Bringing Objectivity into System Decisions between Ballasted Track and Slab Track at Deutsche Bahn

Items of permanent-way infrastructure have a service life of at least 25 years and may even exceed a hundred years. Since investments are nearly always irreversible, fixed-asset management needs clear-cut recommendations for its decisions, which must be underpinned with clear analyses, focused as far into the future as possible and stable in the face of modifications in the general environment. Against this background, a permanent-way strategy project known as "SMP-T" has succeeded in developing long-overdue decision heuristics on the foundation of a sound data and knowledge base to guide system decisions between ballasted track and slab track.

1 Functional strategy for engineering systems, portfolio of engineering systems for the permanent way and system decisions

In 2000, Deutsche Bahn's corporate strategy introduced the strategic management process (SMP), in the context of which its various divisions and departments are now working out business and functional strategies. The "functional strategy for engineering systems" (SMP-T) with a subproject on "permanent-way strategy" was launched in October 2001, initially in the form of a project. In September 2002, the project results were accepted at board level by Deutsche Bahn's Track Infrastructure ("Netz") division and the holding company. Since October 2002, the strategy for engineering systems has been undergoing implementation and further development within the group's line organization.

At heart, this strategy for engineering systems is concerned with the perennial question of "how can we manage to increase the reliability of the means of production (rolling stock and infrastructure) and at the same time reduce their life-cycle costs significantly?" There are now two key levers that form the basis of the strategy for engineering systems:

1. a strongly consolidated portfolio of engineering systems
2. an evolutionary process of innovation.

One of the things that was done as part of the permanent-way strategy project was to consolidate the portfolio of engineering systems for the track superstructure in the sense of standard solutions. Against this background, there was also a need for a fundamental clarification of the system decision: ballasted track versus slab tack. What was called for was the development of a process that would use simple means to facilitate recommendations for decisions that would be as clear-cut as possible yet would have a sound technical and analytical foundation.

In addition to the engineering considerations, the key decision criterion for this process was the business case, which was expressed as the discounted life-cycle costs (cash values) before federal grants. The life-cycle costs include series of payments for (replacement) investments, maintenance and penalty charges (paid to operators for the non-availability of the infrastructure). The computation uses a capital interest of 8 % and an annual rate of inflation of 2 %.

2 Key findings from the process for deciding on one of the two systems: ballasted track or slab track

From a purely engineering point of view, either ballasted track or slab track would be suitable for meeting the user's demands in virtually all cases. It is only in extreme cases that technical grounds would cause one of the two permanent-way systems to be eliminated. As a general rule, it is thus usually the business case that is the decisive selection criterion. When life-cycle costs are considered, ballasted track turns out to be the superior system for most practical cases. However, slab track has been kept in the portfolio of engineering systems because there are certain circumstances in which it does present economic benefits.

In monetary terms, the maintenance and availability advantage of slab track by itself is relatively minor, so that the higher

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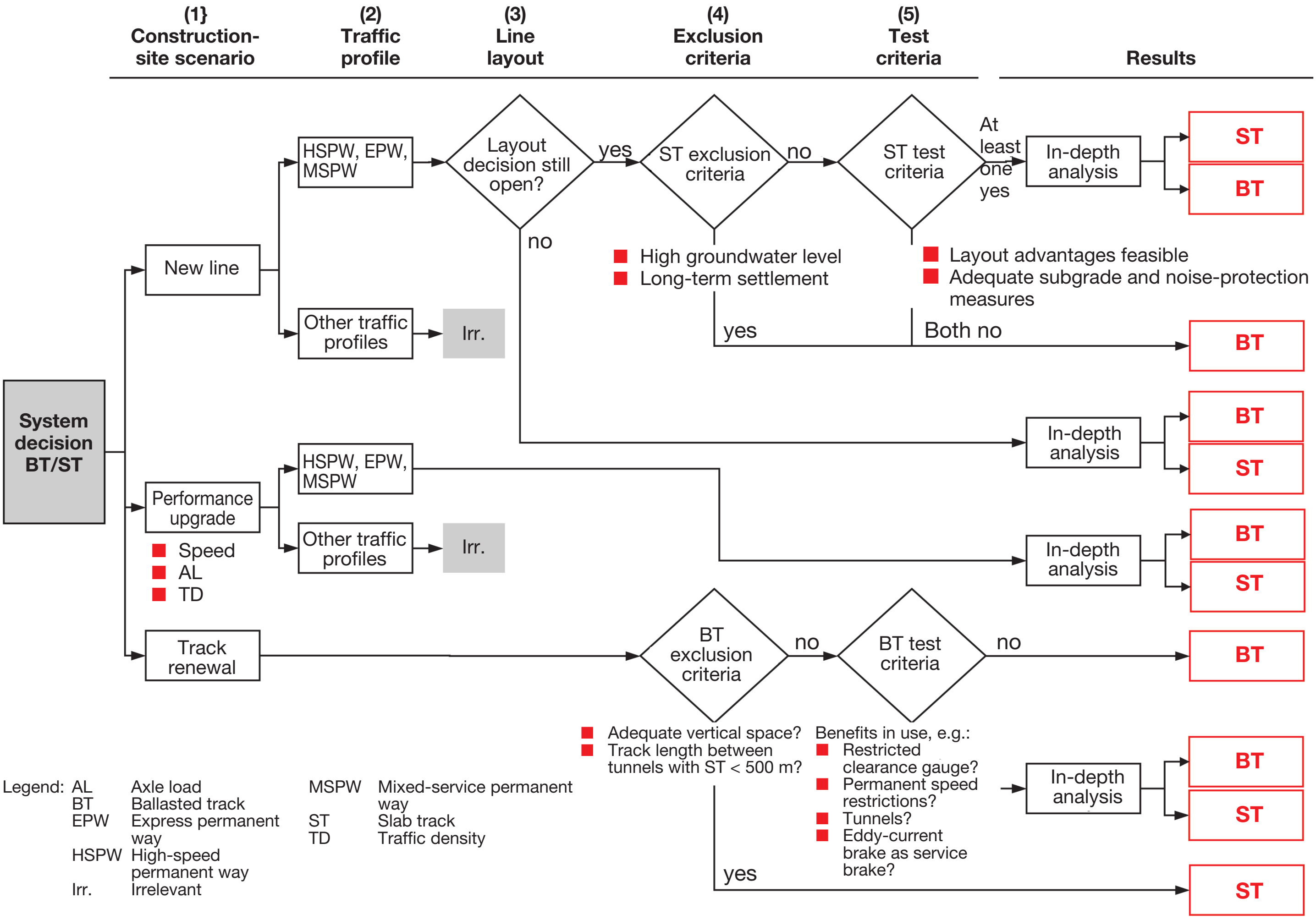

Fig. 1: System decision tree (Source: "SMP-T" permanent-way strategy project)

capital outlay costs compared with ballasted track can only be offset on really heavily trafficked routes with top-grade trains.

It is only when the economic comparison is taken further to encompass the whole of the permanent way, including engineering features, that the really interesting potential of slab track becomes visible: slab track's greater positional stability permits the route to be laid out with parameters that hug the existing topography more closely. This may make it possible to reduce the total length of engineering features, especially where lines are to be built through upland terrain. This potential can, however, only be tapped if the line layout has not yet been finally determined. From this, it follows that merely replacing ballasted track with slab track as part of an overhaul of the permanent way does not make economic sense, since the layout will be immutable. Slab track may become interesting if it is planned to increase speeds on an existing railway line, since a change in system may, under certain circumstances, make it possible to do without increasing the radii of curves (line upgrading).

Another key result is the finding that a further increase in the number of design varieties of slab track simply leads into the complexity trap. A perceptible optimization of the life-cycle costs of slab track is only achieved if it is possible to leverage learning-curve effects and potential for rationalization. This requires a consolidated portfolio of engineering systems. The optimum degree of standardization lies between one and two designs. There will still be scope for innovations, but these must follow an evolutionary path that has been strategically staked out in advance.

3 Practical benefits

Deciding on a system is an extremely complex issue, influenced by numerous parameters. One particular challenge is to be able to process this complexity in a manner that is comprehensible and supportive of the decision-making process, without, however, oversimplifying it. This must lead to a result, whereby the four or five key issues are clearly visible, so that it is possible to use them to obtain a more or less stable response even in early phases of a project.

The outcome of what has been presented so far is a decision tree, which, over several steps, leads either directly to a clear-cut statement or to the recommendation to perform a more detailed analysis. The clear-cut cases can be tested for technical exclusion criteria by applying a "quick check", after which they are regarded as having been sufficiently counterchecked to act as recommendations for decisions. If the recommendation is for a more detailed analysis, the criteria and the limit values for such an analysis are then worked out.

The decision tree has already been tried out in a practical instance and passed the test. In the case in point, parallel planning had already been commenced for both track systems, but the decision tree produced such a clear recommendation in favour of one of them that it proved possible to discontinue the alternative planning.

4 The logic of the system decision

4.1 The five steps making up the decision logic

In the project, it emerged that it is possible to reduce the decision logic to a maximum of five steps. Clear responses can be obtained rather simply in these steps by asking predominantly qualitative questions as to:

▷ whether it is already possible to make a clear-cut recommendation in favour of one permanent-way system
▷ or whether an in-depth analysis is needed.

In detail, the five steps process the following questions (Fig. 1).

(1) Construction-site scenario
For the purposes of arriving at a decision in favour of one of the track systems, a distinction has to be made between three construction-site scenarios. They are "new line", "performance upgrading" and "track renewal". In the first of these scenarios, the new line may be either a completely new route ("green-field site") or new tracks to be constructed along an existing route. The second scenario of performance upgrading concerns existing routes, whose improvement will affect at least one of the three parameters: speed, traffic density and axle loads. Finally, the third scenario, renewal of track, is a pure replacement investment, rendered necessary because the existing permanent way has come to the end of its useful service life.

(2) Traffic profile
Within the context of the strategy for engineering systems, six different traffic profiles were derived for the permanent way on the basis of the desiderata expressed by freight customers and the railway's own permanent-way unit. These profiles categorize the permanent way on the basis of key parameters that are of major technical relevance, such as ruling speeds, axles load, traffic density and minimum radii.

In the decision tree, only two of the construction-site scenarios, "new line" and "performance upgrading", are considered relevant for three of the traffic profiles:

▷ high-speed permanent way (HSPW),
▷ express permanent way (EPW),
▷ and mixed-service permanent way (MSPW).

For all the other traffic profiles (which include "local-train permanent way") only one construction-site scenario is considered, namely "track replacement".

(3) Route layout
The next step, which only concerns the "new line" scenario, is to examine whether the route layout has already been definitively established. If that is so, the process leaves the decision tree and branches into an in-depth analysis.

(4) Technical exclusion criteria
In the fourth step, the technical exclusion criteria are examined. Exclusion criteria for slab track are a high water table or a subgrade that is likely to be subject to long-term settlement or other movements. One of the exclusion criteria for ballasted track is, for instance, shortage of space under bridges. In tunnels, slab track is laid as a matter of principle for lengths of 500 metres and more. Sections of open track measuring less than 500 metres between two tunnels ought also to be executed in slab track so as to avoid excessively frequent system changes.

(5) Test criteria
In the final step, so-called "test criteria" are applied to assess whether an in-depth analysis is still necessary. It may happen, for instance, that the preliminary decision is in favour of slab track, but it is then established that there is no route-layout advantage to be derived and that slab track would also necessitate special noise-abatement measures and remedial work on the subgrade. In such a set of circumstances, it can be assumed that ballasted track is the more economic variant without needing to move on to any closer examination.

4.2 In-depth analysis

In those instances in which steps (1)–(5) do not produce any clear-cut recommendation, a detailed analysis becomes necessary. At this stage, a distinction must be made between new lines and performance upgrading on the one hand and track renewal on the other hand.

Insofar as relevant, the cash-value differences of the permanent-way systems are computed and aggregated for:

▷ the superstructure's life cycle costs,
▷ outlay on subgrade remediation and noise abatement
▷ route-layout properties.

For these computations, practical application assistants have been created and they are used in those cases in which precise calculations are still impossible so as to ensure that what emerges is at the very least a well-founded estimate.

If the sum of the cash-value differences falls outside of particular limit values, the result is a clear decision in favour of one of the two systems. In the mid zone, the business cases of both systems are relatively close to one another, so that, as an alternative to indulging in even more refined analyses, it is already possible to proceed to a management-based decision guided by qualitative criteria, knowing that the economic risk is contained within narrow confines.

5 Consolidating the knowledge base and rendering it more systematic

The decision tree and decision assistants are underpinned with expert knowledge and a whole series of technical and economic analyses. Whereas good technical know-how exists inside the railway and in the specialist press, one big challenge that had to be faced by the project was working out how best to present the demands on the permanent way in a systematic manner as well as arriving at an understanding of the economic behaviour of slab track and modelling it.

This particular task was entrusted by an interdisciplinary team of experts from Deutsche Bahn's Track Infrastructure division (DB Netz) and its engineering unit in cooperation with the Group Strategy function, the strategy consultants "Fontin & Co." and the specialist consultants of "ibt Dr. Ablinger".

The results of this teamwork form the basis for the evaluation criteria and the evaluation model for the permanent-way system decision.

6 Evaluation criteria and evaluation model for the system decision

6.1 Evaluation criteria

First of all, a workshop was organized to produce a systematic view of the requirements formulated for the

Overriding operational concept

- **Availability**
  - Guaranteeing punctuality
  - Minimizing disruptions due to the permanent way
  - Minimizing operational impediments occasioned by maintenance
- **Business case**
  - Life-cycle costs
  - Indirect cost-saving potential through standardization and innovation
- **Riding comfort**
  - Quality and durability of track position

Production and maintenance concept

- **Maintainability**
- **Possibility for making adjustments**
  - Height and position within rail fastening
  - Excessive settlement
- **(Replacement) investments**
  - Dependable construction processes
  - Minimizing operational impediments
- **Ensuring availability of component supplies**
  - Individual components (e.g. individual rail supports)
  - System components (e.g. slabs)

Risks/malfunctions

- **Safety**
  - Minimization of impacts of incidents (e.g. guidance for derailed wheelsets)
- **Pattern of damage and repair thereof following derailments**
- **Remediation of possible patterns of malfunctions for the given type of track**
  - Aim: Planned remedial work within a maximum of eight hours without subsequent running restrictions

Miscellaneous requirements

- **Drainage**
- **Structure-borne noise**
- **Airborne noise**
  - Permanent-way equipment
  - Maintenance of noise-absorbing layers
- **Effects on the subsoil**
  - Minimized pressure intensity
- **Clearance gauge**
  - Improvement to accompany reconstruction work (e.g. tunnels)
- **Eddy-current brakes**

Fig. 2: Track requirements (Source: "SMP-T" permanent-way strategy project)

permanent way and to assign these requirements to one of the four categories (Fig. 2):

▷ overriding operational concept
▷ production and maintenance concept
▷ risks/malfunctions
▷ miscellaneous requirements.

Working on the basis of this "catalogue of requirements", an extensive set of evaluation criteria was drawn up and assigned to one of three categories "mandatory requirements" ("musts"), "tolerated requirements" ("cans") and "ancillary requirements". The first of these – mandatory requirements – are, for instance, provisions contained in official regulations; they offer no decision-making latitude, since there is no alternative to complying with them. It is only in truly justified exceptional cases that their value in practice is ever called into question. The third-named group, the "ancillary requirements", are criteria that it is not possible to assess at present; that being so, they can have no influence on system decisions, but are kept on record for the sake of information. Where there is decision-making latitude, on the other hand, is in the middle group – the "tolerated requirements". That explains why they play the biggest part in the evaluation procedure.

The project team came up with a total of 16 "tolerated requirements". These were then concentrated into six key criteria as a function of what influence they have on the system decision (Fig. 3).

Evaluation criteria

Estimated influence

Minor	Moderate	Major
Maintenance of absorbers	Clearance gauge	Capital outlay
Air turbulence with dust and particles	Costs due to operational disruptions	Line layout advantages of slab track (reduction in engineering features)
Guidance for derailed wheelsets	Line closures for correction, remediation	Maintenance costs
Pattern of damage following derailments	Track position	Penalty charges for planned non-availability
	Repair of damage following extraordinary occurrences	Structure-borne/ airborne noise
	Gain in comfort as a result of slab track	Operational benefits due to the properties of slab track (line layout)

Precise computations of life-cycle costs must be performed for the following essential criteria:

- Capital outlay for the permanent way
- Line layout and design of earthworks and engineering features
- Maintenance costs
- Costs due to operational restrictions
- Structure-borne/airborne noise
- Operational benefits from the line layout

Fig. 3: Working out the key criteria for the system decision (Source: "SMP-T" permanent-way strategy project)

6.2 Types of slab track

Depending on their constructions and characteristics, the various systems and designs of slab track are categorized as follows:

(1) Systems
Compact slab track:
Reinforced concrete slabs with sleepers embedded in backfill concrete.

Prefabricated slab track:
Prefabricated slabs manufactured off-site.

Layered slab track:
A load-bearing concrete slab or asphalt layer with the sleepers resting on it.

Slab track with elastic sleeper supports:
Elastic sleeper supports on reinforced trough-shaped concrete slabs as the load-bearing system, with concrete block and steel tiebars or sleeper blocks with rubber shoes and elastic pads embedded in backfill concrete.

Special systems:
Systems adapted to suit special limiting factors, such as continuously supported rails or mass-spring systems.

(2) Design variants
The term "design variants" is applied to varying slab-track constructions within a system, which differ from one another in terms of their geometry or the components used, but which adhere to the same fundamental principle.

In order to keep the investigations within manageable dimensions, the large number of slab-track designs that already exists today was narrowed down in a representative short-listing process. A total of five designs as typical representatives of four slab-track system were then subject to further consideration. Table 1 lists the principal parameters of the pre-selected slab-track designs.

6.3 Evaluation model

On the basis of the evaluation criteria, the key engineering and economic parameters of the system decision were mapped in a concentric three-layer model (Fig. 4). This model's inner layer contains the analysis of life-cycle costs for the track superstructure in the narrow sense. Its middle layer considers the monetary implications of the route-layout properties of the track system on engineering features for various topographies. The outer layer includes miscellaneous qualitative criteria from the general environment that it is not (yet) possible to quantify.

6.3.1 Inner layer: the LCC tool

In this layer, the life-cycle costs are first compared for the various track systems. In addition to (replacement) investment and maintenance costs, penalty charges are also included in the LCC analysis.
As part of the permanent-way strategy project, a methodology was worked out for considering penalty charges. Downtime, which may be either scheduled (for instance, planned engineering work) or unscheduled (for instance, broken rails) was fed into the simulation model, RailSys®, in accordance with its measured and forecast occurrences, with the

Table 1: Technical properties of the types of slab tack (ST) examined (Source: "SMP-T" permanent-way strategy project)

ST system Element/requirement Model	Compact ST Model A	Prefabricated ST Model B	Layered ST Model C1/C2	Elastically supported ST Model D
Rail profile	UIC60	UIC 60	UIC 60	UIC 60
Rail fastening (standard with exceptions on bridges)	Ioarv 300	Ioarv 300	Ioarv 300	skl 14
Elasticity in the rail fastenings	100%	100%	100%	approx. 10-20%
Elasticity under the sleeper	0%	0%	0%	approx. 80-90%
Fixing the track in position	Backfilled sleepers	Backfilled slab	Rests on load-bearing layer 1)	Backfilled sleepers
Possibility of driving over the system with additional equipment fitted 2)	Possible	Easily possible	Possible within limits	Possible within limits
Likely effects and damage caused by derailments	3)	4)	3)	3)
Possibility of replacing sleepers/ slabs during an all-night closure (approx. 8 hours)	no 5)	Within limits	yes	yes
Correction for settlement of up to +26 mm and -4 mm	in Ioarv 300	in Ioarv 300	in Ioarv 300	skl 14 Vossloh
Correction of settlement of up to 54 mm applying Vossloh's proposal	yes	yes	yes	open
Correction for settlement with under-sleeper linings	–	–	Possible within limits	Possible within limits
Correction through backfilling / pressing down the concrete load-bearing layer of the prefabricated slabs	Possible within limits	Possible	–	–

1) Fine height adjustment by height compensation in the rail fastening.
2) The additional equipment to make it possible for road vehicles to run in single-track tunnels must not interfere with the inspection and maintenance of the permanent-way components or, at worst, only to a minor extent.
3) Derailed wheel flanges cause damage to the rail fastenings and their abutments. It is likely to prove necessary to replace or repair the sleepers themselves.
4) It may be concluded from a derailment that occurred in Melk Tunnel (Austria) on prefabricated slab track ("Porr" system) that the destruction of whole prefabricated slabs is unlikely. In this particular case, lasting repairs were achieved by replacing the rail-fastening equipment (including the sleeper dowels) and the repair of individual abutments with special mortar.
5) Repair concepts including the use of repair supports and prefabricated slabs.

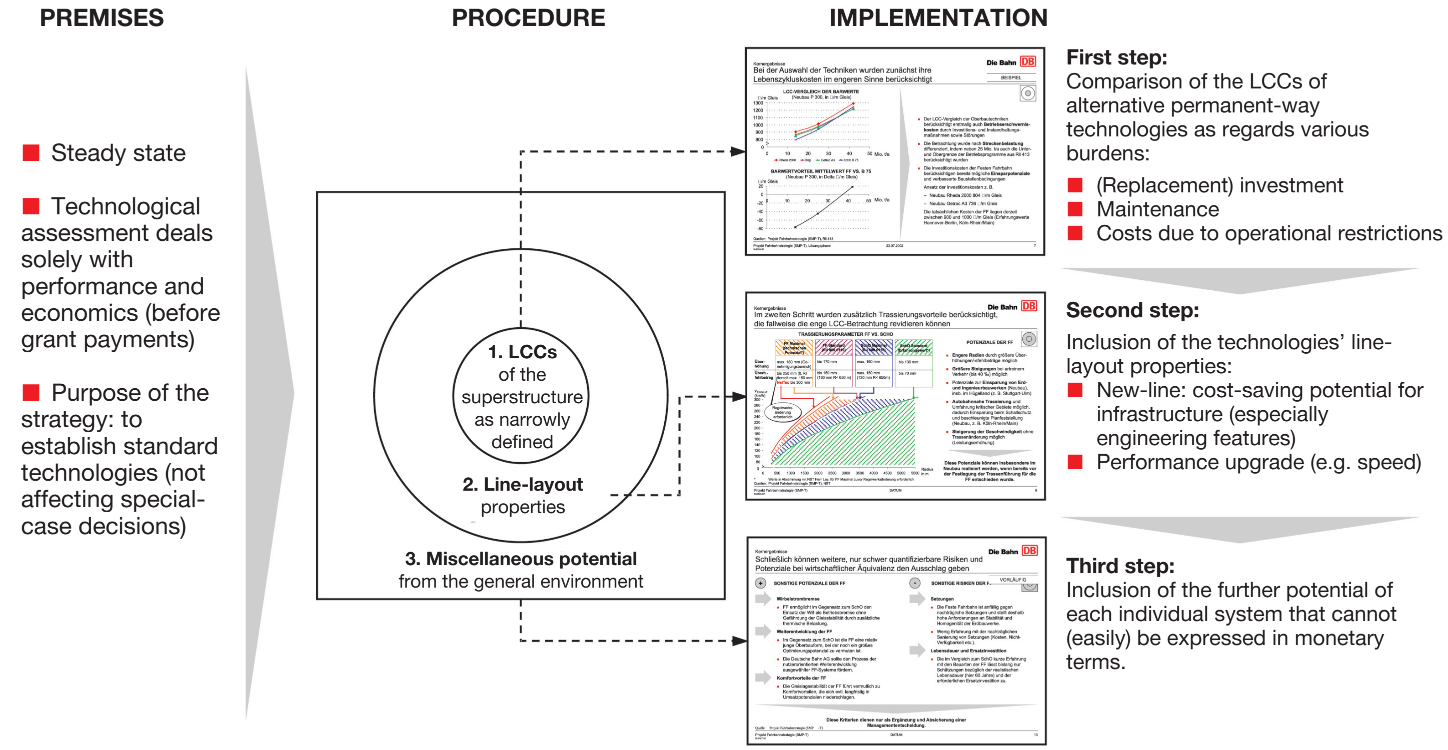

Fig. 4: Three-layered model for the system decision (Source: "SMP-T" permanent-way strategy project)

assistance of the "IVE mbH" company of Hanover. The model then computed the resulting delays, broken down by category of train, depending on the standard of the route and its associated operating programme as defined in Directive 413 [1]. These factors were quantified on the basis of coordinated standard unit costs for each minute of lateness for each train category.

In addition to the computation of penalty charges, the LCC tool also needed to have the capital-outlay and maintenance costs for the permanent way compiled for it. Concentrating on those slab-track systems that had been selected for investigation, the pre-existing database was added to in the course of very detailed consultations with manufacturers and experts. The project also gave consideration to the fact that slab track still has inherent potential for bringing down capital-outlay costs, for instance, if the degree of mechanization can be taken further.

For the LCC analysis, particular adjustments needed to be made to the data material, depending on the construction-site scenario under investigation (new line, performance upgrading or track renewal) and these were fed into the LCC tool through its correction factors.

The most important assumptions made in this context are:

(1) New line

▷ The potential for bringing down the cost of replacement investments in slab track are only partially realized on account of the low volume of new railway lines, providing only irregular work for manufacturers.
▷ During the first period, no penalty charges are due, since there are no trains using the track.
▷ Substructure measures are performed in accordance with the regulations.

(2) Upgrading the performance of an existing line

▷ In this particular case, it is to be assumed that there will be a moderate volume of construction work and that the contractors' workload will be somewhat spread out. Some of the potential for bringing down the costs of the replacement investments in the slab track are thus realized.
▷ It is assumed that for earthworks, part of the measures will involve reinforcing/improving the subgrade. This applies to both ballasted and slab track.
▷ The outlay on measures to improve the subgrade (for the "compact" and "elastically supported" types of slab track) as well as correcting the height of the load-bearing system (for the "prefabricated" and "layered" types of slab track) is reduced to half of what it would be for the construction of a new line.
▷ Penalty charges are not considered to the full.

(3) Track renewal

▷ The potential for bringing down the costs of replacement investments in slab track can be realized to 100%, given the high volumes expected and the balanced work load for contractors.
▷ For earthworks, it is assumed that the necessary upgrading work on the substructure (embankment improvements, replacement of the blanketing and frost-protection layers, installation or remediation of drainage systems) will be required to the same extent as for ballasted track.
▷ The decision basis is taken to be the conversion of the ballast bed into a slab-track load-bearing layer, including the cleaning of the ballast removed.
▷ Penalty charges are considered to the full.

Comparing the business cases of both track systems in the narrow sense shows that there are only very few cases involving the building of new lines to carry extremely dense traffic, in which that slab track has a slight cash-value advantage over ballasted track. Despite considering efficiency potential and penalty charges, slab track is hardly going to be able to compensate for the higher initial capital outlay through lower maintenance costs

Table 2: Slab track potential and risks that are not yet quantifiable (Source: "SMP-T" permanent-way strategy project)

Potential	Risks
▷ Shorter journey times, possibly leading to lower costs for train operating companies if they manage to optimize train rosters; ▷ Greater passenger comfort, possibly leading to additional revenue potential for the train-operating companies; ▷ less rolling-stock maintenance thanks to a track with lasting positional stability.	▷ Slab track is vulnerable to subsequent settlement and therefore requires the earthworks to be of a particularly high quality. There is little experience of remedial work to compensate for subsidence under slab track; ▷ The comparatively short experience with slab track to date compared with ballasted track means that service-life expectations are based on no more than estimates.

and availability advantages later on in the circumstances prevailing at Deutsche Bahn.

6.3.2 Middle layer: route-layout potential

The advantages afforded by slab track for laying out routes are regarded as very significant, even though they may be difficult to quantify. The product management engineering unit within Deutsche Bahn's Track Infrastructure division ("NST") was already in possession of a study for the planned new railway line between Stuttgart and Ulm [2], which had set out to examine this issue and others. This study was also used as an input for the project.

Slab track's layout advantage is a particularly weighty one, since the engineering features make up a large proportion of the total costs of building a new railway line, whilst the permanent way accounts for only 5-10% of the project costs. Significant savings on bridges and tunnels (for example in upland terrain) may thus compensate for the additional costs of slab track several times over. However, this potential can only be leveraged if the decision in favour of slab track is taken before the route layout is immutably fixed.

The layout advantages of slab track are not really reflected at all in the official regulations that exist today. Those reserves that are built in for irregularities in ballasted track in lateral acceleration (cant deficiency) could actually be put to use when projecting slab track for the design parameters and maximum values for the track layout, given slab track's greater positional stability over time. Before that can be done, however, the corresponding modifications will need to be made to the national regulations as well as the TSI (Technical Specification for Interoperability) for high-speed railways, which is restrictive in the limits it prescribes, in particular, for cant deficiencies.

6.3.3 Outer layer: miscellaneous potential and risks

The third layer maps the miscellaneous potential and risks of slab track, which might be the decisive factor for a management decision if the two systems perform equally in the two inner layers of the model. These criteria have not yet been subject to a general economic appraisal and should thus, where possible, be supported with quantitative appraisal models for each individual case (Table 2).

7 Summary and prospects

Deutsche Bahn's strategy project for the permanent way has succeeded in pulling together internal and external engineering and methodological skills in such a way as to be able to create a well-founded yet clear and relatively simple process for future decisions concerning the type of track. The project has sifted through the masses of requirements and criteria and has managed to bring out the central issues that are crucial for track-system decisions and to present these in the form of a clearly-structured contextual decision tree.

The decision tree and the LCC tool map the principal technical and economic factors. The stages of working out the decision process and the computation formulae can basically be regarded as having been completed, since the only changes expected for the foreseeable future will concern just the substantial figures – for instance, updating the prices for materials and services.

One possible methodological extension that might merit consideration would be to try and quantify potential production costs for the railway operators. Before that is done, however, the true relevance for the users should be thoroughly clarified first, since, in the final analysis, it must be shown to have an impact on the profit-and-loss statement. The parameters influencing such an analysis would be:

- ▷ Train diagrams: in some circumstances, increasing line speeds may have the effect of reducing the size of the required fleet;
- ▷ Maintenance cycles for trains: a track that maintains an excellent position for a long time may exert lower stresses on trains;
- ▷ Impacts on demand: shorter journey times and enhanced passenger comfort may lead to an increased demand.

Having elucidated the systematic process of arriving at a decision and having clarified what amount of latitude is truly present in the decision-making process, the question as to the right type of track still has to be settled as a final point. This task is being worked on as the permanent-way strategy is further differentiated in a cooperative process involving Deutsche Bahn' technology and track infrastructure operations and the manufacturers.

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