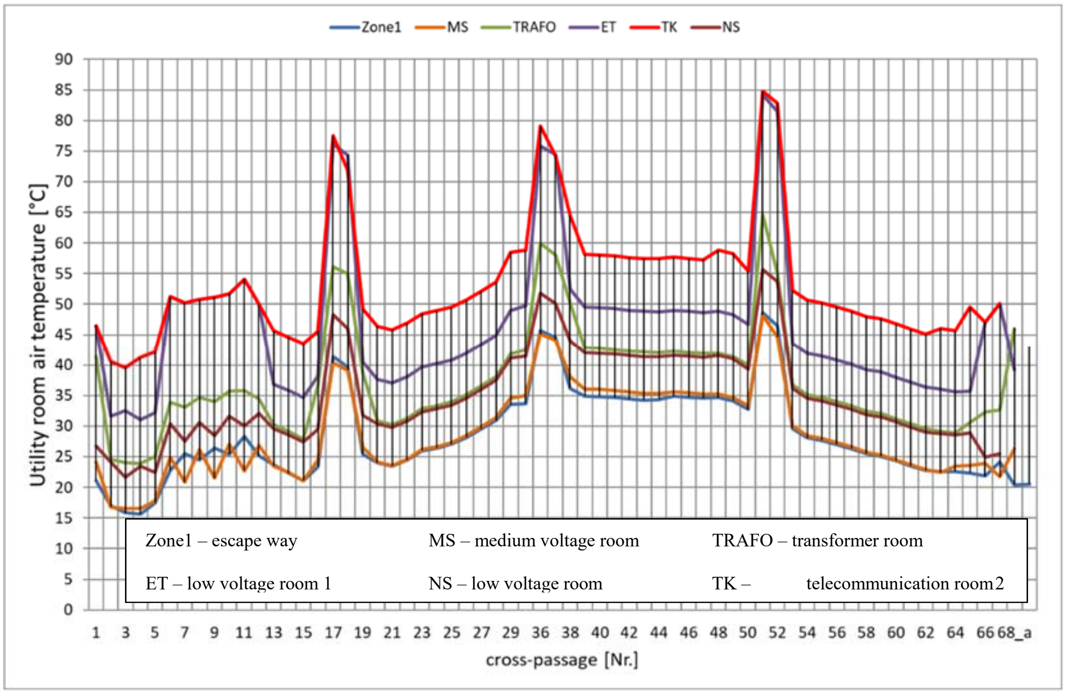

Figure 6: Expected utility room air temperatures without active cooling systems [19]

3.3. Forecast of the tunnel climate

At the beginning of the second investigation step some specifications have to be defined. This includes the definition of the period of time to be assessed in the tunnel climate investigations (see section 2.3). In the case of the KAT a period of 50 years had to be assessed, as several replacement cycles of cross-passage cooling systems should be included.

In the KAT tunnel climate investigations, IDA tunnel [11] was used. It is a commercial solver for the conservation of mass and a balance of total pressure.

Initial conditions:

The initial conditions for the simulation of the tunnel operation phase refer to the conditions at the end of the equipping phase and can vary significantly from the thermal conditions recorded in the construction phase or the early equipping phase of the tunnel. In order to determine these initial conditions for the operation phase, the last two years of the construction/equipping period were considered in the model. Input data for this model were the original rock temperatures, the heat sources and sinks during this period (off-heat from vehicles, evaporation heat during concreting of the trackways and the ventilation system applied during that period. The activity data for calculation these thermal loads was provided by the client on basis of technical reports [15]. The impact of the activities during these two considered years is demonstrated in Figure 7 in which the wall surface temperature curves along the south tube of the KAT for selected time steps are depicted.

Two important aspects have to be highlighted in this context. On the one hand the general temperature level is expected to decrease during the equipping phase and portal regions are strongly affected by the outside air conditions and thereby a certain bandwidth of temperatures can be observed in these areas. Furthermore, the discontinuity right in the tunnel centre has to be explained in more detail. This special fact is a result of the applied construction ventilation system in the KAT. The construction and equipment of the tunnel is done in two totally separated lots, west and east. Most of the time a U-shape ventilation system that uses the south tube for supply air and the north tube as the return air tube will be operated independently in each of these two sections. While the black line in Figure 7 represents the initial rock temperature – as starting condition in the simulation – the other lines show a dedicated temperature offset at the boundary of the both lots, due to the aerodynamic separation by a brattice. Rock temperatures were known from permanent measurements during construction phase.

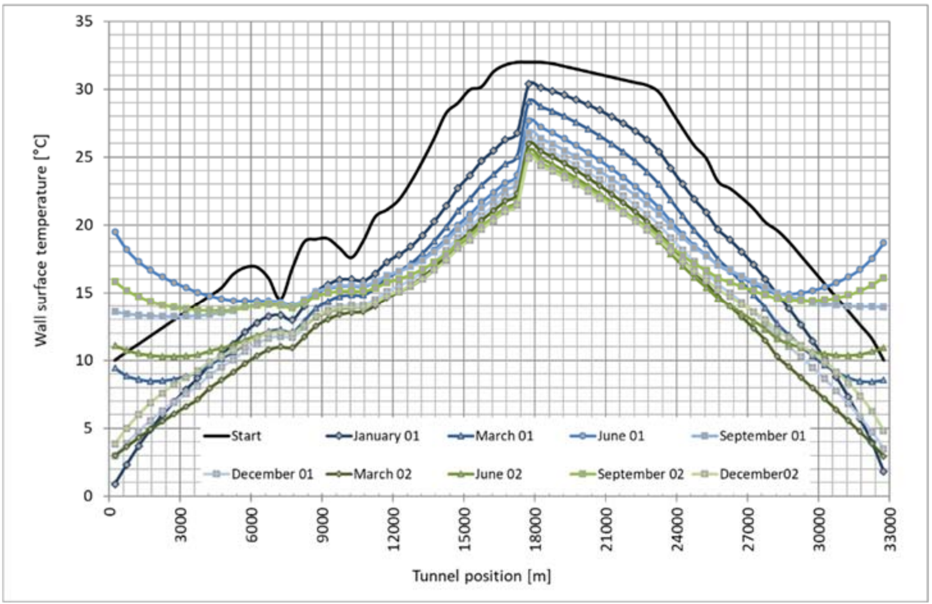

Figure 7: Wall surface temperature curves along the south tube of the KAT at selected points of time in the equipping phase. [9]

<u>Boundary conditions:</u>

Rock temperature:

The most important parameters are the local rock temperatures, the outside air conditions and the train schedule. However, it should be noted that there are many more parameters (e.g. train speed) that have an influence on the tunnel climate. Consideration of all parameters results in a complex system that must be studied if a tunnel climate forecast is to be made.

Nevertheless, one of the most crucial physical effects for the tunnel climate is the heat transfer between the tunnel air and the tunnel wall due to heat transfer by convection. However, long-term effects on the tunnel climate also require the consideration of heat conduction. Therefore, the solid layers of the tunnel lining (concrete), shotcrete layers as well as the rock material have to be discretized in the numerical model. An important aspect in this context is that the rock material may change along the tunnel. Such changes can be caused by different water content in the solid layers or by different geological formations. In the KAT, the solid layers in most tunnel sections were modelled as rock layers with constant property values. In portal sections, the rock layers were replaced by neogene layers with different property values. The rock temperatures up to a penetration depth of 285 m at the end of the pre-simulation were used as initial conditions for the tunnel climate simulations.

Outside air conditions:

The second crucial parameter that has a strong influence on the tunnel climate is the outside air temperature. In order to have accurate data for this boundary condition, long-term measurements from the project area are needed. In the case of the KAT, such data were available [6], since the Federal state of Styria operates a meteorological station near the KAT's east portal. This data set contains hourly mean values of outside air temperature and relative humidity. It has to be noted that daily or monthly average values are not applicable as the daily variations of the temperature have an influence on the thermal conditions in portal regions. The hourly average values of the past 20 years were analysed in detail. It turned out that the summer of the year 2012 was characterized by a high average temperature level and during summer of 2013 high peak temperatures up to 39 °C were recorded. For this reason, the data of both years were used to define the thermal boundary conditions. Because the forecast on the tunnel climate had to cover a period of 50 years, even long-term effects had to be taken into account. In order to do this, the impact of climate change was considered on basis of an expert statement from the local meteorological office [21]. Table 2 shows the monthly average values from a 30-year period in the past, as well as the expected values, 90th percentile values, and expected temperature increase for the period through 2070.

Table 2: Monthly average temperatures of the past and expected values for the period until 2070 for the area of Deutschlandsberg (KAT East portal) (Fruhwirt Daniel, 2021)

No.	Type	January	February	March	April	May	June	July	August	September	October	November	December
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	90-percentile	0.0	2.5	7.1	11.3	16.7	19.9	21.6	21.1	16.7	11.4	5.3	1.3
4	Δ nr2 - nr.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

The expected increase in monthly average temperatures by 2070 (No.4 in Table 2) is about 2.2°C, with a slightly higher temperature increase in winter than in summer. The development of the outdoor air temperature within this period is approximated by a linear function.

Train frequency:

The train frequency is another important parameter that strongly influences the tunnel climate. This is because train movements bring outside air into the tunnel and influence the heat transfer towards the walls. Hence, a plausible train schedule has to be implemented into the 1D simulations. As the train schedule was not defined at the design stage of the cross-passage cooling systems, a high traffic scenario and a low traffic scenario were considered. The low traffic scenario was defined by one single train per hour and direction and the high traffic scenario considered six trains per hour and direction.

<u>Results from 1D simulations:</u>

Finally, the result of the 1D tunnel climate simulations are the hourly average values of tunnel air temperature and relative humidity. Figure 8 shows as an example the curves of the maximum, minimum and average temperature along the south tube of the KAT for July in the first year of operation based on a high traffic scenario. Two important aspects should be emphasized in this context. On the one hand, a homogeneous temperature curve at a high temperature level can be observed in regions around the tunnel centre, and on the other hand, there is a strong influence of the outside air conditions in portal areas. This effect leads to a large temperature range, since the daily fluctuations of outside air temperatures have an impact to the tunnel sections near the portals. This fact underlines the importance of the hourly average temperatures used as thermal boundary conditions in the tunnel climate simulations.

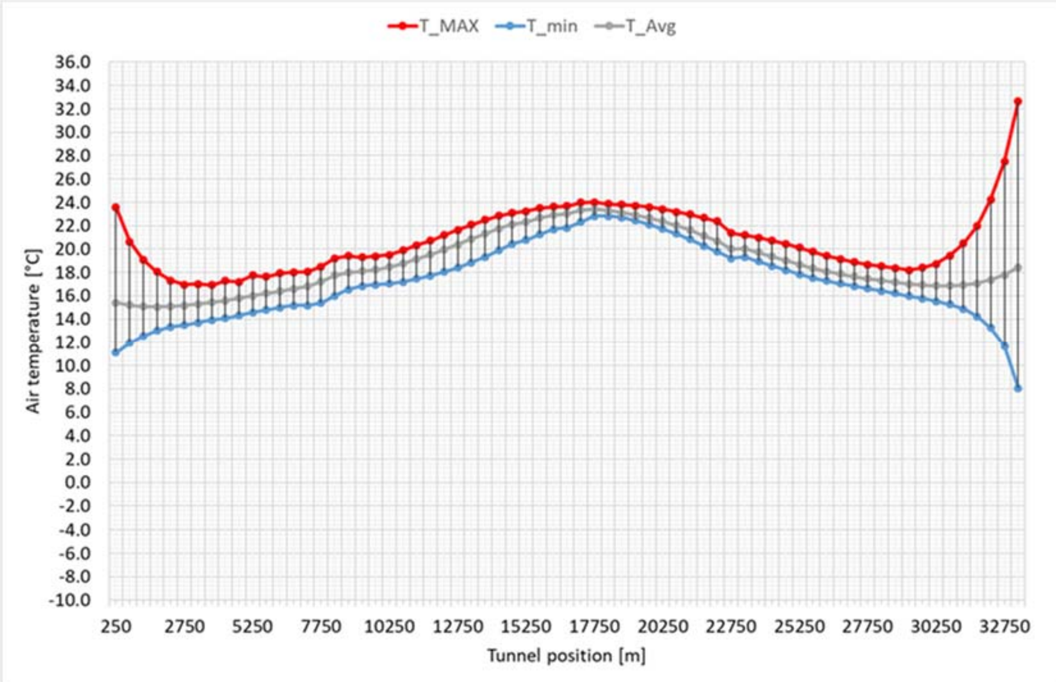

Figure 8: Tunnel air temperature curve in KAT south tube – July (1st year of operation) [8]

3.4. Determination of utility room air temperatures with active ventilation system

The results of the 1D simulations for tunnel climate provide boundary conditions for the design of the cross-passage cooling system. However, at this stage still no statement can yet be made concerning the type of cooling system required to keep the utility room air within the target temperature range. Therefore, an additional calculation of energy balances for the utility rooms with a certain cooling demand is necessary. The methodological approach used in this step is described in section 2.4. Figure 9 depicts the scheme of the thermodynamic system to determine the expected utility room air temperatures, in this case for the telecommunications room.

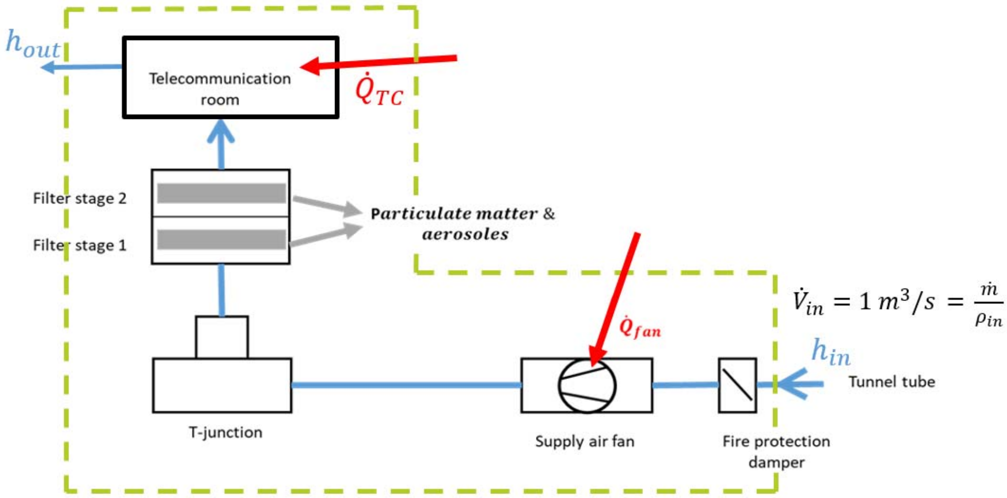

Figure 9: Thermodynamic system for the determination of the utility room air temperature

The final result of this calculation procedure is the average room air temperature in the TC room. This temperature is then compared to the target temperature of the TC room (22°C). Figure 10 shows how often the expected TC room air temperatures of selected cross-passages along the KAT will exceed the target temperature. The numbers are changing over operation time due to the projected change of tunnel climate over the years. At the beginning of the operation phase, only a few exceedances of the target temperature (22°C) are expected in portal areas. In contrast, the target temperature will be permanently exceeded in the TC rooms located near to the centre of the tunnel. In the first twenty years of operation, two opposing trends can be observed. While temperature exceedances in the portal areas will increase significantly, temperatures in the centre of the tunnel are expected to decrease. These trends will continue until the effects of climate change become more pronounced and the temperature rise affects the entire tunnel system.

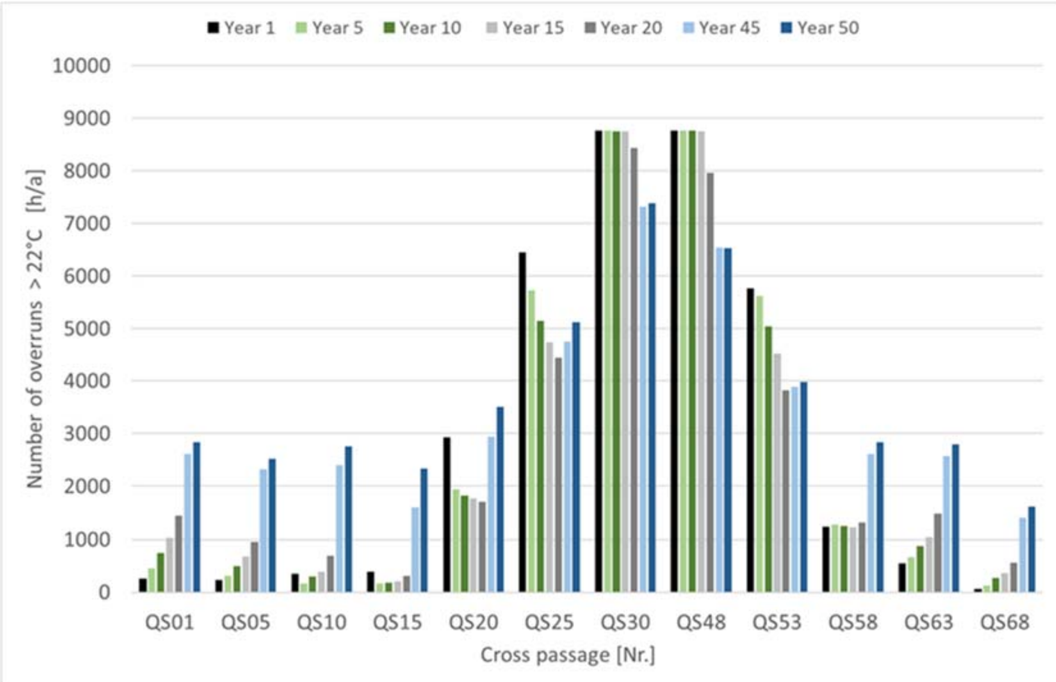

Figure 10: Number of exceedances of the target room air temperatures in the telecommunication room as a function of operation time in selected cross-passages along the KAT [8]

In a strict interpretation of these results, there is no cross-passage in which the TC room temperature can be kept permanently in the target temperature range. Consequently, every cross-passage would have to be equipped with an air conditioning system. However, the approaches used so far are subject to some uncertainty because the derived temperatures represent average room air temperatures and do not account for 3D effects such as temperature stratification. To obtain more information about these 3D effects, additional 3D CFD simulations were performed in the third investigation step.

3.5. Detailed 3D CFD Simulations

In the course of the 3D investigations of the utility room temperature (mainly the TC room), Ansys Fluent was the chosen 3D CFD solver. The geometrical 3D model covered a cross-passage equipped with a mechanical ventilation system. Utility rooms that do not require cooling are not included in the air path of the ventilation system and thus were neglected in the 3D CFD simulations.

The most relevant boundary conditions in the 3D simulations are the supply air temperature and the heat sources inside the TC room. For the simulation runs described below the supply air temperature was 20°C and a heat dissipation of 6 kW at the top of two implemented control cabinets were set. Heat transfer through walls was neglected, representing a thermal setup expected in tunnel sections with similar TC room air and rock temperatures.

Based on this setup, two simulation runs were performed. The first run included a permanent full load operation of the supply air fan with a constant supply air flow rate of 1 m³/s at the inlet. In comparison, the second simulation run was performed in a transient mode with on/off operation of the supply air fan. While the first simulation run aimed at determining the temperature distribution in the TC room or the suitability of a ventilation system to meet the cooling requirement, the second simulation run aimed at some optimization of the control regime of the ventilation system. The results of the 3D CFD simulations are shown in Figure 11. The temperature contours are depicted on a vertical plane through the TC room. The exact location of the vertical plane is indicated in the image on the right side of Figure 11.

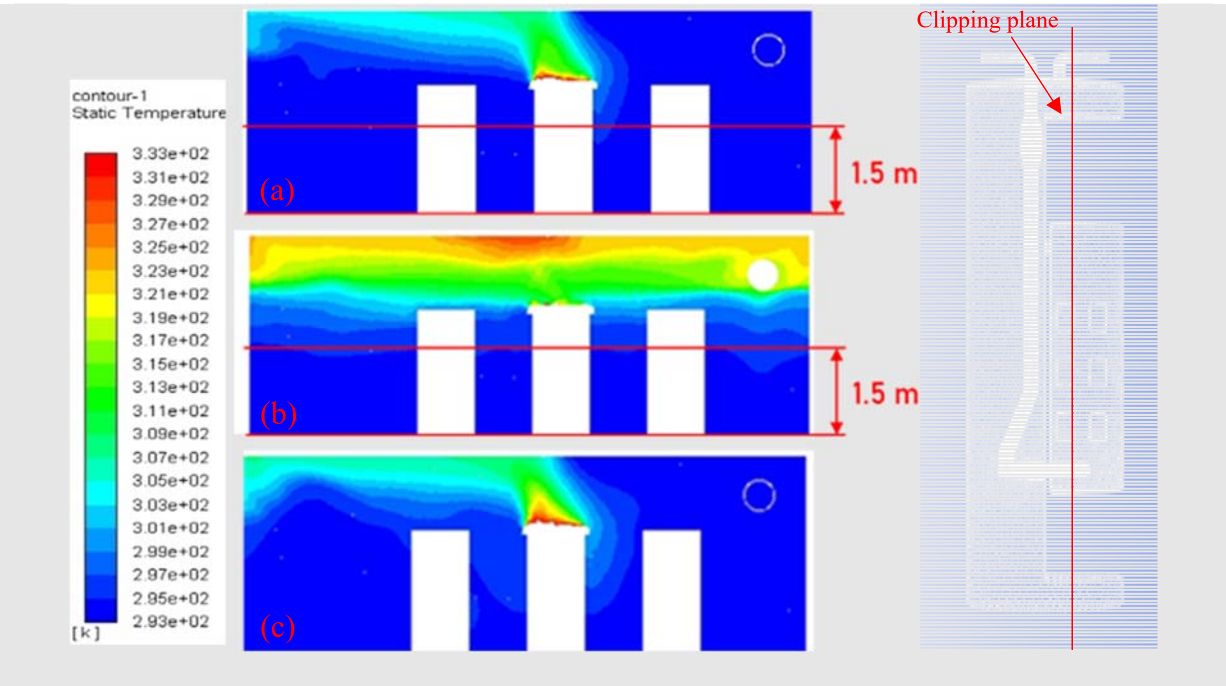

Figure 11: Results from 3D CFD simulations (a) steady state, (b) transient case, 75 sec after fan deactivation, (c) transient case, 65 sec after fan-reactivation [8]

Three important aspects are evidenced by the results of the 3D CFD simulations.

The first is the well-established temperature stratification within the TC room. While the space above the control cabinets acts as a thermal buffer with temperatures up to 45°C, the control cabinets themselves are not exposed to unacceptable temperatures. The 1D simulation as described in section **Fehler! Verweisquelle konnte nicht gefunden werden.**. would have resulted in an average room air temperature of 24.8°C, i.e. above the target air temperature of 22°C.

The second aspect is the asymmetric temperature distribution, which is caused by the massive influence of the supply air. Cabinets located near the supply air inlet are permanently exposed to the cooler supply air temperature. As a consequence of the findings of the first simulation run (steady state – see (a) in Figure 11), the temperature criterion for the TC room was modified, in so far that the target temperature must be maintained at a height of 1.5 m. This should be sufficient, since room air extracted close to the floor is used for the internal cooling of the control cabinets.

The last important information was derived from the results of the transient simulation. The deactivation of the supply air fan leads to a temperature distribution as depicted in image (b) in Figure 11. Only 75 seconds after deactivation, the target temperature (22°C) is exceeded at a height of 1.5 m, resulting in reactivation of the supply air fan. After another 65 seconds, the warm TC room air is removed and the initial temperature distribution is reached again (see image (c) in Figure 11). Based on these results, an on/off control regime does not appear to be appropriate and a control regime on two or more discrete fan speed levels is recommended to provide some flexibility.

Since the results of the 1D and 3D approaches are different, a validation of the 3D results was performed in the escape tunnel of an Austrian railway tunnel. Within this escape tunnel, a dedicated test room with similar characteristics compared to the KAT utility rooms was set-up and several test scenarios with variations of supply air temperature and heat release were performed [12]. The general outcome of the in-situ tests confirms the results of the 3D CFD simulations, as a well defined temperature stratification could be observed and the integrated control cabinets were never exposed to temperatures above the target temperature.

Based on the findings from the 3D CFD simulations, it can thus be concluded that 3D effects in the temperature distribution offer some potential for optimization of the target temperature. It should be noted that the results of the 3D CFD simulations depend on the arrangement of the cabinets. However, the basic conclusions concerning temperature stratification are found to be valid.

3.6. Cooling concepts

Since there is a need for active cooling in most of the KAT cross-passages, a principle cooling concept must be defined. Due to the fact that there is no continuous water supply in the KAT, tunnel air is the only available cooling medium. This limits the choice of cooling systems to two types. One is a mechanical ventilation system that uses tunnel air to cool the utility rooms, and the other is an air conditioning system that uses tunnel air for re-cooling. Figure 12 shows the principle layout of both cooling systems. Note that due to redundancy purposes both systems are duplicated in the same cross passage.

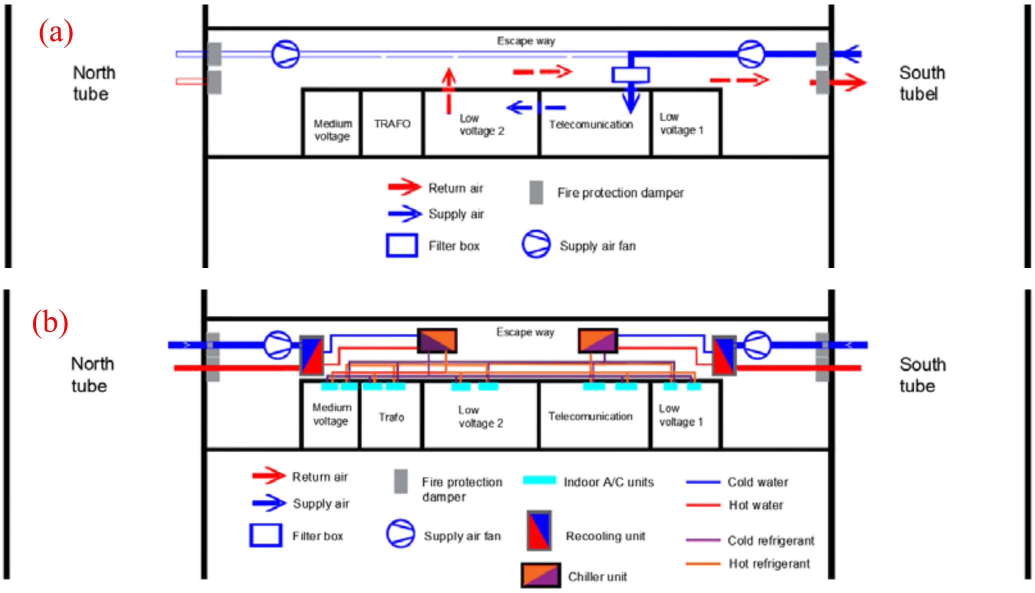

Figure 12: Principle layout of the cross-passage cooling systems in the Koralm Tunnel, (a) ventilation, (b) air conditioning [8]

Both systems have advantages and disadvantages. The ventilation system has its main benefits in its simplicity, as it contains only few electro-mechanical components (fans and dampers). This causes a moderate maintenance effort and keeps the power consumption and operation costs on an acceptable level. One disadvantage is the limited cooling effect due to the strong dependency on the tunnel air temperature respectively the tunnel climate. The second disadvantage is the required supply air treatment, since the tunnel air must be filtered due to high PM concentrations in the tunnel. This can be a knock-out criterion if the filter service life does not reach an acceptable level. However, tests demonstrated that the expected filter life when using the KAT ventilation system is approximately between 4.5 and 21 months, depending on the filter specification [20]

In contrast to the ventilation system, the air conditioning system requires an increased electromechanical effort. The system design according to Figure 12 covers a refrigerant cycle, a water cycle and an air cycle. The necessity of a water cycle is mainly a result of regulations related to the maximum amount of refrigerant mass acceptable in an escape way [5]. In the end this results in higher cost for construction and operation compared to a ventilation system.

However, as a result of the investigations about tunnel climate it was concluded, that for many cross passages, a ventilation-based cooling system is not sufficient, hence air conditioning is required.

In the end the decisive criteria pro or against a system are the achievable track availability and the financial aspects. The ventilation system proved superior; however, the limitations imposed by the temperature requirements force the use of air conditioning systems at cross passages with enhanced cooling demand. The target temperature not to be exceeded in the telecommunication room is the decisive parameter for system selection. However, as this target temperature is given due to lifetime considerations of the equipment, a LCCA might be used to decide weather a reduced lifetime (higher target temperature) and lower system costs are beneficial compared to extended lifetime but higher system costs.

3.7. Economic considerations

In the last investigation step a LCCA was made for the cross-passage cooling systems and the TC systems. In general, the cost development for both system is driven by investment, operation and maintenance costs. The latter are dominant in the evaluation of the total life cycle cost of the cross-passage cooling systems and the TC systems. For this reason, accurate approaches to estimate all relevant cost elements are required.

The service life of both cooling systems (ventilation and air conditioning) was assumed to be 20 years for ventilation and 10 years for air conditioning systems. These values represent empirical values derived from previous tunnel projects. In contrast, the service life of TC 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 [4], which is commonly used to approximate ageing processes on chips and sensors due to thermal stresses. This results in a formulation as shown in equation (6).

$$\tau_E = \tau_Q * e^{\frac{E_a}{R} * \left(\frac{1}{T_E} - \frac{1}{T_Q}\right)} \quad (6)$$

Using this equation, the service life of the TC systems was determined for selected TC room air temperatures in the range from 22 °C up to 60 °C (Table 3). Consequently, a temperature range of 22 °C up to 35 °C appears to be suitable, since a further increase in room air temperature reduces the expected service life of TC systems to less than 6 years, which reduces the track availability significantly due to tunnel closures that would be needed for the replacement of broken down systems.

Table 3: Approximation of the Telecommunication system service life as a function of the utility room air temperature [8]

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

For the estimation of maintenance service costs, a similar approach was found as for the estimation of the service life. The annual cost for maintenance services of the cooling systems were approximated as a constant on basis of investment costs (1 % ventilation and 6 % air conditioning). In contrast, the annual maintenance cost for the electrical installations (TC systems) I_m were approximated by equation (7). There I_0 denotes the initial investment cost for the TC systems and $\frac{\tau_{22°C}}{\tau_T}$ is the quotient of expected service life at a target temperature of 22 °C and a target temperature T according to the selected scenario. This quotient expresses the dependence of the maintenance cost on the room air temperature and takes into account increasing cost with increasing room air temperature.

$$\boldsymbol{I_m = I_0 * 0.0638 * \frac{\tau_{22°C}}{\tau_T}} \qquad \textbf{(7)}$$

Within the temperature range of 22 °C to 35 °C, four temperature scenarios were defined and evaluated in the LCCA. For each temperature scenario, a cross-passage classification was made as to weather they can be equipped with a mechanical ventilation system (low cooling demand) or an air conditioning system (enhanced cooling requirement). Figure 13 shows the cross-passage classification for each of the temperature scenarios. While for the 22°C scenario almost no cross-passages could be equipped with ventilation systems, in the 35°C scenario, cooling by ventilation would serve for almost all cross passages.

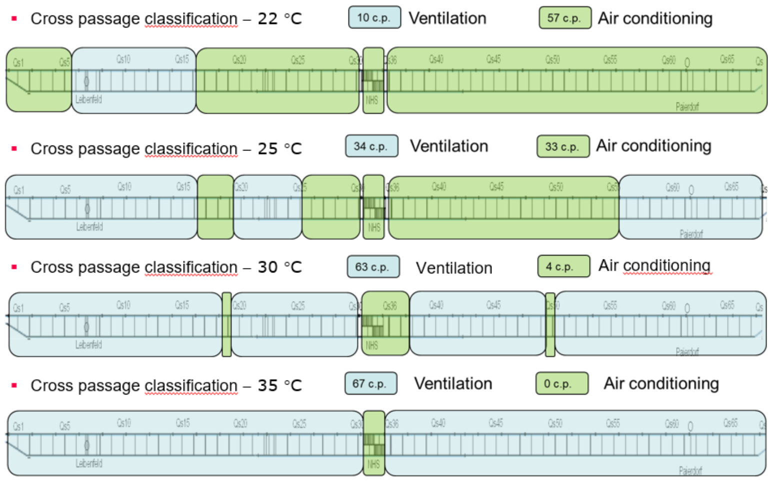

Figure 13: Cross-passage classification related to the implemented cooling system for four selected target temperature scenarios [8]

Based on a target temperature of 22°C, a comparison was made in the first simulation run between a cross-passage classification according to Figure 13 and a variant in which only air-conditioning systems are used. Figure 14 shows the results derived from this simulation run. The offset already at the beginning is due to the variation in initial investment cost. During the considered 50 year of operation the total life cycle cost (LCC) differ at the end by roughly 30% in which a cross-passage classification according to Figure 13 (roughly 15% ventilation and 85% air conditioning) accounts for the lower cost compared to a full installation of air conditioning systems. Hence, in cross-passages with lower cooling requirement the installation of a ventilation system should be aspired.

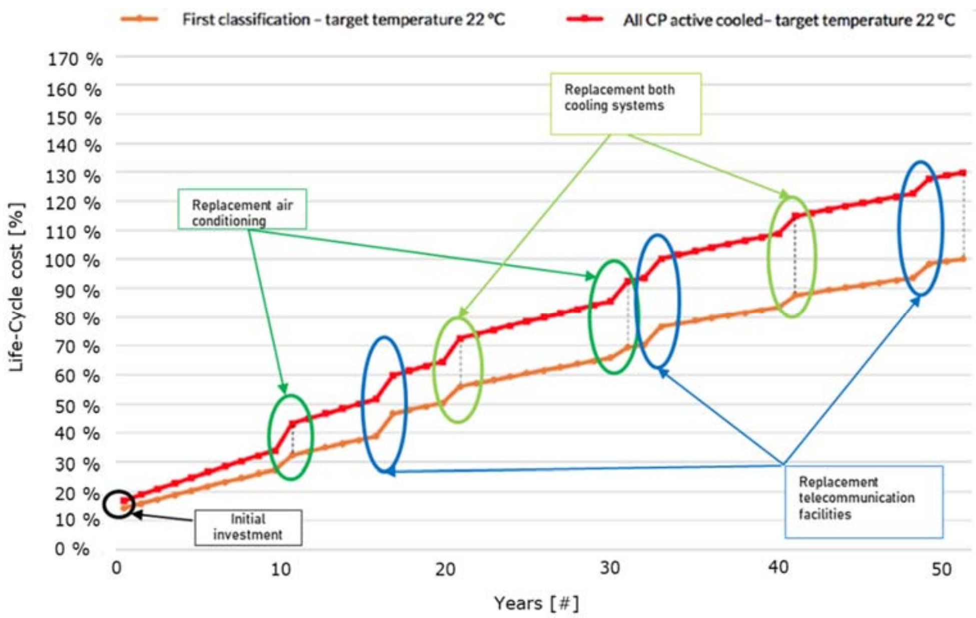

Figure 14: Comparison of life cycle cost for a combination of ventilation and air conditioning and for full equipment with air conditioning units [8]

Therefore, in further simulation runs, the remaining temperature scenarios were evaluated. The higher the room target temperature the smaller the number of cross-passages being equipped with air conditioning systems. Figure 15 shows the cost development and total LCCs of the studied target temperature scenarios. The total LCCs in the 22°C scenario were defined as reference costs (100%). The results show a decreasing trend in total LCCs as the target temperature increases. This trend continues until a target temperature of 30°C is reached. At the end of the 50-year period, the difference between the reference costs and the lowest LCC in the 30°C scenario is about 21 %. A further increase of the target temperature to 35°C leads directly to the highest LCC (107 %) due to increased costs for reinvestments and maintenance.

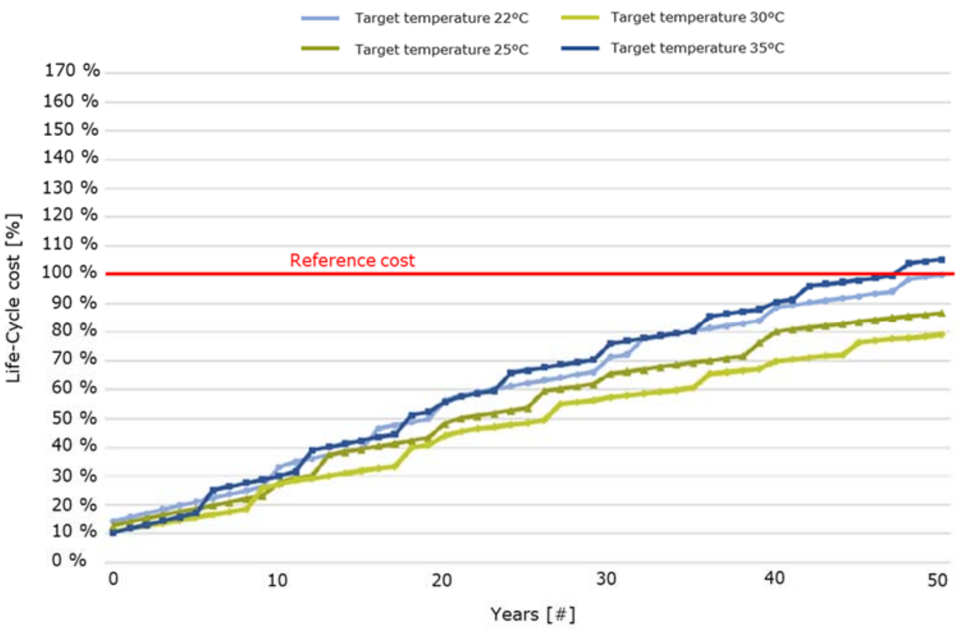

Figure 15: Life-Cycle cost in four selected target temperature scenarios [18]

The accuracy of these results was tested by a dominance analysis and a sensitivity analysis for each temperature scenario. The dominance analysis provided information about the cost elements and their impact on the total life cycle cost. The operation cost (86% of total life cycle costs) dominate over initial investment cost (14%). When examining the total cost for the individual systems, it was found that the cost for TC systems (79.6 %) are dominant and the cost for ventilation systems (15.8 %) and air conditioning systems (4.6 %) are of minor importance.

From an economic point of view, 30°C seems to be the optimal target temperature for the TC rooms. Nevertheless, at the end the 25°C target temperature scenario was recommended with a cross-passage classification similar to Figure 13. The longer lifetime of the equipment (3 years) increases the track availability, and this outweighs the small loss in LCCs (8%) between the 25 and the 30°C scenario. (Remark: the track availability was not considered in the objective LCCA).

4. CONCLUSIONS

This paper contains a model chain applicable for investigating the tunnel climate of very long railroad tunnels as well as the design processes for cooling systems in such tunnels. The derived method consists of four main examination steps that have to be run through one after the other.

As the tunnel climate is specific for each geographical location it must be investigated individually for each tunnel. The first question to be answered is always whether there is a cooling demand (mainly for the technical equipment) in the tunnel under investigation. Conservation equations for energy are the core of the calculation procedure. Since there is a temperature criterion for all electrical systems, the first step it is to be investigated whether external cooling is required in order not to exceed the target temperatures.

In many cases, tunnel air is the only available cooling medium, so there is a dependency on the tunnel climate or thermal conditions regardless of the type of cooling system. Therefore, in the next investigation step a forecast of the tunnel climate is required. For this investigation step important parameters like rock temperature, the outside air conditions (temperature and relative humidity) and the train frequency are needed. It should also be mentioned that the tunnel climate in the first years of operation is strongly influenced by the thermal conditions prevailing during the construction phase. Therefore, these situations have to be taken into account when defining the initial and boundary conditions for the simulation. The derivation of applicable data for outdoor air conditions should be based on long-term measurements in the project area. Depending on the time period to be assessed, long-term effects such as climate change should also be taken into account. Methods based on a 1D simulation of the aerodynamics and thermodynamics of the tunnel have proven to provide the required information about the tunnel climate. The results of this second investigation step can be used for a first statement on which type of cooling system is sufficient to meet the temperature requirements.

However, this statement has only an indicative character, since no 3D effects in the temperature distribution within the individual locations of the electrical equipment are considered. In order to close this information gap, additional 3D CFD simulations should be performed in the third investigation step. The results of these simulations are characterized by a higher accuracy and offer a certain optimization potential with regard to the equipment arrangement and cooling systems to be applied.

At this point, the basic design of cross-passage cooling systems has been completed and technical feasibility has been demonstrated. However, feasibility is only one aspect, the final design must also be cost effective. For this reason, a life cycle cost analysis should be performed for the most relevant systems. Ultimately, the developed method provides the necessary information for a data-based decision on the design of the equipment/cross-passage cooling system in a long railway tunnel.

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