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Success criteria and success factors for the planning and realisiation of underground structures

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SUCCESS CRITERIA AND SUCCESS FACTORS FOR THE PLANNING AND REALISIATION OF UNDERGROUND STRUCTURES

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ABSTRACT: Underground construction is an important branch of infrastructure building in many countries. Underground power generation plants, transport routes, supply and disposal structures are all significant to securing economic prosperity. Society expects such projects to be completed successfully and sustainably.

Success here is predicated on a consensus definition of project success, i.e. agreement on the criteria constituting success. To this end, there first needs to be a comprehensive catalogue of requirements. Rather than being limited to quality, costs and deadlines, said catalogue must encompass ecological and social requirements as well. Moreover and in the interest of direct comparability between projects, success criteria that are specific to the project at hand must be structured according to standardised overarching criteria.

As the project progresses, periodic comparisons are made with the catalogue of requirements; this facilitates controlled intervention should deviations be identified. A project-specific catalogue of requirements is therefore necessary, but insufficient on its own for achieving project success. Attaining that goal requires a conducive environment, implementation of appropriate processes, and putting in place measures designed to avert threats and exploit opportunities.

While project-specific success criteria may be derived from the project's ecological, social and economic environment, the easiest way to derive overarching success criteria is from retrospective analyses of completed and operational projects.

Such analyses show that in the present, as in the past, the human factor matters just as much as the means and methods employed. Human failings are what cause the vast majority of loss events.

Technical innovations, awareness-raising and training are necessary to minimise the impacts of such failings. Yet most important of all is commitment and motivation on the part of all staff working on the project. Organisational models that align the interests of the project owner, designer and contractor help to avoid confrontation. They foster cooperation and thus the commitment and motivation of all project participants.

Developments aimed at further progress are under way everywhere. The coming years will show whether and which successes will materialise. What is needed here are appropriate success criteria and their monitoring by qualified bodies.

1 BASIC CONSIDERATIONS AND TERMS

For centuries, built infrastructure has been satisfying basic human needs such as the supply of essential goods (water, food, energy, etc.), safety, security and social interaction. These basic needs have to be satisfied long-term and effectively. Effectiveness is a function of precise and efficient direction – no unnecessary detours, minimal use of resources, resulting from projects that are fit for the task at hand Figure 1. With this achieved, the project can be described as successful.

In practice, a project objective cannot be reduced to one single goal. Instead, it consists of a **comprehensive catalogue of multiple, phase-dependent subgoals** (see Chapter 2). Throughout a project's entire lifecycle, such a **requirement catalogue** serves the following purposes (see Figure 2):

1. **Clear definition of expected outcomes** to avoid misunderstandings among project stakeholders (ex-ante perspective).
2. **Establishment of clear and measurable criteria** for selecting the optimal solution.
3. **Early identification of opportunities and threats** to facilitate goal achievement or recognise potential obstacles in time (see Figure 3).
4. **Continuous comparison of the current project status** with the defined objectives (**ex-nunc** perspective).
5. **Evaluation of success after each project phase** to gain valuable insights for future projects (**ex-post** perspective).

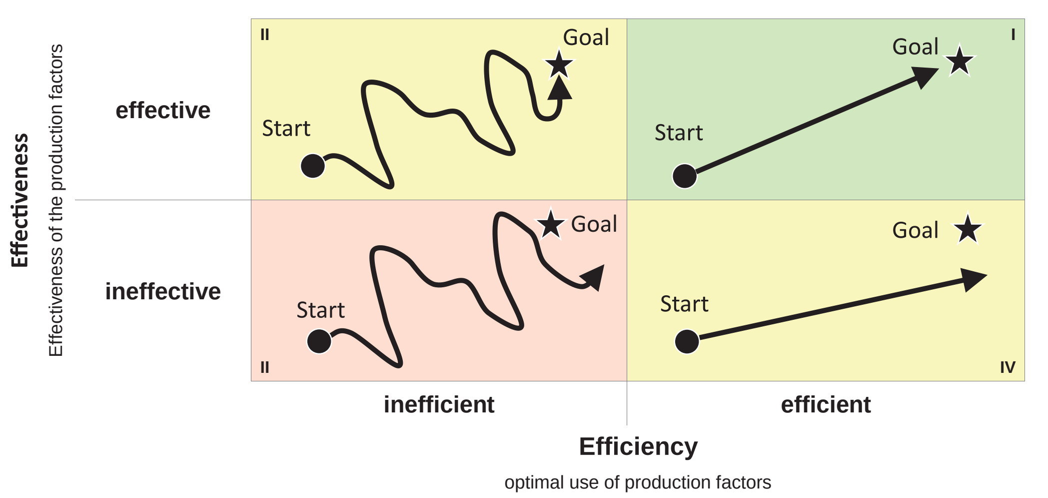


Figure 1 Illustration of the terms 'efficiency' and 'effectiveness' [1]

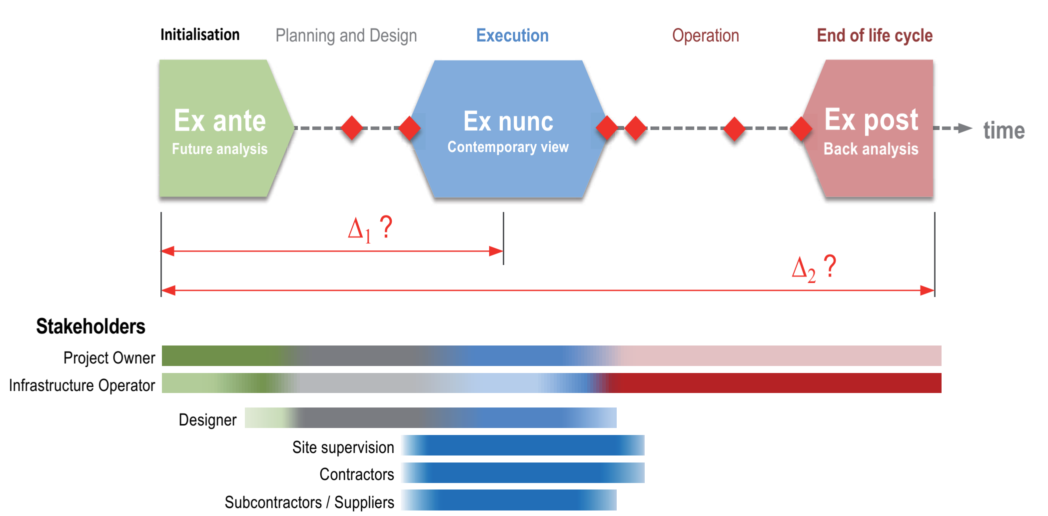


Figure 2 Evaluation of success criteria Over the project lifecycle by key project partners in a design bis build project

The stated purposes can only be achieved if the project goals and success criteria are devised according to the SMART principle. They must be **specific** (clearly defined), **measurable** (quantifiable), **attractive** (motivating), **realistic** (achievable), and **time-bound** (set within a defined timeframe).

The clear definition of project goals according to the SMART principle is a necessary but not a sufficient condition for project success. Sir Michael Latham highlighted in his report "*Constructing the Team*" [2] that no construction project is entirely free of risk. Threats can hinder or even prevent project success, while opportunities can enhance it. This makes it all the more important to identify threats and opportunities early on and to establish targeted measures to manage risks as key factors for project success (see **Figure 3**).

The key terms "success criteria" and "success factors" used in this document are to be understood as follows:

Success criteria are a set of measurable or verifiable requirements that determine when a project can be considered successful. They help to evaluate progress and identify deviations from the requirements as means to ensuring that the established requirements are met.

Success factors are the conditions, processes and measures that contribute significantly to proper fulfilment of a project's requirements. They are what determine whether a project is successful or not.

Success criteria are not static variables. Their evaluation and weighting depend significantly on the phase in which they are assessed, whether during planning, design, construction or operation. Criteria that play a major role in the early phases (e.g., construction costs and schedule) may become less relevant towards the end of a project's lifecycle. Conversely, factors initially given less emphasis (e.g., operational costs, maintainability, and renewability) may gain critical importance over time. Project stakeholders must always be aware of this dynamic and ensure that success criteria for the operational phase are considered from the outset.

The generation responsible for project development must be aware of the shifting importance of success criteria throughout the project's lifecycle.

The generation responsible for project development bears a significant responsibility toward future users and operators and must take their future success criteria into account from the outset.

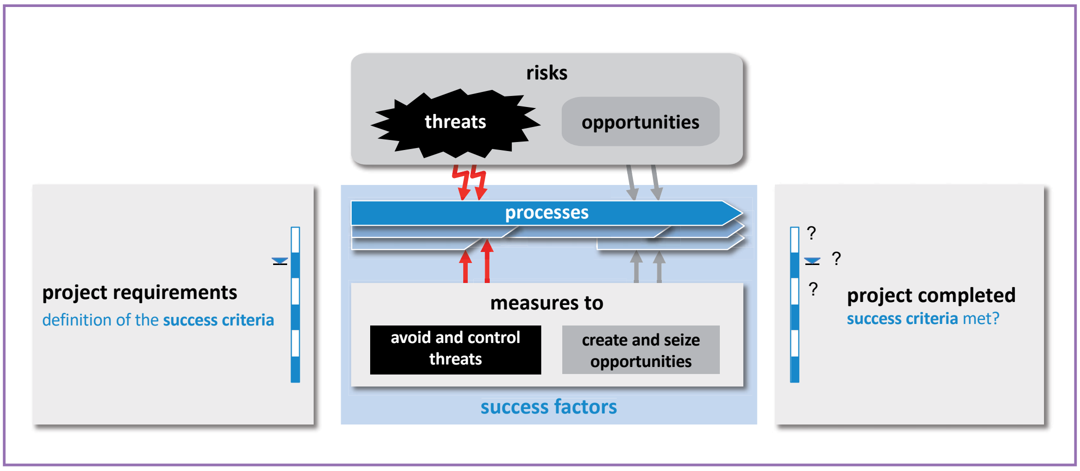


Figure 3 Illustration of terms surrounding project success

2 SUCCESS CRITERIA – DEFINITION AND APPLICATION

2.1 Success Criteria – Type and scope (ex-ante Consideration)

Preceding any formulation of success criteria is the project idea. In deliberations over the building of infrastructure – underground structures are almost always infrastructural – the impetus usually comes from a specific need for transport services, energy supply, water supply or waste disposal.

The needs of users, the society, the environment and of the project owner become subjects of a focused analysis, from which the overarching project requirements are derived. A concrete example here is the need that was identified around 40 years ago to build additional transport capacity for transalpine railway traffic (see 3.2.2).

Based on the identified need, a project concept was developed: the construction of new railway transit routes through the Alps in Austria and Switzerland. Specific project requirements were derived from this concept, such as capacity specifications, operational requirements, geometric parameters, and construction standards. These requirements were refined through different project variants, which were then evaluated using standardized criteria catalogues, ultimately leading to the selection and recommendation of a preferred variant for implementation.

An objective project evaluation, aimed at selecting the best variant, is only possible using uniform and transparent evaluation criteria. In the past, the selection of the preferred option was often based solely on a purely economic cost-benefit analysis.

Today, however, there is a societal expectation to also consider ecological, social, and macroeconomic factors (see **Figure 4**). With long-term projects, the task may be complicated by a certain degree of change in the ecological, social and economic environments over the project lifetime, which must be anticipated through appropriate sensitivity analyses.

While a cost-based commercial assessment rests on clearly quantifiable (monetary) parameters, monetary quantifiability is by no means assured with regard to an extended catalogue of criteria. Although an extended approach does include success criteria that are amenable to objective measurement (e.g. costs, deadlines; occupational safety), there exist other, not so amenable criteria that can only be assessed qualitatively, based on relevant parameters (e.g. social acceptance, quality, organisation and processes, environment). Hence, a distinction between qualitative and quantitative criteria needs to be drawn.

Assessing projects across all criteria requires an assessment system that, in addition to the quantifiable parameters, is also able to capture and consolidate criteria amenable to qualitative assessment only. One approach is to use a points system (see 2.4) and utility analyses.

Various assessment systems exist. Examples include the BREEAM system, Germany's *Standardisierte Bewertung* for rail-based local public transport and DGNB system for buildings, and the SNBS in Switzerland. All of these are highly complex and differ to some degree in their objectives and design. As such, there can be no direct comparison between their results.

The DAUB analysis of 2025 [3] shows that current systems offer few possibilities for mapping baseline conditions specific to underground construction. They are less than adequate at identifying the positive ones, such as avoidance of fragmentation effects, emissions reduction, social impacts in inner-city areas, etc. Those systems' applicability to underground construction is thus limited.

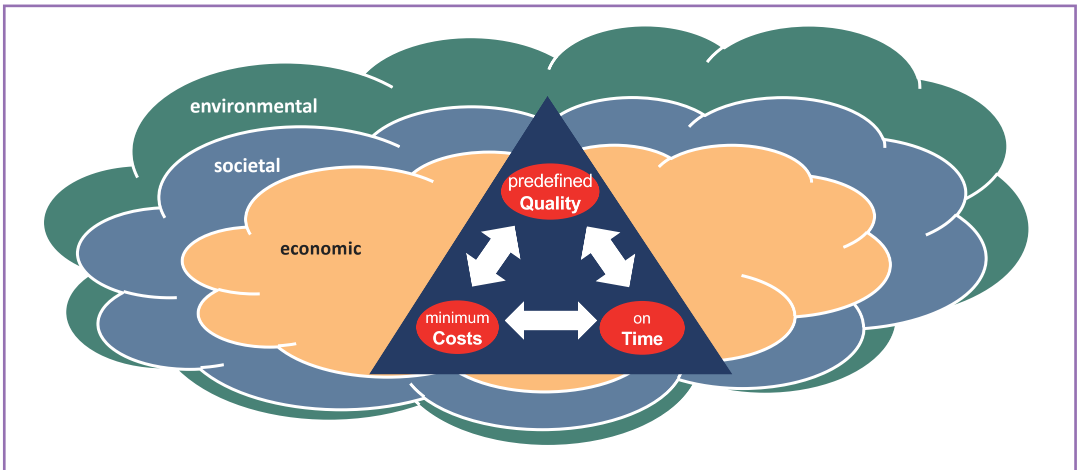


Figure 4 Embedding a project in the ecological, economic and social environment

To ensure a fair evaluation of underground construction projects, existing assessment systems need to be further developed. The goal should be to reflect clearly the specific characteristics of underground construction projects.

As food for thought, **Table A-1** in the appendix contains a catalogue of criteria based on the Swiss SNBS. Weightings for individual criteria are not specified; these are set specifically for the project, with due consideration for the respective baseline conditions.

2.2 Contemplations of the present

As the project progresses, the actual status is regularly compared with the predefined catalogue of success criteria ("ex-nunc" evaluation).

At defined milestones, the relevant success criteria are recorded and documented in the form of standardized key performance indicators (KPIs). Trend analyses of these KPIs, along with updated risk assessments, indicate whether the required target values are likely to be met in the future or if deviations exist or emerge, necessitating corrective measures (see **Figure 3**).

2.3 Retrospective view (ex-post Consideration)

With the commissioning and later the completion of a project's lifecycle, a comprehensive assessment of its success across different phases (planning, construction, operation) becomes possible. However, this evaluation is highly dependent on perspective of the assessor: what the client considers a success at the time of commissioning may be seen as a failure by the contractor – and vice versa (see 4.2.1).

The retrospective ("ex-post") analysis aims to examine deviations (Δ_2, **Figure 2**) and understand their causes. The insights gained from this process are intended to optimise future projects, ensuring a continuous improvement process. Without such a learning mechanism, there is a risk that, despite innovations, progress in developing the state of the art may prove slow or even stagnate (see **Figure 5**).

2.4 Example of an ex-post analysis of several project portfolios

2.4.1 Assessment tool

Several years ago, multiple master's and project theses at ETH Zurich aimed to analyse the success of a significant number of Swiss and German tunnelling projects from the past 40 years. These studies employed a self-defined, simplified catalogue of success criteria. The analysis set out to discover whether such an evaluation system could deliver reliable and verifiable findings.

The ESCHERICH master's thesis [4] defined seven success criteria with associated sub-criteria and assessment parameters (see **Table 1** and **Figure 6**).

A 7-point Likert scale ranging from -3 to +3 was defined for all projects. This allowed directly comparable measurement of quantitative and qualitative evaluation parameters across the entire project portfolio (see **Figure 7**). Complete target achievement was scored at +2. This made it possible, where deemed applicable, to depict target achievements that turned out better than planned (e.g. earlier commissioning, project coming in below the cost target, better-than-expected efficiency). Detailed evaluation criteria were stored in definition tables associated with each sub-criterion.

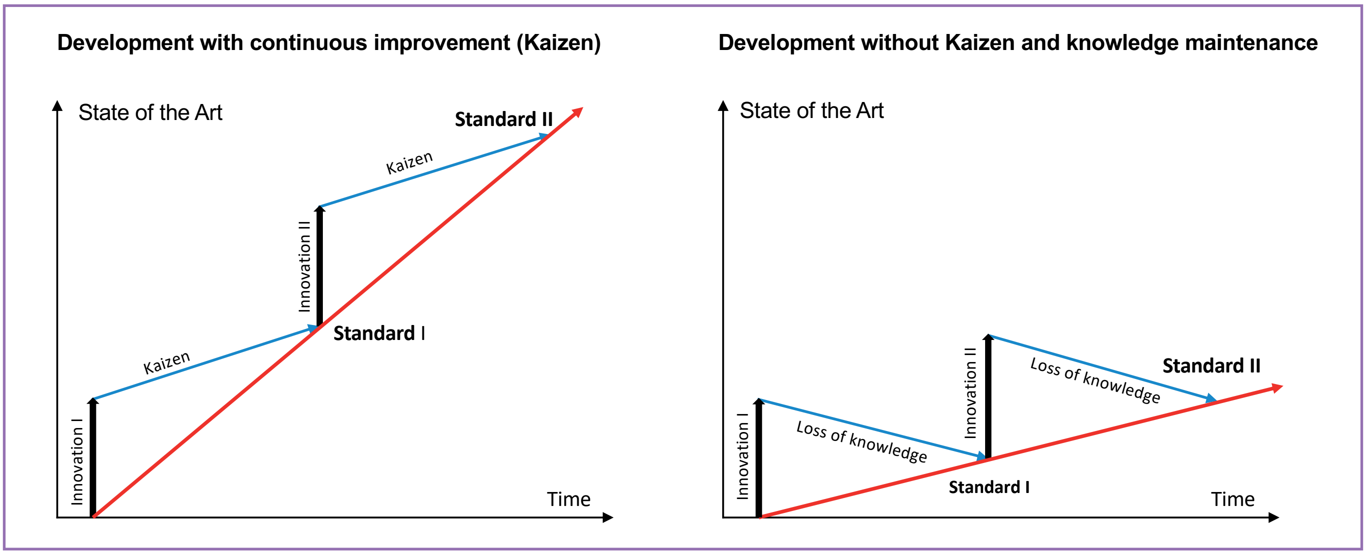


Figure 5 Different approaches to developing the state of art

Table 1 Simplified evaluation system (based on [4])

Range	Criterion	Sub-criterion	Assessment
Ecological aspects	Environment	Environmental compatibility	– Minimisation of dust and pollutant emissions – Minimisation of water consumption – Minimisation of pollutant discharges – No impairment of water quality – Avoidance or minimisation of noise emissions – Assurance of access to property used by third parties – Limitation of surface deformations to a permissible level
		Circular economy	– Type of excavated material and proportion utilised – Waste management concept
		Compensatory measures	– Preservation and nurture of ecosystems – Preservation and nurture of biodiversity
Societal aspects	Social acceptance	Approval/rejection of the project	– Degree and scope of opposition to the project
		Engagement with affected persons/ entities	– Timing and extent of involving those affected – Involvement of the public during the construction period
	Occupational health and safety	Accidents at work	– Number of fatal accidents / accident-related absences
Economic aspects	Quality and functionality	Compliance with the agreed quality	– Operating restrictions due to remedial work
		Maintaining functionality	– Availability, maintainability, safety in operation
	Organisation and processes	Decision management	– Delays ensuing from decisions not taken
		Working in partnership	– Number of disputes – Monetary amount in dispute
	Deadlines	Commissioning date	– Number of months' deviation from the agreed date
	Costs	Deviations from the initial cost budget	– Budget over/underrun in %
		Deviations from the contract amount	– Contract amount over/underrun in %

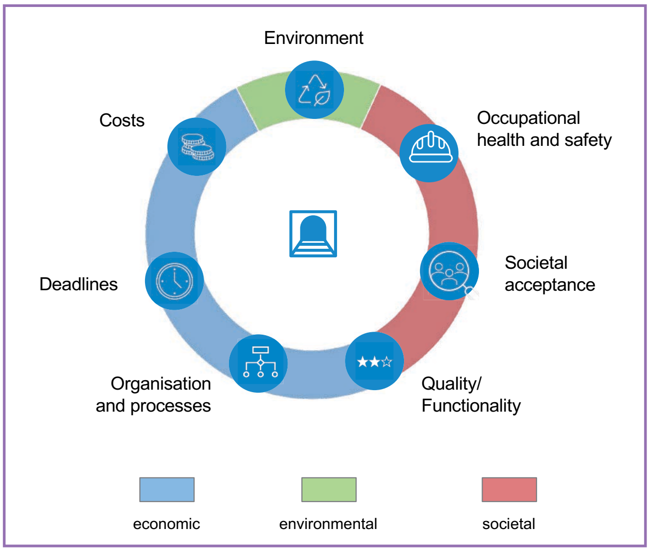


Figure 6 General criteria for evaluating project success [4]

2.4.2 Data situation and methodological challenges

The studies came upon great variances in the amount of data available on particular projects. Well-documented information for the AlpTransit projects continued to be readily accessible, whereas the archives of many other projects proved barely accessible only a few years after project completion – a shortfall that ought to be urgently remedied in the future with the aid of digitisation.

Information gathering therefore necessitate:

- interviews with involved key persons from the construction client, the project engineers, the construction managers, the contractors and the experts,
- all in addition to analysis of publicly available sources.

In result, the data basis is characterised by a certain degree of subjectivity. Looking to the future, it would be necessary for at least public construction clients to monitor and document key data on project develop-

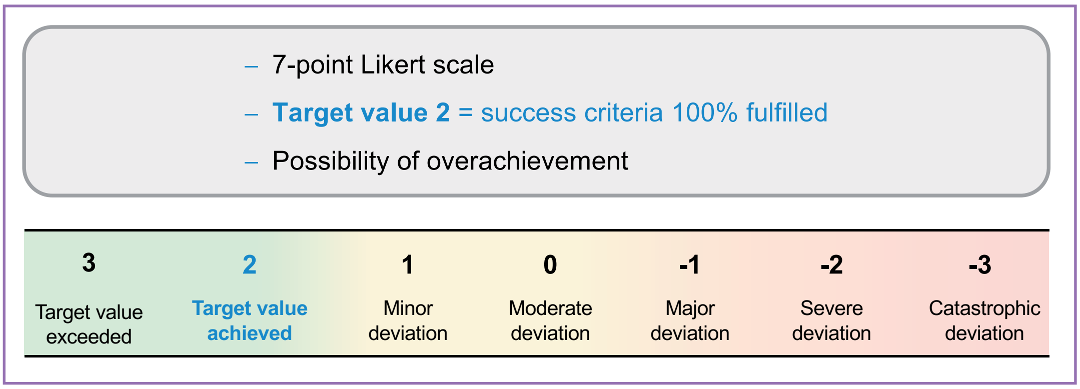


Figure 7 General Likert measurement scale used

ment according to standardised criteria and make that data available to follow-up projects and researchers.

The results obtained were analysed under four categories of consideration:

- by mode of transport (road and rail),
- by development over time (1980–2000 and 2001–2020),
- by style of cooperation (cooperative vs. confrontational),
- by country (Germany and Switzerland).

2.4.3 Development over time in Switzerland since 1980

The radar chart **Figure 8** shows clearly that the past 40 years of Swiss underground construction have seen improvement in the fulfilment of most success criteria, excepting only a mildly negative trend in the "organisation and processes" success criterion. This finding corresponds with the subjective perception in many projects that construction has grown in complexity. The "cost compliance" criterion displays barely any change, while "compliance with deadlines" shows slight improvements.

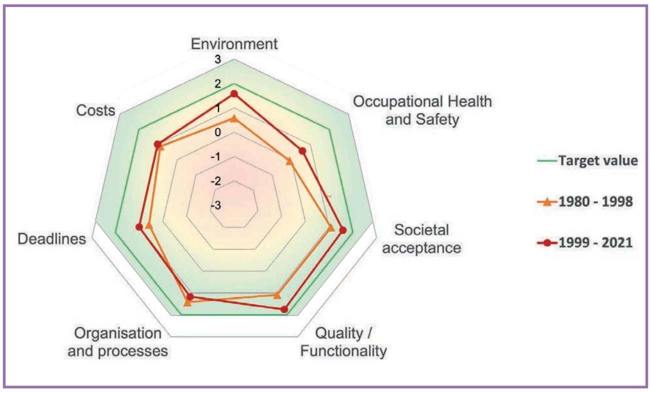


Figure 8 Fulfilment of success criteria in Swiss underground construction since 1980 [5]

2.4.4 Style of cooperation

All Swiss projects from 1980–1921 are considered here. **Figure 9** clearly shows that confrontational project management leads to major deviations from targets in the "organisation and processes", "costs" and "deadlines" criteria. However, this statement brings no clarity to the chicken-and-egg question of whether it is emerging deadline and cost deviations that lead to confrontation, or whether a confrontational approach the root cause of failure to achieve deadline and cost targets.

That being said, confrontational project management barely affects other success criteria such as "occupational safety", "environment", "acceptance" and "quality". Indeed this must be the case, as disputes over economic success are not to be fought at the expense of third parties.

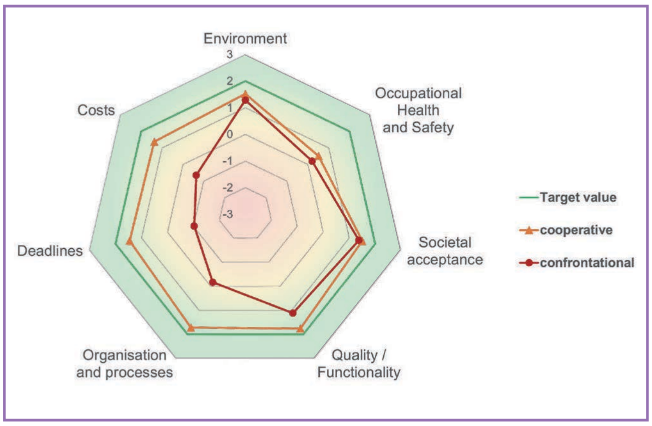


Figure 9 Influence of the quality of cooperation on the success of the project

2.4.5 Comparative analysis of Germany and Switzerland

The analysis of 25 German tunnelling projects using the same evaluation system allowed drawing a direct comparison between the two countries (see **Figure 10**).

This comparison shows that the German projects perform slightly worse than the Swiss projects in terms of met costs and deadlines, a finding concurred with by the German media. [6]

Conversely, occupational health and safety requirements in Swiss underground construction are significantly less well met than in Germany for the period under review. This statement is also consistent with the perception of companies and individuals working in both countries. The Swiss construction industry came to the same realisation at the same time, precipitating a general campaign to promote occupational safety that was launched in concert with the responsible supervisory agency. [7]

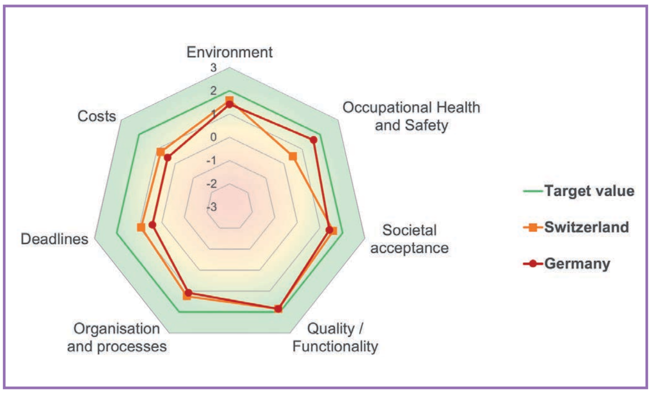


Figure 10 Comparison of the fulfilment of success criteria for Swiss and German tunnelling projects [4]

2.4.6 Comparison with historical projects

This raises the question of whether such an evaluation system can also be applied over a longer span than the 40 years considered by the aforementioned study. Given that in only a few cases were absolute values used as a criterion in the evaluation scales and that relative deviations are applied otherwise, it feels natural to extend the period under consideration to include historical projects. This was undertaken by the author of this paper in respect of five individual cases. The projects analysed in a sample taken from the period 1882 to 1916 are briefly described in the appendix (**Table A-2**).

Although the environmental and occupational safety standards of that time were significantly lower, only a uniform evaluation scale allows for meaningful comparisons. The results (see **Figure 11**) using current criteria show:

- Significant progress over the last 140 years, especially in the areas of occupational safety, environmental protection and organisation and processes,
- Modest improvements in cost adherence, schedule adherence, public opinion, and quality/functionality.

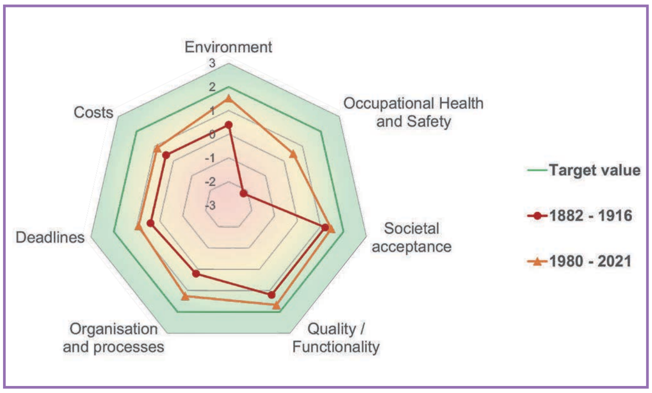


Figure 11 Comparisons of the fulfilment of the success criteria for historical and modern tunnelling projects

2.4.7 Conclusions and recommendations

From the above considerations, it can be concluded that a purely qualitative evaluation system with a modest catalogue of success criteria leads to reasonable results and valuable indicators of where action is needed.

Concerning such action, the ESCHERICH master's thesis derived the following overarching recommendations:

- Continuation and intensification of measures to improve occupational safety
- Strict consideration of risks
- Fostering of partnership-based cooperation
- Focus on meeting cost and deadline targets
- Learning from the experience of previous projects
- Not allowing successes to feed complacency that risks reversing positive trends
- Monitoring negative trends and initiating countermeasures
- Even-handed consideration of all success criteria when comparing projects/portfolios

The implementation of these recommendations depends on specific success factors. Chapter 4 examines the conditions and processes under which this can be realised.

But first it is necessary to clarify what are the baseline conditions to be fulfilled in a large infrastructure project if it is to be realised at all.

3 IMPORTANT PROJECT FRAMEWORK CONDITIONS

3.1 Hypotheses on key framework conditions

Figure 4 shows how projects are embedded in an ecological, social and economic setting. For a project to have any chance of realisation, there are overarching conditions to be met as success factors in those respective settings.

For example, the ground in which construction is envisaged must be suited to a structurally feasible project at an economically justifiable cost. Then again, without social and political acceptance and without the availability of resources – material, human and financial – nothing can be realised.

The social and economic environment often raises high hurdles to creating sufficient acceptance, especially considering the large number of stakeholders. To overcome these hurdles and get a project off to a successful start, at least the following conditions must be met:

- Stable political environment
- Availability of early, stable financing
- Early involvement of those affected and their participation to create acceptance
- Willingness to seek compromises and room for manoeuvre in reaching them

These four hypotheses will be verified below on the basis of two typical case studies drawn from a set of many similar cases.

3.2 Plausibility check of the hypotheses put forward

3.2.1 Stable political framework and stable financing at an early stage

There are many projects that demonstrate the importance of the political environment and stable financing at an early stage. The example used here is the dispute between the Lukmanier Railway and Gotthard Railway variants for Switzerland's first transalpine rail route.

Modern Switzerland emerged as a federal state from the former confederation of states in 1848. Seven neighbouring monarchies surrounded it. To the south lay the Kingdom of Lombardy-Veneto, which belonged to Austria, while the Kingdom of Sardinia to the west was allied with France (see **Figure 12**).

The newly-fledged Swiss federal government immediately addressed the issue of systematically developing a national railway network. To this end, it commissioned the English experts R. Stephenson and H. Swinburne with a report, which they delivered in October 1850. [8] In it, they advised against constructing a railway across the Alps, as it would primarily only benefit neighbouring countries. Yet if an Alpine railway were to be built through Switzerland, it should be routed over the Lukmanier, as this would not require a long tunnel. No prior experience of such a tunnel existed at that time.

In 1852, the Swiss parliament decided that railway construction was the responsibility of the cantons and the private sector. This gave opportunity for rapid realisation of the existing project for a Lukmanier Railway. 1853 saw the granting of a concession to build the railway and the signing of a state treaty on its construction between the cantons concerned and the Kingdom of Sardinia. Work on building the first access routes began immediately – and then soon came to a standstill because of insufficient funding.

Under the terms of the concession, proof of financing for the entire project had to be provided within two years. Despite an extension to the concession period, this proof was not initially forthcoming. In 1859, Italy having won its second war of independence against Austria, the Kingdom of Sardinia agreed to contribute substantially to the construction costs, subject to solid Swiss co-financing and the deposit of a financial guarantee. This arrived in Turin two days past deadline in 1861 and was no longer accepted by Italy. [9]

Under these circumstances, the Gotthard Committee, founded back in 1853, launched a massive push for its own project and lobbied in Turin. With this new situation, the window of opportunity for the Lukmanier railway began closing and never reopened.

The creation of the Kingdom of Italy in 1861 brought ever-greater need for a direct transalpine railway link.

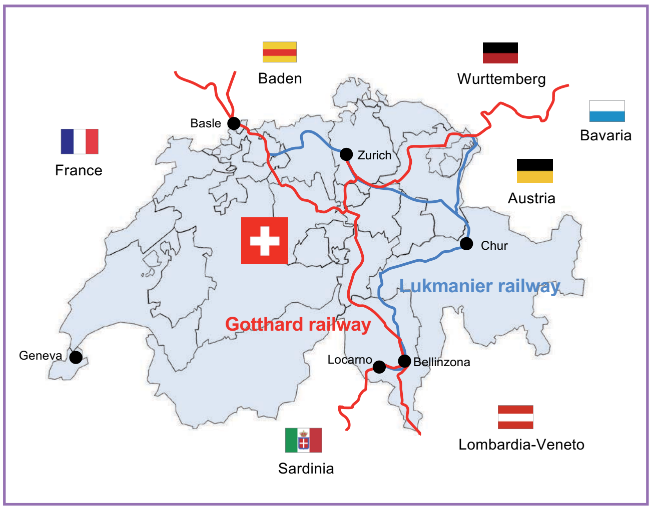


Figure 12 Political environment from 1848 to 1861 when the decision was made on the route of the railway across the Swiss Alps

In 1866, the Italian parliament decided in favour of the Gotthard project.

A state treaty between Italy, the North German Confederation, the Grand Duchy of Baden and Switzerland for the construction of the Gotthard railway was concluded in 1869. The financing agreement stipulated construction capital totalling 187 million francs, of which Italy was to contribute 45 million and Germany and Switzerland 20 million each. The remaining 102 million would have to be raised privately on the stock and bond markets. [10] The Gotthard railway was built between 1872 and 1881 and began operation in 1882.

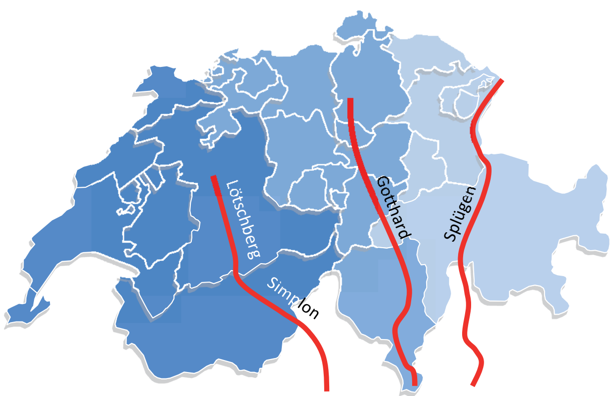
Insights:

- Changes in the political environment influence a project's chances of success.
- Success is contingent on early and comprehensive financing.

3.2.2 Early involvement of those affected and willingness to compromise

This hypothesis also needs substantiating with a suitable case study. This one concerns the choice of variants for the new transalpine railway through Switzerland.

1980 saw the opening of the Gotthard road tunnel. Europe's increasing economic integration led to a far greater than expected rise in lorry traffic through the tunnel, and in transalpine transit traffic generally. It would be necessary to shift future growth in goods transit traffic from road to rail.



	Lötschberg – Simplon	Gotthard plus Lötschberg – Simplon	Gotthard only	Splügen
Number of cantons	7	7 + 8	13	6
Share of the population	38 %	38 % + 33 %	49 %	13 %
Approval in 1992 referendum		63.3 %		

Figure 13 Variant decision with the involvement of those affected

In light of the failed Lukmanier Railway (see 3.2.1), there was strong entreaty in eastern Switzerland for a railway connection, this time under the Splügen Pass.

The federal government set up a contact group with the affected cantons of eastern Switzerland, which came to the realisation that the problem of increasing transit traffic through the Alps could only be solved by international agreement. The ensuing consultations with Germany, Austria and Italy led to the 1989 recommendation to build two new railway lines through the Alps: one at the Brenner Pass and one through Switzerland, but without making any statement on the route of the latter. [11]

Deciding on the route thus became a national issue, with a national process for choosing the preferred option. A survey of all the cantons made it clear that only a network solution involving construction of the Gotthard and Lötschberg-Simplon axis had majority support (see **Figure 13**).

The network variant was approved in a 1992 referendum, with 63.3 % voting in favour. Early involvement of all those affected and willingness to seek compromises had proved its worth.

Early involvement of those affected makes particularly good sense when there is a corresponding willingness to compromise and if the people involved are given the necessary room for manoeuvre to reach compromises. Willingness to compromise can be encouraged through clear communication of the project's benefits to those affected, thus making them participants in the project.

"Goods on the rails" was the slogan that effectively communicated the benefit of the AlpTransit project to the broad population. Other projects have fared worse in this respect; a 'NIMBY' (Not In My Back Yard) mentality may take hold and obstruct compromise. The results: long delays, protracted legal proceedings and in extreme cases, cancellation of the project.

Examples of such patterns can be found in many places. This is also affecting construction of the access routes in Germany to the base tunnels on the Brenner Pass, as well as in Switzerland. The access routes to the Swiss base tunnels are now more than 20 years behind the schedule envisaged by the intergovernmental agreement of 1996 [12], with the effect that already-built infrastructure cannot be utilised to the extent planned. [13] It cannot be ruled out that similar scenarios will follow at the Brenner Pass.

Insights:

- Early involvement of those affected bears positively on project success.
- Without the willingness to compromise, no project can be realised.

4 KEY FACTORS FOR PROJECT SUCCESS

4.1 Hypotheses on the key success factors

For successful implementation of the recommendations for action set out at the end of chapter 2.4 it is necessary to implement appropriate measures as success factors. These are best derived from ex post analysis of projects with a long operating track record. This is why the projects analysed below have all been going for over 100 years.

Based on observation of many projects, the following hypotheses can be formulated as key factors for project success:

1. **Respect for the task and the project partners**
2. **The right people in the right place at the right time**
   - Committed project team with high professional and social competence
   - Leadership with clear objectives and character
3. **Appropriate corporate and project culture**
   - Solution-oriented culture of cooperation that learns from mistakes rather than apportioning blame
   - Partnership-based cooperation with all project participants
4. **Diligent project preparation and implementation**
   - Clear formulation of project requirements aligned with the entire life cycle
   - Optimal forms of organisation and clear processes
   - Careful project planning
   - Consistent quality and risk management, incl. systematic dual control principle
   - Selection and application of the most suitable means and methods

4.2 Plausibility check of the hypotheses put forward

4.2.1 Respect for the task and the project partners

There are hardly any examples of underground construction known to the author where the **task** was **approached with insufficient** respect. Project managers usually know the challenges of underground construction from the outset.

The beginnings of the 15.3 km long Furka Base Tunnel in Switzerland, which was built between 1973 and 1982, could be cited as a rare example of poor management due to inadequate project organisation during the initial phases. Critical issues were not investigated. [14], [15] The project ended with delays and a cost overrun of around 300 % (disregarding inflation). [16]

A worthwhile example of **lack of personal respect** concerns the construction of the 14.9 km long Gotthard railway tunnel. Louis Favre was the sole contractor commissioned to build the tunnel, on the basis of having submitted the cheapest and most favourable bid. The contract was extremely one-sided. Favre accepted the contractual clause making him personally liable for the expense and risk of such unforeseeable difficulties **"***as may arise during the completion of the work as a result of the nature of the rock or the rock mass in general, as a result of unusually strong water ingress, as a result of natural disasters* ***or for similar reasons of any kind.***" [17]

The commercial terms (bonus/penalty, fulfilment guarantee) were extremely harsh.

That same contract also gave the project owner a large say in the deployment of personnel and equipment, as well as decision rights on the type of vault lining. Not all of the construction client's promises were met and instructions on the type and method of vault lining were sometimes delayed.

The construction process was marked by considerable technical and geological problems, repeated disputes with the financiers and the construction management of the Gotthard Railway Company, some of which went to court, and a strike by tunnel workers in 1875 that was bloodily suppressed by the local authorities.

The tunnel went into operation on 1 January 1882, 14½ months late. Actually, this was an extraordinarily good performance given the extremely difficult construction circumstances. [10] Although the costs exceeded the contract sum by 39.5 %, they exceeded the construction client's original budget by only 11.1 %. Nevertheless, Favre was blamed as the main culprit for the enormous cost increases of the overall project, even though the primary cause of these was the construction of the access routes, which were outside his area of responsibility.

Louis Favre died in July 1879, around 7 months before the tunnel breakthrough. His heirs bore the full brunt of the harsh contract. Yet Louis Favre's daughter and heiress lost her entire fortune. Only a pension from the project owner enabled her to maintain a reasonable lifestyle and avoid total poverty.

The tunnel was very successful in operation. Indeed, it was the cash cow of the Swiss Federal Railways until the opening of the Gotthard road tunnel. [18]

Insights:

- From today's perspective, the Gothard Railway Company's treatment of the entrepreneur Favre can be described as unfair and lacking in respect.
- Such times should be over.

4.2.2 The right people in the right place at the right time

The Simplon I Tunnel makes a good example of a project being influenced by bringing in the right people at the right moment. Ideas for a tunnel on the Simplon already existed at the time it was decided to build the Gotthard railway. In 1893, a contract was signed for the construction of the 19.8 km long Simplon Tunnel. This was the first base tunnel through the Alps and for a long time the longest railway tunnel in the world.

For financial and logistical reasons, the 1893 project specification envisaged full excavation of only the first tube to begin with. The second tube would be driven as a smaller exploratory tunnel and only after commissioning of the first tube would the second be widened into a fully-built operating tube (see **Figure 14**). [19]

In 1894, the Swiss Federal Council commissioned an expert report on the 1893 project. The experts Colombo (Milan), Fox (London) and Wagner (Vienna) submitted their report that same year. It included immense foresight where future operation of the tunnel was concerned. Sir Douglas Fox was familiar with the negative experiences of operating tunnels with steam locomotives [20] and played a key role in the construction of the City and South London Railway, which is considered the first electric underground railway. Professor Colombo was instrumental to the introduction of electric power in Italy. The experts therefore recommended that the project consider the emerging technology of electric traction. [21] The recommendation was immediately accepted and implemented. Tunnel operation was all-electric from 1906 onward (see **Figure 15**).

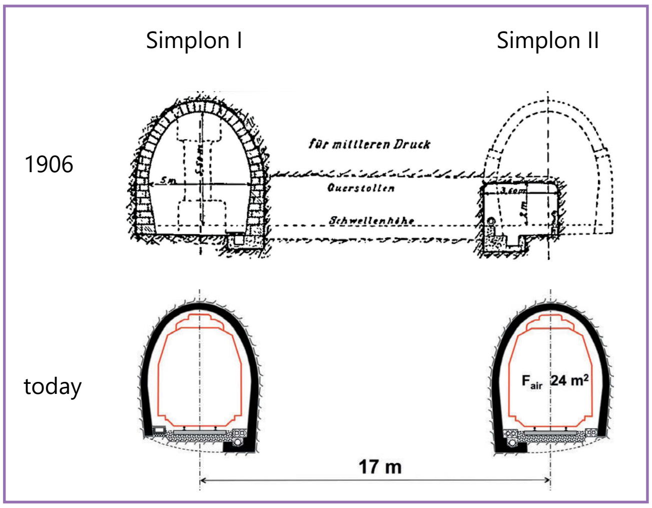


Figure 14 Transverse profile of the Simplon Tunnel when it was commissioned with only the side tunnel (1906) and as a fully-built twin-tube system from 1922 onwards

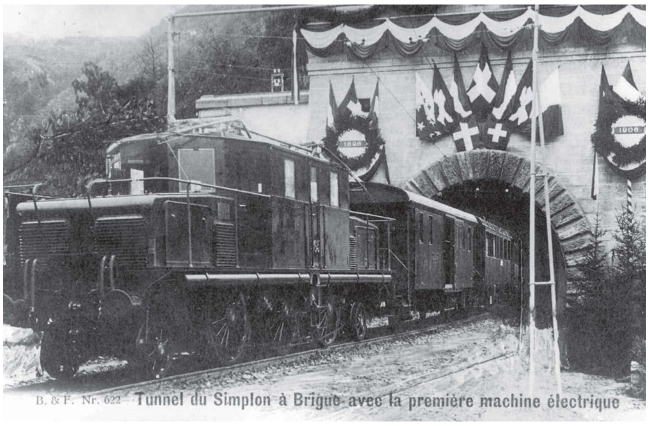


Figure 15 The north portal of the Simplon Tunnel at its ceremonial opening in 1906 (source: Keystone-sda)

Similar experiences regarding well-timed influence from the right individuals are also evident from the construction of the Gotthard railway. Its route with helical tunnels rather than inclined planes is likewise attributable to the timely involvement of highly qualified experts.

Insight:

- Having the right people on board at the right time can significantly increase the success of a project.

4.2.3 Appropriate corporate and project culture

The construction of the Gotthard road tunnel can serve as a model for the importance of the right corporate and project culture. From 1970 to 1980, there were two different organisations completing directly comparable tasks for the construction of the 16.9 km long tunnel, the longest road tunnel in the world at that time.

Although the federal government was by far the largest source of funding, back then the cantons were still responsible for highway construction. Two consortia of contractors worked on the north and south sides respectively. Both tunnel drives involved overcoming difficult construction zones: Mesozoic rock on the north side and paragneiss rock on the south side (**see Figure 16**).

On the north side, the correct methodology was determined in part empirically [22], which led to considerable time losses (see **Figure 17** left). The project owner also publicly doubted [23] the correctness of the

Figure 16 Squeezing paragneiss zone in the south (photo W. Scheidegger)

contractor's means and methods, leading to tensions and recriminations between the project owner and the contractor on the north side. The resulting unresolved contractual problems placed the contractor in serious difficulties which, without the intervention of the Swiss Federal Council, would very likely have caused the lead contractor to declare insolvency. [18]

On the south side, measures necessary to mastering the structurally difficult stretches were determined in consultation with the construction client. Solutions to emerging compensation issues were quickly found.

In retrospect, project participants noted that while there were disputes on the north side, problems on the south side were resolved amicably. [18]

Insights:

- Confrontation hinders project success, whereas cooperation promotes it.
- The project culture is decisive for the success of all involved.

4.2.4 Diligent project preparation and implementation

Project requirements aligned with the entire life cycle
Construction of the 14.6 km long Lötschberg tunnel was necessary to connect the Swiss capital Bern with Valais and with Italy via the Simplon. It was built between 1906 and 1913, under sometimes difficult conditions.

The project for the access railway lines envisaged single-track operation only. With a view to the entire service life of the undertaking and with construction work already underway, the Swiss federal government demanded in 1908 that the ramp sections be designed for dual-track operation. [25] Following intensive negotiations with the contractors, the tunnel sections and the bridge abutments were then designed for dual-track (see **Figure 18**).

In this sense, the early 20th century generation of political decisionmakers thought big with regard to future requirements. They defined the project objectives with the entire life cycle in mind, a requirement that is still important today.

Moving ahead 90 years or so, we encounter a generation of political decisionmakers that was no longer so cognisant of its responsibility to future generations. During the construction of the 34.6 km Lötschberg

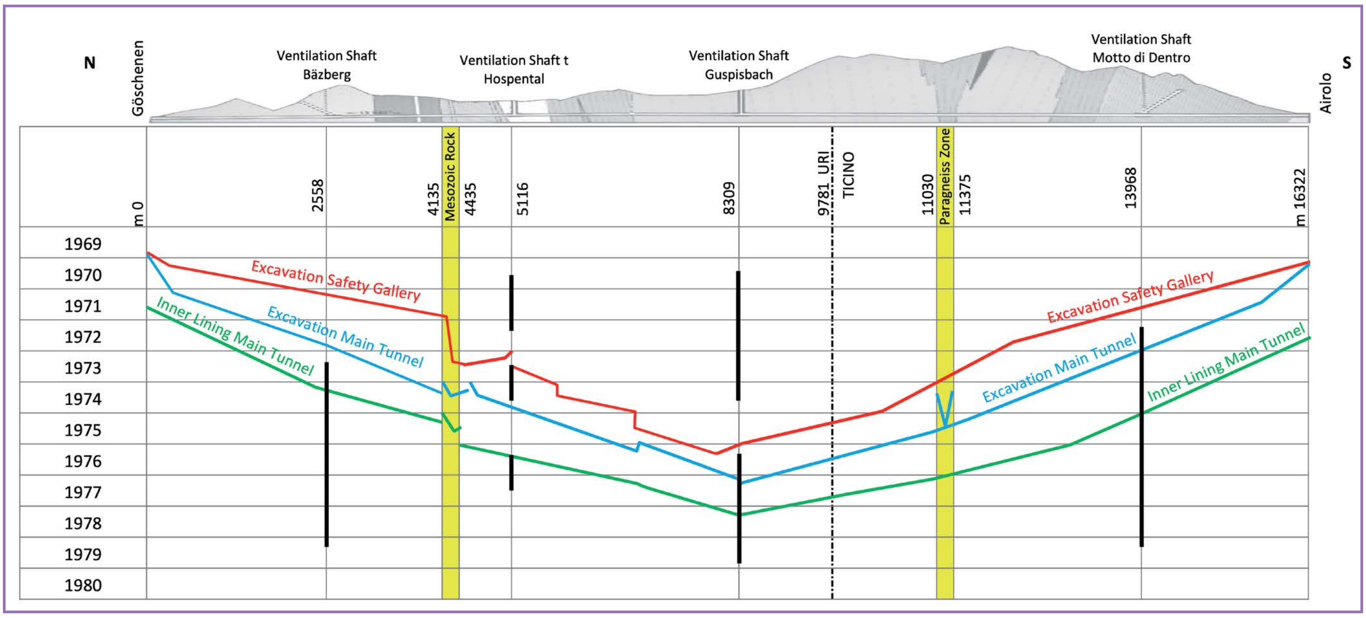


Figure 17 Gotthard road tunnel construction schedule [24]

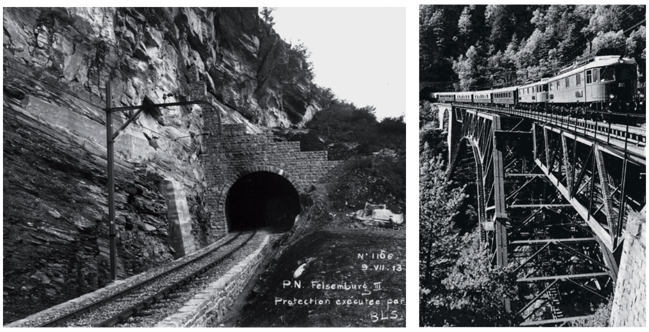


Figure 18 left: Dual-track tunnel excavated on the formerly single-track Lötschberg line(source: BLS)
right: Bietschtal Bridge before 1980, main arch already designed for two-lane operation [26]

Base Tunnel (1996–2007), financial constraints and political considerations led to the decision not to excavate the 7.5 km section between Frutigen and Mitholz (see **Figure 19**). For a dual-track extension to be possible in the future, this bottleneck will have to be remedied over the next few years at much higher cost and under more difficult conditions.

Insight:

- Formulating project requirements with an eye to the future is decisive to the functionality of a project over its entire service life.

Consistent quality and risk management

We stay with the construction of the Lötschberg tunnel (1906–1913) as an example of dealing with risks. It was known in project circles that the tunnel would pass under the Gasterntal valley at a depth of 175 metres.

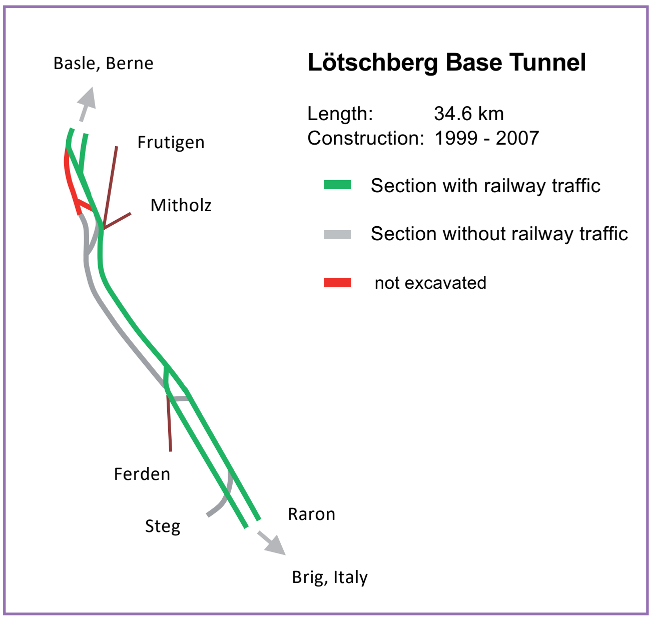


Figure 19 Tunnel system of the Lötschberg Base Tunnel (source: BLS AT)

Whether the loose material exposed at surface level would continue all the way down to the tunnel was a matter of debate among the geologists (see **Figure 20**).

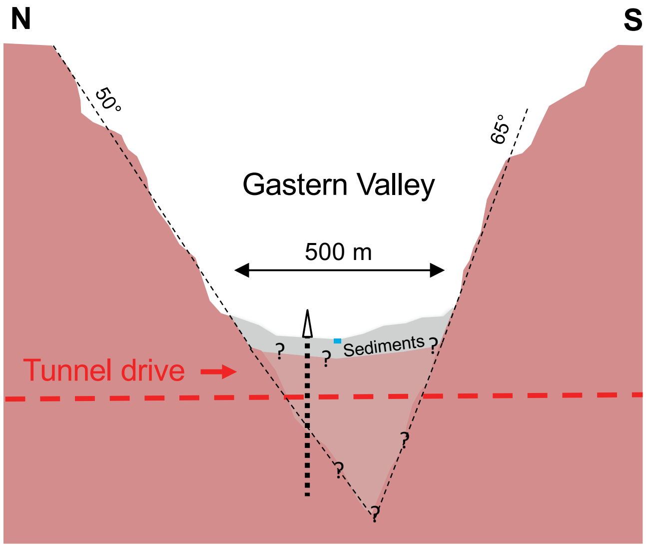


Figure 20 Lötschberg Tunnel Geological uncertainties below the Gastern Valley

The independent geologist commissioned by the chief engineer to report on water sources and geological conditions at the two tunnel entrances stated in his report in November 1906 [27]:

*"**I believe that the alluvial formations, ground moraine, valley fillings and embankments go deeper** than the expert profile suggests. However, whether they are present to a depth of 200 metres can only be assumed if the formation of the glacial till is attributed to glacial erosion. Expert opinion on this still differs widely. Should the alluvium (ground moraine, gravel and sand layers) reach that deep, it would be present through a tunnel stretch of 100 metres and more. **Such ground is not favourable for tunnel construction; however, it does not represent an absolute obstacle...**"*

At the end of 1906 there was already a clearly formulated potential hazard from a deep-penetrating trough of loose material, but the possible impacts were underestimated. Whether there were prior exploratory bores and whether these reached sufficiently deep [28] cannot be conclusively determined on the basis of documents that are publicly available today (see **Figure 21**). However, it is reasonable to assume that those responsible would have chosen a different route if an early borehole had already shown in 1906 that the Gasterntal valley was filled with gravel, sand and water all the way down to tunnel level. [28] As it was, not drilling such a borehole, or not drilling to a sufficient depth, would bring extremely serious consequences.

Figure 21 Drilling tower in Gasterntal (1906 (?)/1908) (Krebser Historical Collection 111/15)

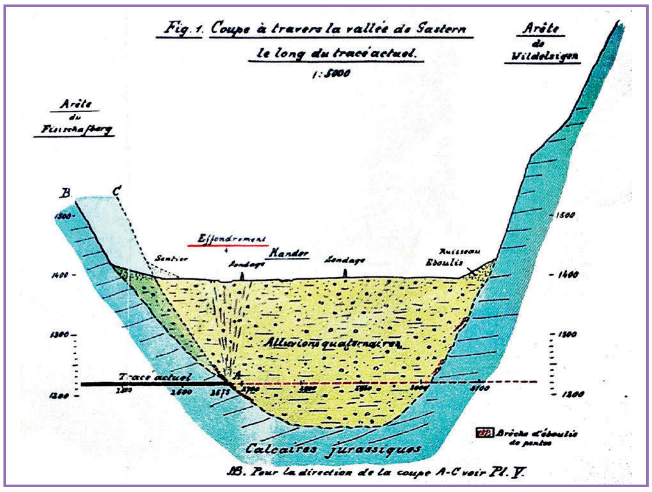


Figure 22 Diagram of the collapse below the Gastern valley [30]

On 23 July 1908, blasting took place 2.675 km into the tunnel (see **Figure 22**). Around 7’000 m^3 of sand and gravel mixed with water immediately gushed in, completely flooding the first 1.5 kilometres of the tunnel and killing all 25 workers. As a result of this collapse, the loose material trough of the Gastern Valley had to be bypassed using a new route. [29]

Avoiding such events requires a rigorously implemented risk management process (see **Figure 35**). It should also be noted that misjudgement of risks by persons involved in the construction industry is not the exception, but rather the main cause of damage events (see **Figure 23**), as a scientific study by ETH Zurich shows. [31] Most damage events come as the result of human failings.

Insights:

- Rigorous risk management is essential to project success.
- The “Four-Eyes Principle” is to be consistently implemented.
- Humans remain the weakest link in the chain.

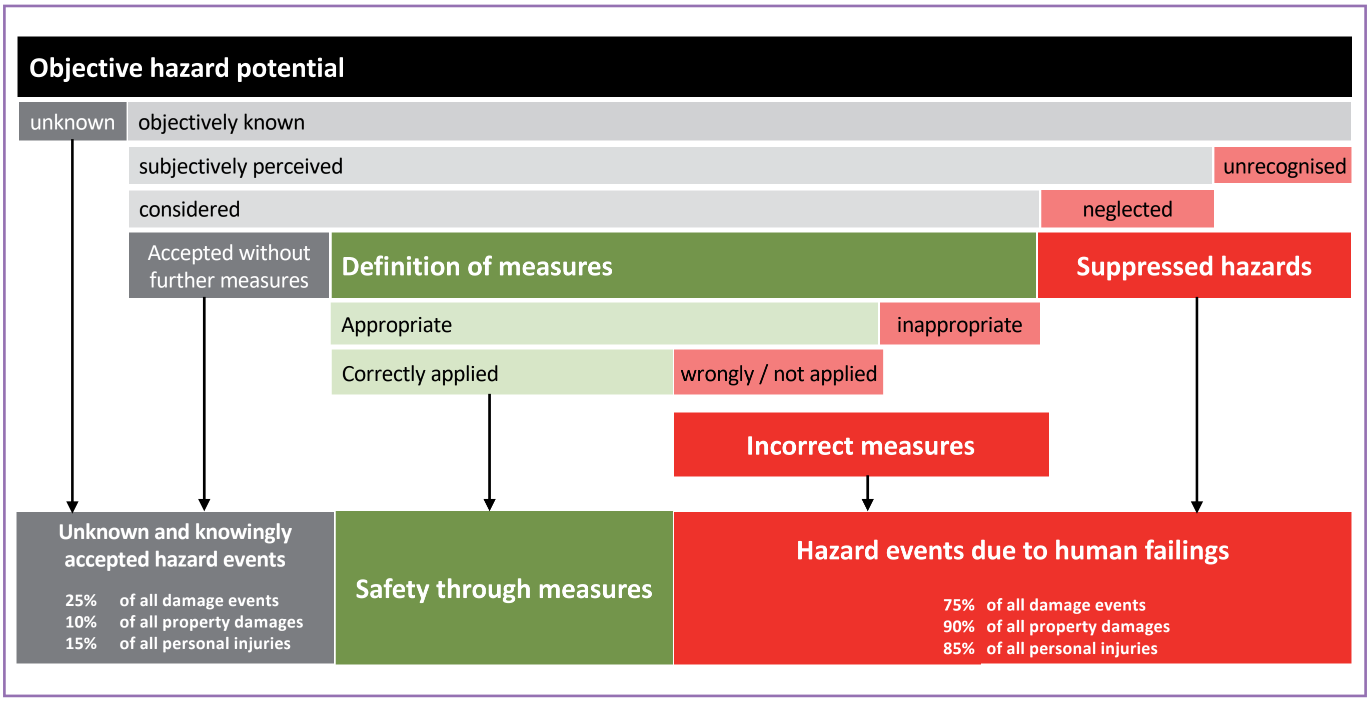


Figure 23 Causes of loss events as a result of human failings (based on [30])

Careful project planning

Geotechnical investigation is of central importance to project success in underground construction. The Simplon Tunnel mentioned in 4.2.2 is an example of where this did not function optimally.

Subsoil profiling for the first base tunnel through the Alps, with a maximum overburden of over 2,000 metres, was a major challenge in itself. Between 1878 and 1890, *"no more than a few weeks of work in the field were expended"* on preliminary geological investigations. [32] Actual tunnelling then revealed significant surprises.

The ground did not match predictions (see **Figure 24**, top); neither did the amount of water ingress or the expected rock temperatures – the project assumed a maximum temperature of 40 °C, but the actual temperature was 55 °C. The different ground conditions encountered resulted in delays and cost overruns due to adjustments needed in the construction processes.

A storm broke over the geologists; people in authority decried their predictions as a debacle. [31] Yet the fact was that they had to issue a prediction of ground conditions using scant resources and by methodologically inadequate means. Responsibility for this lies not only with the geologists, but with the project owner as well.

This example clearly shows the importance of diligent project ground investigations.

Insight:

- Diligent and sufficient project planning work is essential.

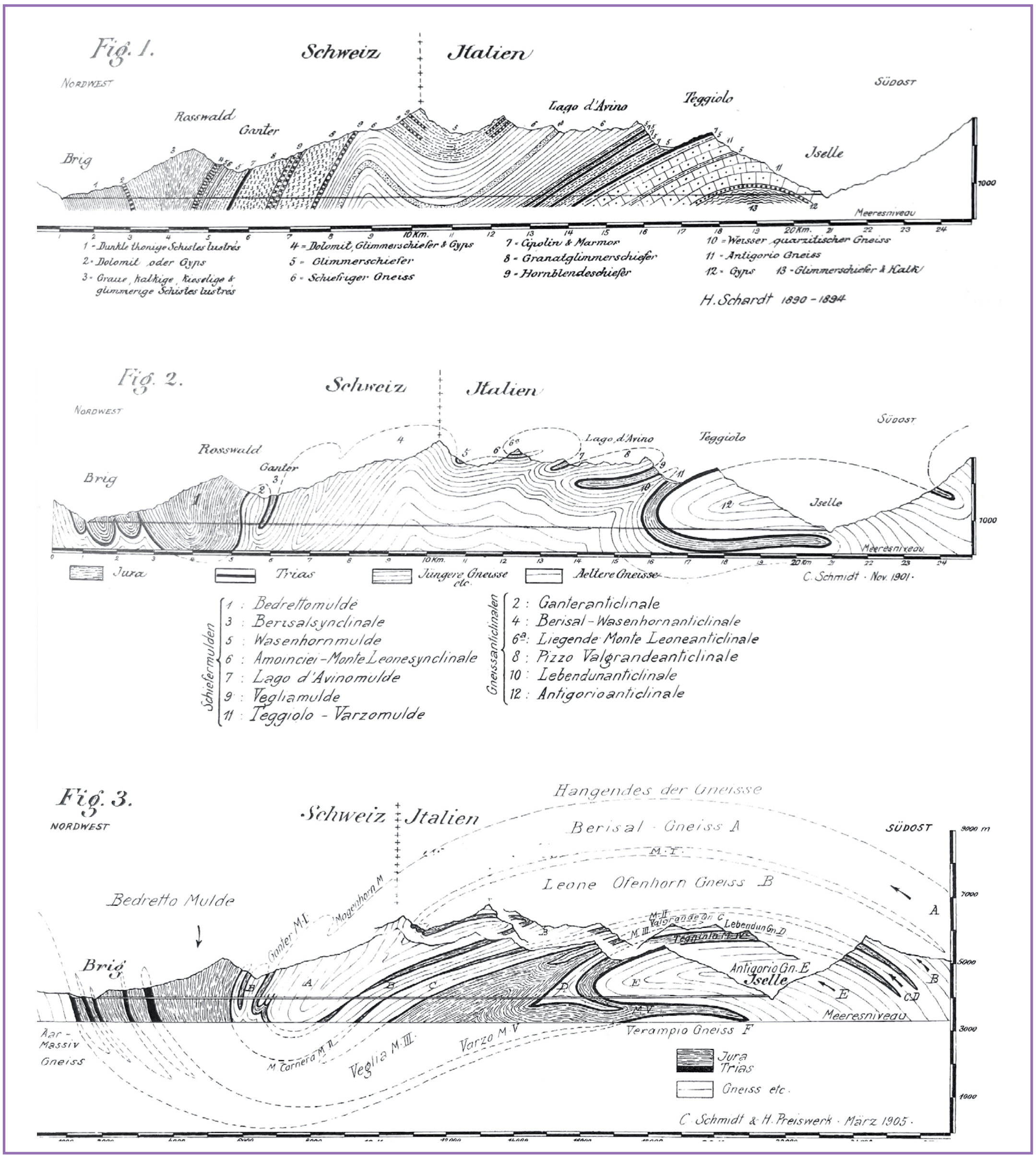


Figure 24 Development of the geological longitudinal profile at the Simplon Tunnel from 1890 to 1905 [31]

Use of best-suited means and methods during execution

A good illustration of how important it is to employ the best-suited means and methods comes from the 12.2 km long Mont Cenis Tunnel. Built between 1856 and 1870, this was the first major Alpine tunnel linking Italy and France.

Excavation used black powder explosive, with manually guided carriages used initially to drill the blast holes. Average tunnelling rates were between 0.5 and 0.6 m/working day (WD), extrapolating to a total construction time of over 31 years. There were doubts about the success of the project. The English engineers Brassey and Fell therefore built a railway over the Mont Cenis Pass from 1867 to 1868 (see **Figure 20**).

But starting in 1862, Sommeiller-type drilling machines were deployed on the Italian side and from late 1864 on the French side too, which of itself doubled the rate of progress to 1.0–1.3 m/WD.

Further measures (including amendment of the contract to include a financial incentive system) [33] later tripled the original capacity to 1.9–2.2 m/WD (see **Figure 25**), such that the Mont Cenis Tunnel could open on 17 September 1871. Two days later, the railway over the pass was closed after just three years in operation.

Dynamite, patented by Alfred Nobel in 1866, was not used at Mont Cenis. But starting in 1872 it was used in construction of the Gotthard railway tunnel. Helped also by further improvements in drilling technology, tunnelling performance at the Gotthard could be increased to 3.2 m/WD, a further 45 % compared to the average peak performance at Mont Cenis. Total construction time for the 14.9 km long Gotthard tunnel (= 122 % of the length of Mont Cenis) was reduced to 68 % of the construction time for Mont Cenis, i.e. average performance almost doubled.

It is remarkable that both the Mont Cenis Tunnel and the Gotthard Railway Tunnel are still in use today – impressive proof of the lasting quality of these engineering achievements.

Insight:

- Employing best-suited means and methods promotes project success.

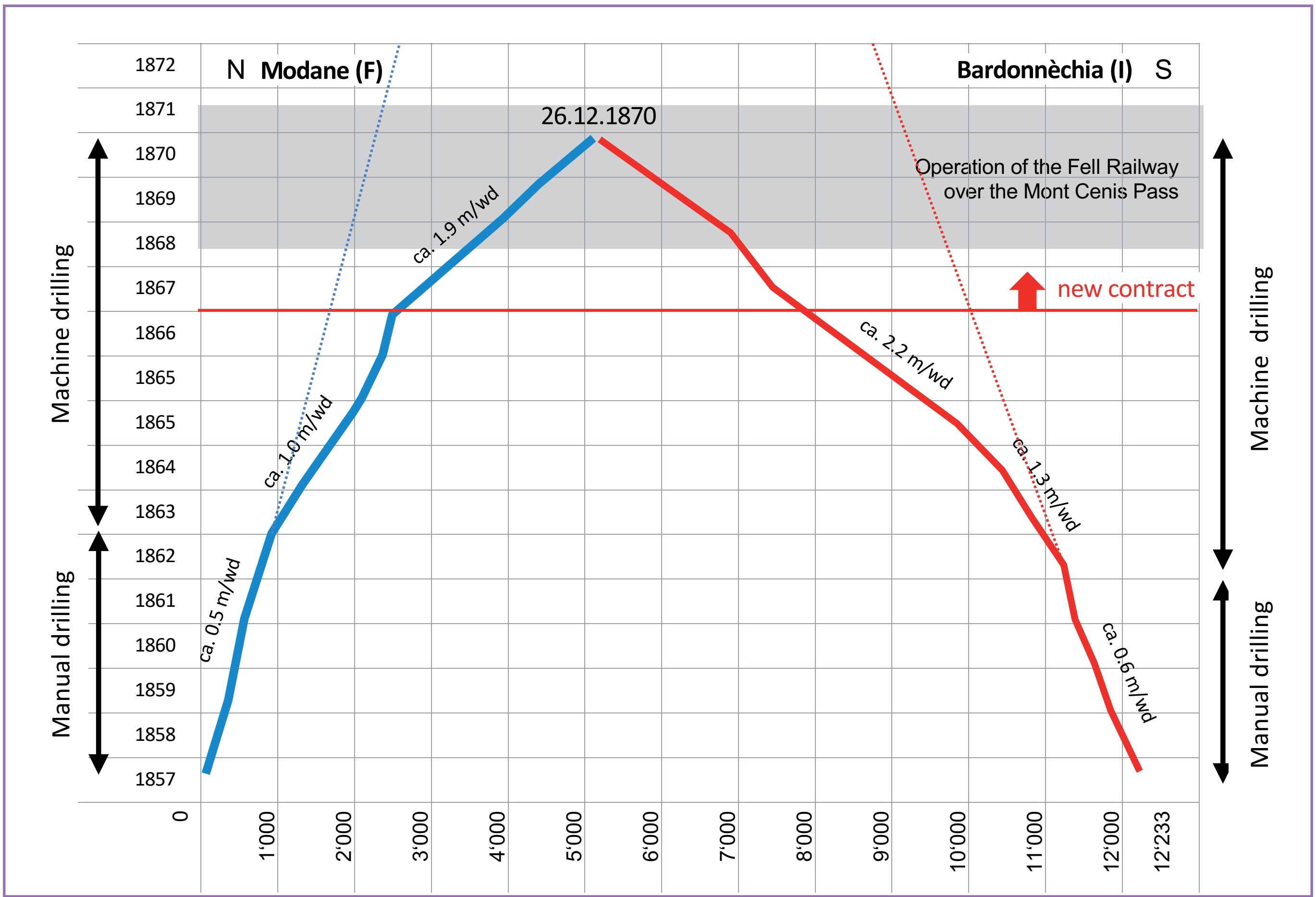


Figure 25 Construction fulfilment at the Mont Cenis Tunnel including the effect of the technology deployed (data from [34]

5 PRESENT-DAY CHALLENGES

The question now arises as to whether the key success factors derived in Chapter 4 are also relevant to the current challenges. This question will be examined in this section.

5.1 Environmental challenges

5.1.1 Climate protection

Underground construction is only a small segment of the construction industry and economic activity as a whole. [3] Nevertheless, underground construction must also make its contribution to climate-neutral construction methods of the future. That especially involves minimising the use of concrete and steel and switching to climate-neutral construction materials.

Although this is a challenge for the construction materials industry in particular, it is also incumbent on project owners, regulatory authorities, designers and contractors to help achieve a rapid breakthrough in applying innovative industrial developments in this field. **Success will depend on close cooperation between the parties involved**.

Figure 26 Gravel processing plant at the Gotthard Base Tunnel (photo M. Krause)

Figure 27 Inner concrete lining of the Gotthard Base Tunnel built 100% with concrete gravel from excavated material (photo ATG)

5.1.2 Circular economy and resource-conserving construction

With above-ground construction, the load-bearing structure encloses the usable space to be created. Contrastingly, with underground construction this space must first be created by excavation and then partly backfilled by the building work necessary to ensuring long-term structural safety and functionality. So with any underground structure, excavated material is the largest volume of material to be processed.

The present-day requirement (as often provisioned in law) is not to treat these large quantities solely as waste, but also to use them as raw materials in a way that promotes the circular economy. Such use includes the extraction of concrete aggregates (see **Figure 27**) or the provision of raw materials for the construction materials industry, where technically feasible and economically viable. **This, too, calls for joint effort by all project participants**.

Another major area of development is underground construction designed to conserve resources. Major efforts are needed to minimise the use of materials as far as possible as a means of conserving natural resources. Here too, new baseline conditions could help, such as allowing non-reinforced inner vaults (where this is not already the case).

5.1.3 Biodiversity

Society and the business world recognise promotion and preservation of biodiversity as more of a long-term issue [35] – and yet it is an important one. Underground construction makes a valuable contribution to preserving biodiversity by virtue of not fragmenting ecosystems, a fact that needs due recognition.

Appropriate utilisation of the excavated material can also contribute positively to creating new ecosystems and promoting biodiversity (see **Figure 28**). Such solutions require early, forward-looking action that starts at the planning stage. **Here too, it is crucially important to have the right people in the right place at the right time.**

Figure 28 Renaturing of the overexploited Reuss delta in Lake Lucerne with tunnel excavation material to promote biodiversity [36]

5.2 Societal challenges

In the social field, it is likely that the current key success criteria are effective for projects to gain social acceptance and achieve health and safety targets.

5.2.1 Social acceptance

Large infrastructure projects often encounter difficulties with gaining the social and political acceptance they require. Underground structures do have certain advantages in this respect: they are barely visible apart from the portal structures, take up very little space in the long term and cause hardly any emissions from the operation of the facilities.

Nevertheless, underground construction projects still meet with resistance in many places.

The sole way to improving social acceptance is by communicating a project's benefits and added value to a broad audience at an early stage. **This requires the early involvement of those affected** to gain their participation in the project via cooperation groups set up for the task (see 3.2.1).

5.2.2 Occupational health and safety

Occupational health and safety is probably the most impressive example of just how much progress has been made in recent decades. Thanks not only to improved technology, better personal protective equipment and training, but also to changed social values, tunnelling has lost the horror associated with it a century ago. [37] Serious accidents are no longer accepted as an inevitable part of tunnelling. A "target zero" culture now prevails in many places. As **Figure 29** shows, this target is now also within reach for major projects or has already been achieved in some cases.

However, further effort needs to be put into ensuring that "Target Zero" becomes the standard. Occupational safety starts at the planning stage, which is why these requirements also require joint action by all parties early on in the project. **This in turn calls for a project culture that embraces the "Target Zero" objective.**

Moreover, there is continuing need to **raise everyone's awareness of their personal safety responsibility, and for technical developments** (automation, robotics, use of AI (**Figure 30**) to further minimise risks to persons.

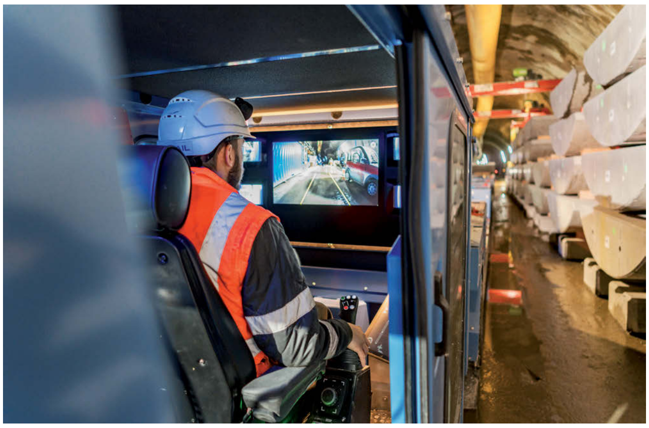


Figure 30 Automated, virtually guided service vehicles assisted by AI (photo Virturail)

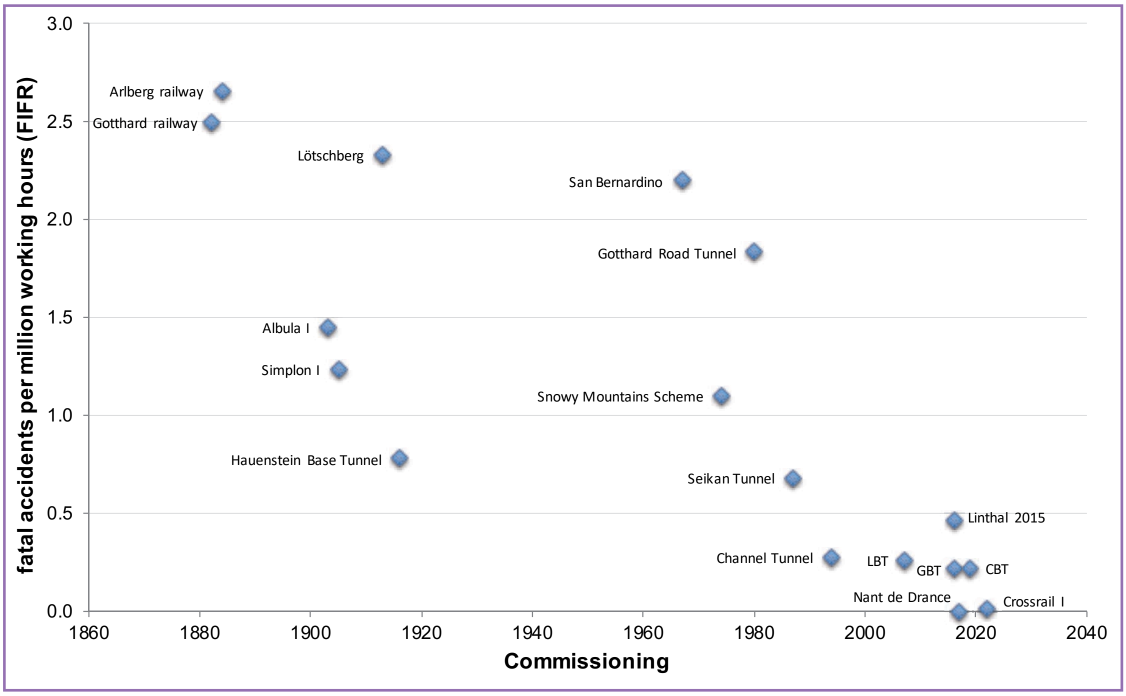


Figure 29 Progress and cultural change in occupational safety

5.3 Challenges from the economic environment

5.3.1 Costs and deadlines

The last 140 years or so have seen little progress in terms of economic success criteria, particularly when it comes to meeting cost and schedule targets during construction (see **Figure 31**). There seems to be no learning in this area, an observation made back in 2003 by Prof. B. Flyvbjerg on the basis of the projects he had analysed. [38]

There are barely-changed reasons underlying this observation (see **Figure 32**, **Figure 33**):

- Generally non-existent or underestimated financial risk provisioning,
- Politically unwanted financial risk provisioning,
- Underestimated project duration and costs of delays,
- Zero or insufficient consideration of expected changes in the project, (e.g. safety requirements or improvements for the population and the environment)

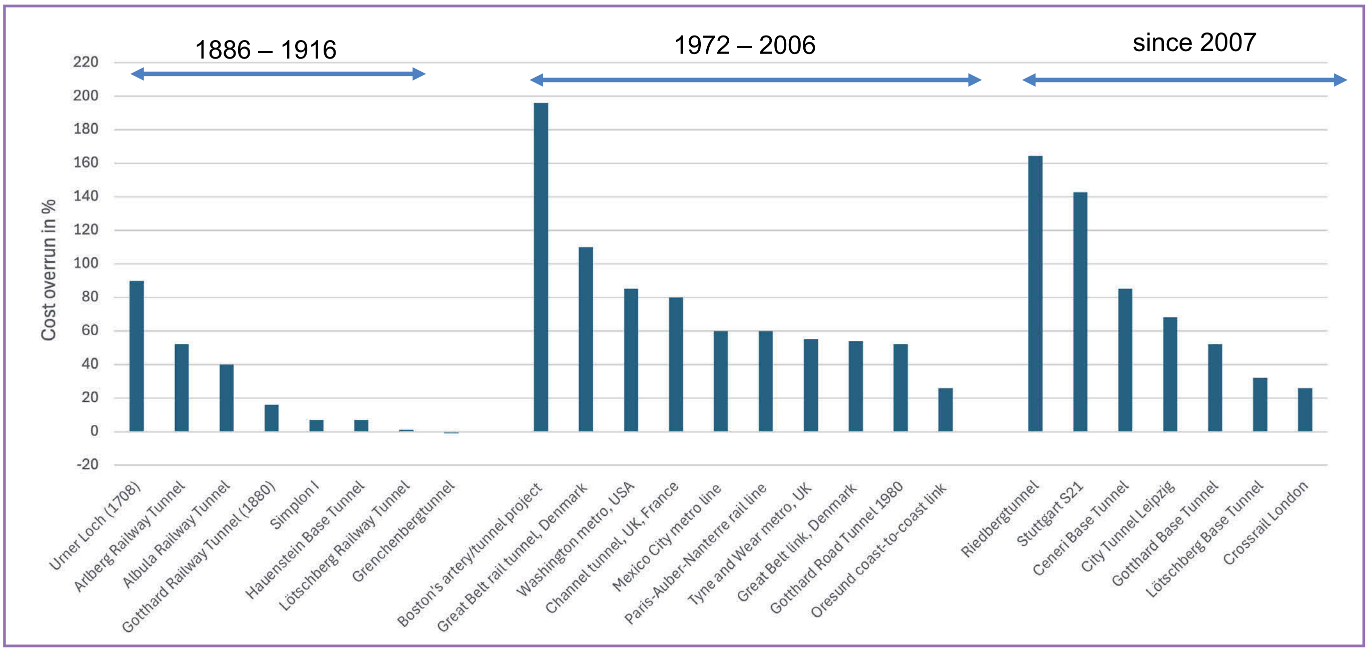


Figure 31 Cost overruns for major projects compared to the initial cost budget at fixed prices

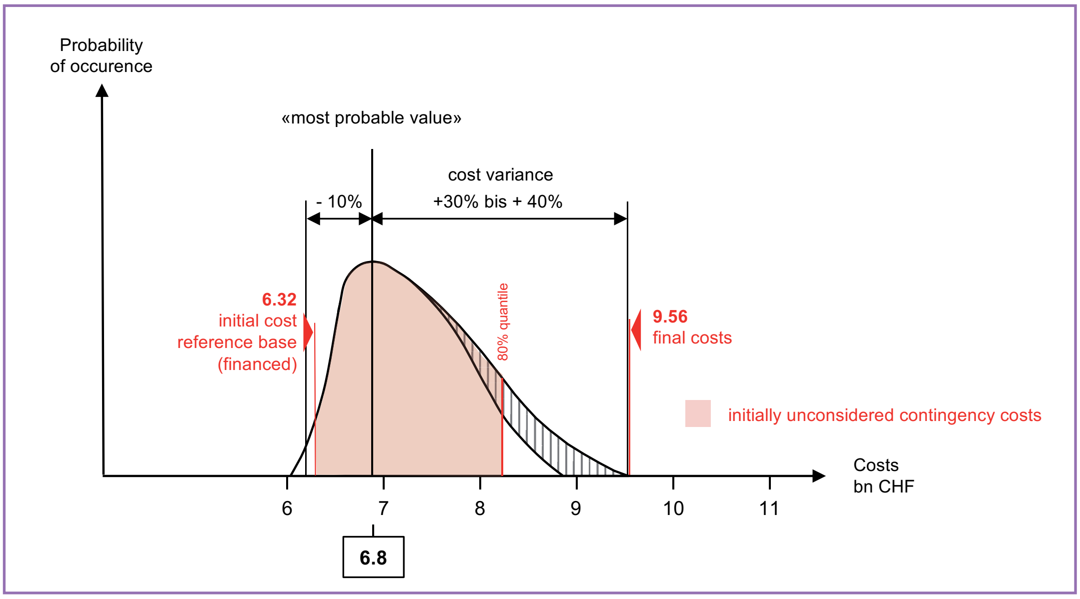


Figure 32 Development of costs and financing for the Gotthard Base Tunnel (price basis 1998, based on [39]

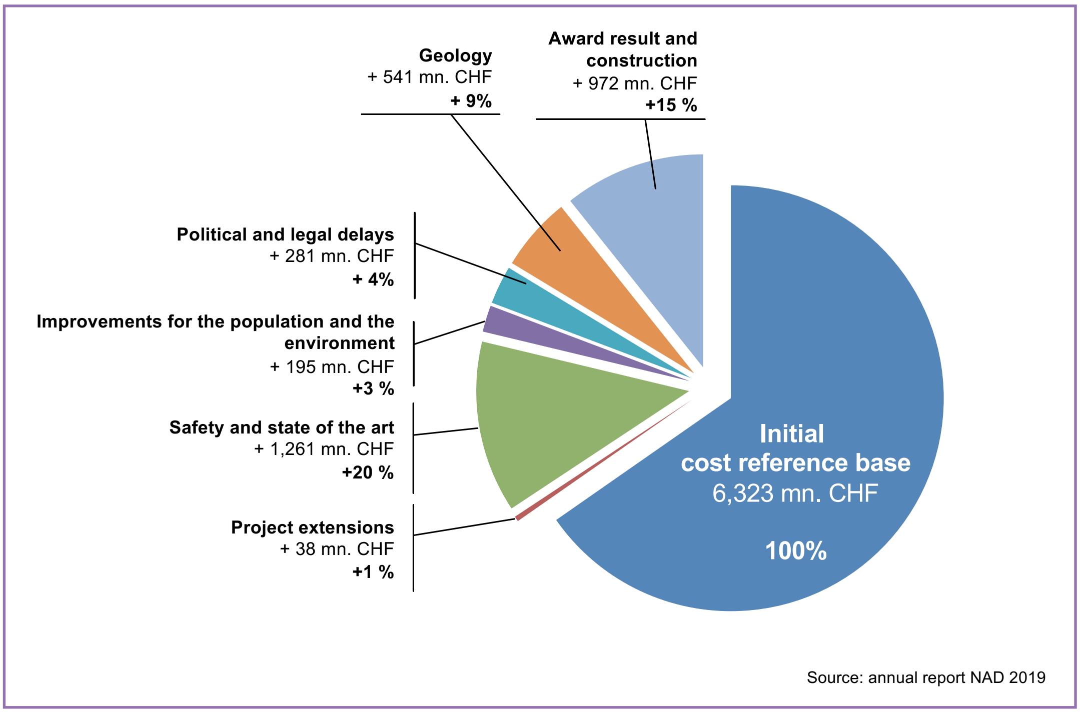


Figure 33 Reasons for cost overruns on the Gotthard Base Tunnel (1998 Price Basis) [40]

- Zero provision in long-term projects for updating the project to the current state of the art,
- Zero or insufficient consideration of quantity and price changes

It is not for project organisations to remedy a lack of political will to finance risks properly. All that can help is to keep educating the politicians.

On the other hand, project organisations are perfectly capable of formulating more reliable cost and deadline targets. **Correctly applied risk management methods for assessing risks render valuable service in this respect.** Best results are achieved when the assessment is comprehensive, i.e. also encompasses the contractor carrying out the work.

Two comparable samples (see **Figure 34**) demonstrate the verity of this statement.

- The left-hand scatter plot shows the deviation from cost targets for traditional unit price contracts as **estimated by the project owner alone and without provisioning for financial risk**.

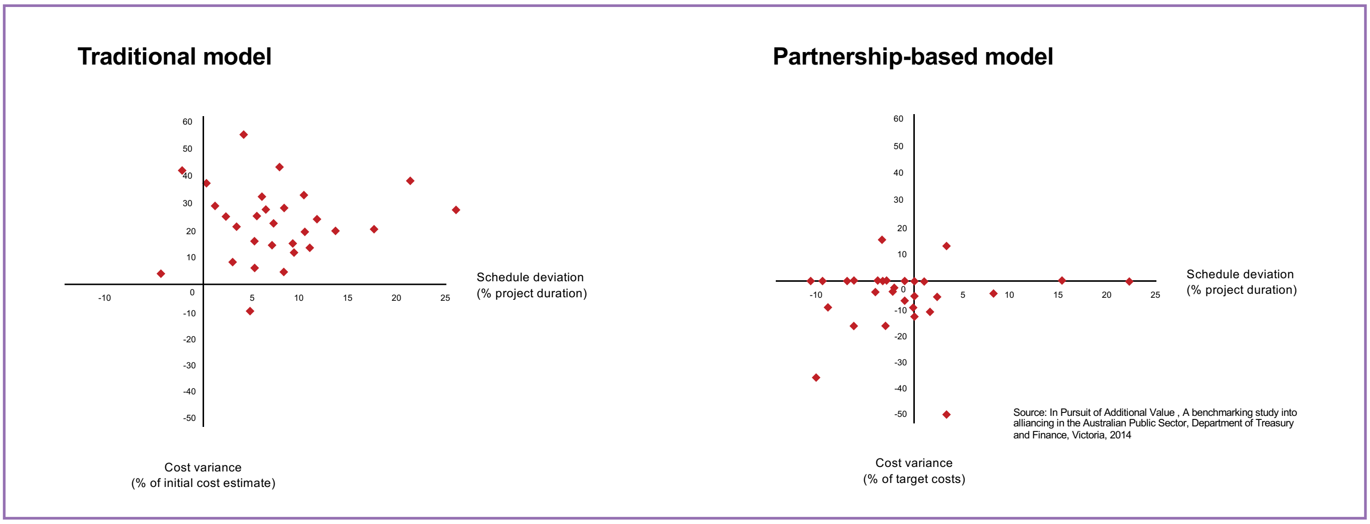


Figure 34 Compliance with cost and schedule targets for two samples from infrastructure construction

- In contrast, the right-hand scatter plot [41] shows a project portfolio based on alliance contracts with target costs, including the financial risk provision determined **jointly with the contractor and applying an incentive-based remuneration** according to the principle of cost price remuneration with surcharges. This model promotes close collaboration between the project owner and the contractor, enhances accountability, and ensures more precise and realistic cost and schedule planning.

This example demonstrates that a **collaborative working culture** based on **openness and transparency** has positive effects on project success.

5.3.2 Processes

As shown by the example of the Lötschberg tunnel (see 4.2.4) and the preceding considerations of cost and schedule targets, rigorously implemented project risk management (see **Figure 35**) from the earliest phases is essential to successful project realisation.

Recognised and effective means and methods for project risk management in underground construction have been developed and documented in various countries (e.g. [42], [43], [44], [45], [46]). Their implementation needs to focus on planning and putting measures in place that will avert hazards and exploit opportunities. **Here, too, achievement depends on the collective will of all involved parties.**

5.3.3 Organisation

The project examples listed in the preceding chapters all illustrate the importance of the quality of interaction between key project partners. Time and again it is evident that the prime orientation of the project organisation must be towards the success criteria of the project, rather than the success of individual participating companies. Their success should derive from project success also having been achieved. A company's success should no longer be one-sided, that is to say, the company wins even though the project itself is not so successful, or one-sided in the other sense, when a project succeeds but a participant comes under existential threat (4.2.1). The applicable principle must be "win-win or lose-lose".

The underlying principle of traditional organisational models (from total contractor to individual awards) is the mutual exchange of services. Such models are inherently conflict-prone because there is no agreed, shared goal to be achieved. Hence there is no shared alignment of interests. There is a clash of interests between those of the project owner (agreed quality, minimum costs, meeting deadlines) and those of the contractor (securing profit, limiting expenditure). This often leads to conflict situations that are effortful to resolve. Frustrated and demotivated project participants are often the result.

With underground structures, the often-long project duration and the ground risk make it impossible to fully and precisely describe from the outset all the requirements to be fulfilled. This leaves a considerable risk potential. One way to delineate spheres of risk among the project participants is through contractual provisions, either balanced or one-sided (see **Figure 36** left). However, a materialised risk often leads to haggling over who is responsible. Conflict situations arise.

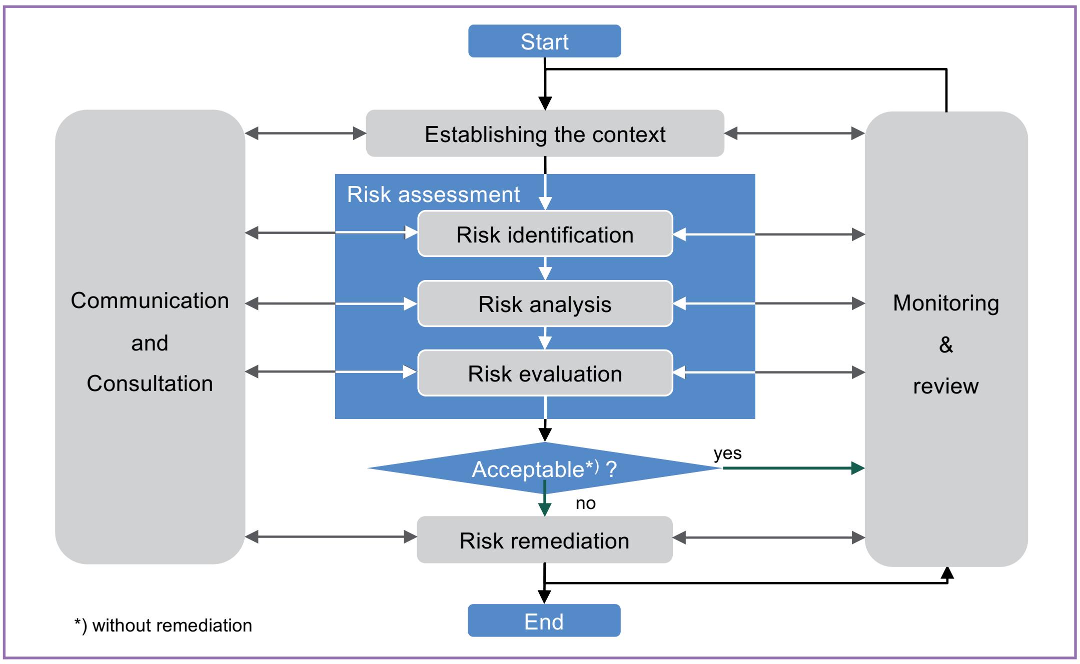


Figure 35 Project risk management process [42]

In various regions of the world, it has been recognised that the only systematic solution to this dilemma is to abandon the principle of individual risk allocation and, through aligned interests of all key partners in the project, bear the risks jointly. Rather than conflicts of interest, there is now alignment (see **Figure 36**). Conflict potential is eliminated; staff motivation is kept going or even boosted.

Such an approach rests on willingness to cooperate on the aim of jointly achieving the project objective; hence companies refrain from focusing primarily on their own business success. This kind of culture, oriented towards the project objective, has to be based on more than declarations of intent. Rather, robust agreements must be in place that, through clear economic incentives, encourage the contractual partners to align their interests.

Development of such organisational models has been under way for quite some time in the Anglosphere (alliance agreements in Australia and New Zealand, NEC agreements in the UK, IPD model in the USA). In mainland Europe, this type of model has become established in Scandinavia and is starting to see wider use in German-speaking countries (Germany, Austria, Switzerland).

The contractual tool is usually a multi-party contract – the so-called alliance contract – similar to a contract for work and labour, characterised by the following:

1. **A scope of services defined jointly** through a dialogue process.
   Identified gaps in the definition of work and services are closed in the dialogue.
2. **Joint risk bearing rather than individual risk allocation** (excepting cases of wilful intent or gross negligence).
   This leads to far-reaching mutual exclusions of liability.
3. **Target costs calculated to factor-in a financial provision for risks.**
   Remuneration is based on the principle of cost reimbursement. Extras for business overheads and profit are remunerated on a performance-related basis. Deviations from the target costs are shared within predefined ranges according to an agreed apportionment scheme (“pain/gain share”).
4. **Joint project management** in the hands of an integrated project team. Decisions are taken together in a “best for project” spirit.

Essential to the functioning of such an organisational model are the courage to break new ground, mutual respect and willingness by all project partners to engage in a culture of cooperation, and the availability of suitably motivated, capable staff. There have been positive experiences with such partnership models in many places. That being said, where these basic requirements cannot be met, a partnership model cannot help and should not be used.

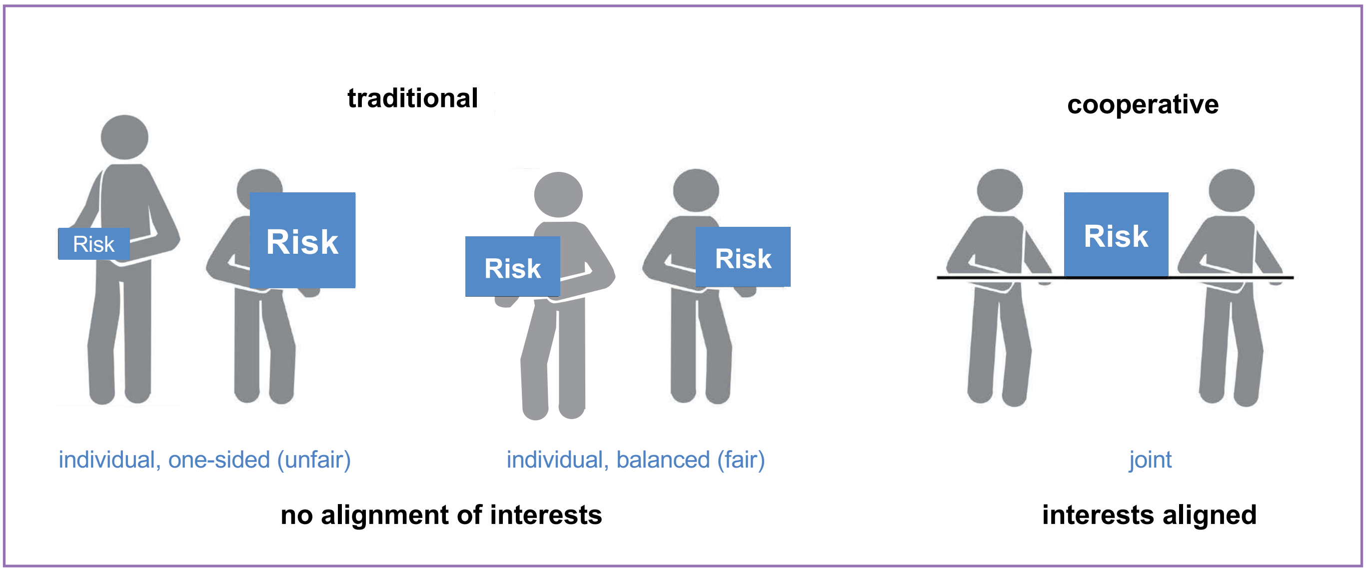


Figure 36 Basic principles for dealing with risks (illustration: M. Grether)

6 SUMMARY AND RECOMMENDATIONS

Infrastructure projects – especially in underground construction – are expected to contribute meaningfully and sustainably to societal goals such as secure supply, economic resilience, and social connectivity. To meet these expectations, project success must be clearly defined from the outset and its realisation systematically monitored throughout the project lifecycle. This requires a precise, comprehensive catalogue of measurable success criteria, encompassing not only cost, schedule, and quality, but also environmental sustainability and social acceptance.

Yet such a catalogue, while necessary, is not sufficient to ensure success. The actual outcome depends on the suitability of the project environment, the clarity and consistency of applied processes, and the appropriateness of selected tools and methods. These contextual and procedural conditions constitute the key success factors of any major infrastructure initiative.

In the course of this analysis, the author has derived the following key success factors:

1. **Respect for the task and the project partners**
2. **The right people in the right place at the right time**
   - Committed project team with high professional and social competence
   - Leadership with clear objectives and character
3. **Appropriate corporate and project culture**
   - Solution-oriented culture of cooperation that learns from mistakes rather than apportioning blame
   - Partnership-based cooperation with all project participants
4. **Diligent project preparation and implementation**
   - Clear formulation of project requirements aligned with the entire life cycle
   - Optimal forms of organisation and clear processes
   - Careful project planning
   - Consistent quality and risk management, incl. systematic dual control principle
   - Selection and application of the most suitable means and methods

This illustrates that so-called soft factors – such as mutual respect, the right people in the right roles, and the quality of collaboration – are of critical importance. Despite the strong influence of technical tools and methods on project outcomes, the human factor continues to play a dominant role in determining project success.

This insight is also supported by scientific studies and by evaluations of incident causes in underground construction, including those conducted by insurance companies.

More than 40 years ago, German engineer Dr Hans Blaut addressed the principles of safe and successful construction – and arrived at remarkably similar conclusions. In 1982, he developed what is now known as **Blaut's Formula**, which expresses these interrelationships in a remarkably clear and memorable way [47]:

$$T = m \times k^2 \times i^3 \times a^x$$

Where:

T	=	quality of task execution
m	=	material and human resources
k	=	knowledge and expertise (weighted quadratically)
i	=	information and communication (weighted cubically)
a	=	ambition to achieve excellence
x	=	team climate, influenced by internal and external project conditions; x may be positive or negative

Blaut's formula offers a compelling heuristic for understanding and managing the complexity of large-scale underground infrastructure projects.

Its application is strongly recommended as a strategic tool to foster clarity, cohesion, and collective performance across multidisciplinary teams.

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8 APPENDIX

Table A-1: Example of assessment criteria for underground structures based on sustainability criteria (SNBS system) [20]

Range	Topic	Criterion	Indicator	Assessment paramaters
Ecology	Energy, raw materials and land use	Energy	Energy consumption	▪ Minimisation of energy consumption
		Land use, land recycling, soil	Efficient use of space	▪ Careful soil handling
		Utilisation of uncontaminated and contaminated excavated and demolition materials (waste)	Method and proportion of utilisation	▪ Minimisation of contaminated waste ▪ Maximised recycling of uncontaminated waste
		Environmentally friendly and resource-saving use of materials	Resource efficiency	▪ Minimising the use of materials ▪ Ensuring optimum deconstructability
	Nature and environment	Impairment of the climate	GHG emissions	▪ Minimisation of GHG emissions ▪ Compensation for unavoidable residual emissions
		Impairment of the air	Air pollutants	▪ Minimisation of pollutant emissions ▪ Minimisation of dust/fine particulate emissions
		Impairment of water bodies	Qualitative/material effects on surface water and groundwater	▪ Minimising water consumption ▪ Minimisation of pollutant discharge/no damage to water quality ▪ No impairment of flow capacities and the water cycle
		Impairment of the environment	Ownership and rights of third parties	▪ Avoidance or minimisation of noise emissions ▪ Ensuring the accessibility of third-party property ▪ Limitation of surface deformations to a permissible level
		Biodiversity and landscape	Preservation and enhancement of ecosystems	▪ Preservation and promotion of ecosystems ▪ Preservation and promotion of biodiversity ▪ Preservation and promotion of undissected, low-traffic areas ▪ Creation of connecting corridors in ecosystems ▪ Preservation of typical landscape elements
	Hazard prevention	Natural hazards	Hazards from natural hazards	▪ Avoidance or minimisation of the effects of natural hazards (storms, floods, avalanches, etc.)
		Incidents	Hazards from incidents	▪ Avoidance or minimisation of the effects of incidents (e.g. transport of hazardous goods, collisions, etc.)

Continuation Table A-1 Example of assessment criteria for underground structures based on sustainability criteria (SNBS system) [20]

Range	Topic	Criterion	Indicator	Assessment paramaters
Economy	National economy	Economic benefit	Economic analysis Cost-benefit analysis	▪ Travelling time gains ▪ Reduction in environmental costs ▪ Reduction in consequential accident costs
		Regional economic aspects	Utilisation and creation of regional resources and competences	▪ Utilisation of regionally available raw materials ▪ Utilisation of regionally available personnel resources and skills ▪ Promotion of regional attractiveness
		Economic utilisation of existing infrastructures	Existing infrastructures	▪ Multifunctional or shared use of infrastructure
	Business Ad-ministration	Business success	Economic cost-benefit ratio	▪ Guarantee of the required quality and functionality ▪ Optimum organisation and processes during planning and imple-mentation ▪ Meeting deadlines and cost targets ▪ Technical service life of the components ▪ High reliability, availability, maintainability and operational safety ▪ Minimisation of life cycle costs (operation, maintenance, renewal)
		Enabling changes of use	Flexibility of use, adapt-ability and dismantling	▪ Technical utility rooms ▪ Conversion and dismantling options
	Financing	Long-term stable financing	Sponsorship and financing model	▪ Cost recovery ratio after realisation ▪ Stable cost target ▪ Financial risk provisioning
Society	Spatial development	Landscapes, townscapes and cultural space	Changes to landscapes, townscapes and cultural areas	▪ Compliance with landscape protection ▪ Compliance with townscape protection ▪ Compliance with monument protection
		Quality of social coexistence	Creating high-quality living, meeting and recreational spaces	▪ Green spaces ▪ Elimination of fragmentation effects ▪ View
	Society	Quality of the infrastructure from the user's point of view	Easy access and high quality of stay	▪ Functionality of the system ▪ Barrier-free access and signposting ▪ Ensuring well-being during use
		Communication and participation	Early involvement of those affected	▪ Information ▪ Consultation ▪ Co-operation ▪ Acceptance
		Legal certainty	Implementation of the legal and normative framework conditions	▪ Compliance with legal procedures and normative regulations ▪ Mechanisms for conflict resolution
		Impact of emissions	Emissions from construction and operation	▪ Noise protection ▪ Dust protection ▪ Vibration protection ▪ Protection from exhaust fumes
		Solidarity, justice, distribution effects	Fair consideration of needs	▪ Consideration of the regions ▪ Social and intergenerational justice ▪ Project-internal equity
	Health and safety	Occupational health and safety	Health protection during construction and operation	▪ Conceptual layout (resilience and reliability) ▪ Protective measures ▪ Safety and rescue concepts ▪ Prevention of serious accidents at work and permanent damage to health
		Users' sense of security	Layout of the systems and quality of the operator organisation	▪ Resilience of the systems/infrastructure ▪ Clearly recognisable escape and rescue routes ▪ Presence of operator and security personnel

Table A-2: Historical projects analysed

Name of the project	Gotthard Railway Tunnel	Simplon I Tunnel	Lötschberg Railway Tunnel	Hauenstein Base Tunnel	Albula I Tunnel
Length	14.9 km	19.8 km	14.6 km	8.1 km	5.9 km
Owner	Gotthard Railway Society	Jura-Simplon Railway, later Swiss Federal Railways	Bernese Alpine Railway Company Bern-Lötsch-berg-Simplon	Swiss Federal Railways	Rhaetian Railway
Contractor	Louis Favre	Brandt, Brandau & Co. Locher Cie. GmbH	General Enterprise Lötschberg (EGL)	Julius Berger Ltd.	Ronchi & Carlotti, Ronchi & Majoli later self-directed by the construction client
Construction period	1872–1882	1898–1906	1907–1913	1912–1916	1899–1903
Target construction time **Effective construction time** **Time deviation**	*8 years* 9 ¼ years 1 ¼ years (18.8 %)	*5 ¾ years* 8 years 2 ¼ years (39.1 %)	*5 ½ years* 5 ½ years —	*5 years* 4 years -1 year (-20 %)	*4 ½ years* 4 ½ years —
Cost estimate ***Contract amount*** **Invoice total** **Cost variance (%)**	CHF 60.0 million *47.8 million CHF* CHF 66.7 million 11.1 %	CHF 54.5 million *CHF 54.5 million* 58.3 million CHF 6.8 %	CHF 50.0 million *CHF 40.2 million* CHF 50.3 million 0.6 %	CHF 18.6 million *CHF 19.8 million* CHF 19.9 million 7 %	CHF 5.2 million *n.a.* CHF 7.3 million 40 %
Fatalities	177	67	6	12	16
Operation	Carrier of the main traffic load in transalpine freight transit traffic until 2016; cash cow of the Swiss Federal Railways until the opening of the road tunnel in 1980. The performance assumptions on which the project was based were exceeded by a factor of around 100.	A sustainable transport infrastructure that still meets today's requirements even after refurbishment.	Even after the opening of the Lötschberg Base Tunnel in 2007, it remains an essential element for rail transit traffic. Offers a car transport service between German-speaking Switzerland and Valais.	One of the busiest railway tunnels in Switzerland. Due to defects dating back from the construction period necessitate regular refurbishment work.	Metre-gauge tunnel to connect many valleys in the canton of Graubünden by rail. After around 100 years of operation, new construction proved to be a better solution than refurbishing the existing structure while keeping it in use. The Albula I tunnel is now a safety tunnel for the Albula II tunnel.
Factors for success/failure	Highly qualified people led the project. An unfair contract led to frequent disputes, legal disputes and ultimately to the bankruptcy of the contractor.	Highly qualified people led the project. Similar difficulties to those at the Gotthard were resolved fairly through negotiation.	Highly qualified people led the project. Nevertheless, not all the information was passed on or taken seriously enough, which led to a serious accident.	Deadline and cost targets were clearly the priority, the quality target less so. Quality defects appeared early on. According to the construction client's expert appointed later, the client's representatives were insufficiently professional.	Difficult ground conditions led the contractor to withdraw from the contract. The project owner took over the tunnelling, paying for the work on a time and material basis, with bonuses for the workers. In the end, the deadline was met. Because there was no insurer offering accident insurance, the project owner set up his own insurance.
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