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Finest Link – WP3 Technical concept and economic assessments

Evaluation of transversal tunnel scheme

Memo, Rev. 0

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1. Introduction

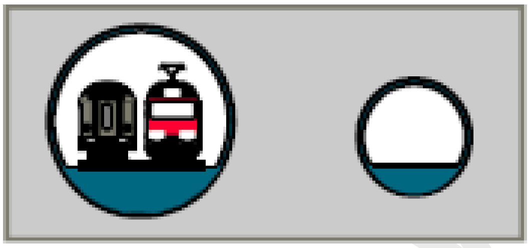
As a first step in the technical design process, six transversal tunnel schemes were evaluated in a generic way in order to solve in a plausible and robust manner the question of the best-possible system for the planned Finest link. Therefore, a matrix was developed to assess the different tunnel options by using seven criteria categories with several subordinate criteria each.

1.1. Transversal tunnel schemes

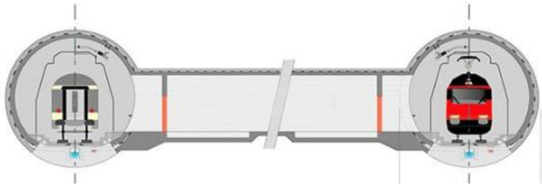
For the evaluation process, the following transversal tunnel schemes were analyzed and assessed:

- A – one double-track tunnel with dividing wall (no service tunnel or cross passages)

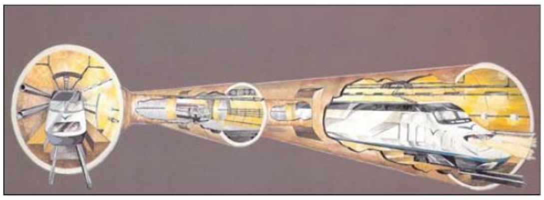
- B – one double-track tunnel and one service tunnel with cross passages



- C – two single-track tunnels with cross passages

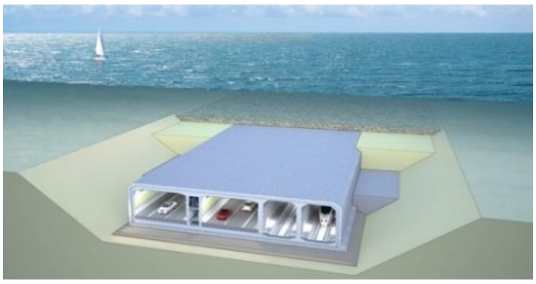


- D – two single-track tunnels and one service tunnel with cross passages



- E – three single-track tunnels with cross passages

- F – immersed tunnel with separate cross sections and cross passages



1.2. Criteria categories

Seven different criteria categories with several subordinate criteria were considered for the evaluation of the transversal tunnel scheme. The main criteria were:

- Train operation concept (TR)
- Tunnel concept and construction including construction costs (TC)
- Maintenance and operation (MO)
- Tunnel safety management (TS)
- Geology, ground and rock engineering (GG)
- Strategic environmental assessment (SE)
- Additional functions of the tunnel (AF)

1.3. Methodology and assessment principles

A utility value analysis (a variants analysis based on a “scoring model”) was used as the methodology for decision-making in the analysis of the transversal tunnel schemes. This is a quantitative, not monetary analytical method in decision-making theory (points procedure). This method has advantages in the case of primarily “soft” decision-making criteria; i.e. those which can be only poorly expressed in monetary or other numerical quantities. For this reason, the utility value analysis is frequently applied in the early project phases, when the project and follow-up costs are only vaguely known.

The benefits of this method can be found in its simple treatment of complex interrelationships, making it possible to achieve in a short time direct comparability between different schemes. The disadvantage is the fact, that the selection and weighting of the criteria are susceptible to highly subjective influences. Therefore the JV has held an internal workshop with all experts in order to discuss the rating, so that the best solution was defined in a transparent, holistic, traceable and robust manner.

A scale of grades, ranging from one (worst solution) to five (best solution), was selected for the evaluation of the individual criteria. Linear interpolation was applied between the two grades, resulting in the following marks:

- 1 – not suitable
- 2 – poor
- 3 – medium
- 4 – good
- 5 – excellent

2. Evaluation criteria and assessment

2.1. Train operation concept

A number of the parameters described below, such as capacity and timetable stability, are generally dependant on train operational conditions such as:

- Quantity of trains per day
- Number of tracks per direction and sidings for overtaking
- Number of cross overs to enable track change
- Portion of passenger and freight trains respectively
- Differences in speed between the train types
- Sequencing of trains, i.e. concentration of freight trains to night time or embedded in morning-evening passenger traffic
- Etc.

In the evaluation of the alternative tunnel schemes listed in chapter 1.1 above, the train operational conditions mentioned above (timetable, quantity and mix of trains, number of cross overs, etc.) are regarded to be the same for all schemes.

Therefore, with the same given train operational conditions for all schemes, the evaluation below considers how the actual design of each tunnel scheme may affect the different parameters.

Below in Table 1 are the ratings, ranging from 1-5 points, for all parameters for the tunnel schemes respectively. In the following sections are some comments about each parameter.

Parameter	Tunnel scheme					
	A	B	C	D	E	F
timetable stability	3	2	3	3	5	3
availibility	3	2	3	3	5	3
travel time	3	2	3	3	5	3
Redundance	3	2	3	3	5	3
Possibility to prolong tunnel in under city centre	3	3	3	3	3	2
Capacity	3	2	3	3	4	3

Table 1 Tunnel scheme scoring for subordinate criteria of "Train operation concept"

2.1.1. Timetable stability

The tunnel schemes A, C, D and F all have two railway tracks, one for each direction, which are physically separated. The rail separation ensures preconditions for a good time table stability (3 p) since the operation in one direction is normally unaffected by the other.

Unlike the four schemes above, the design according to concept B is considered to grant a slightly lower timetable stability (2 p). The reason for this is a probable need for speed reduction when two trains meet to avoid/reduce shock/pressure wave. In addition, any unscheduled train stop in the tunnel in one direction will probably cause significant speed reduction in the other direction.

The three-tube scheme E is rated to have the highest (5 p) stability since all tracks are separated and it should be possible to have two tubes permanently available for operation with respect to maintenance. Furthermore, at traffic peaks three tubes could be in use in a short time span dedicating the third tube for freight trains for example.

2.1.2. Availability

Similar to the subject timetable stability above, tunnel schemes A, C, D and F all have prerequisites for a normal availability (3 p). This is because the operation in one direction is normally unaffected by operation or maintenance in the opposite direction.

Regarding tunnel scheme B, it is evaluated to have a slightly lower availability (2 p). This is caused by the fact, that disturbances or train stops in one direction most probably will stop the operation in the opposite direction.

Scheme E is rated to have the highest (5 p) availability. This is due to the fact that it should be possible to have two tubes constantly open to traffic and the third either in maintenance or available for temporary use at peaks or as a spare for switching over traffic from another tube at disturbances or maintenance.

2.1.3. Travel time

For all tunnel schemes, travel time is rated identically as for timetable stability (see Table 1 above) and the reasoning behind is very similar (see section 2.1.1).

For tunnel scheme E, the third tube should enable a better separation between slower freight trains and passenger trains. A factor that has obvious positive impact on travel time during periods of the day with higher portion of freight trains.

2.1.4. Redundancy

Redundancy is the rail system´s capability to maintain train traffic if a track is taken out of operation due to disturbances or train stop. The logic behind the redundancy rating of the tunnel schemes is similar to the scoring of the parameter availability and the scores are identical (see Table 1 above).

2.1.5. Possibility to prolong tunnel in under city centre

Especially on the Helsinki side, it is very complicated to design an ideal train route above ground which:

- connects to the existing strategic station points
- doesn´t conflict with existing built environment and infrastructure
- allows an attractive train speed/travel time

Therefore, the tunnel schemes, which can be prolonged underneath the city, have a number of advantages regarding train operational parameters compared to schemes which can´t be prolonged. This is reflected in the rating, where all concepts except F (which gets 2 p) are scored good (3 p).

2.1.6. Capacity

Capacity wise, the tunnel schemes A, C, D and F are evaluated to have normal (3 p) dual track capacity due to low influence from trains in opposite direction thanks to the physical separation wall.

Concept B is rated to have a lower capacity (2 p) because of potential speed restrictions for oncoming trains in the open tunnel and/or a limitation of number of oncoming trains during a tunnel passage for a certain train.

Scheme E is assessed to have highest (5 p) capacity. Reason for this is that it should be possible to have two tubes constantly open for traffic and the third available for temporary use at peaks or to separate freight trains from passenger traffic.

2.1.7. Summary

From a train operation point of view, there are no scoring differences between all the concepts with two separated tracks, apart from the lower possibility to prolong an immersed tunnel than the others. These concepts overall score good (3 p) for the evaluated parameters.

The single tube-scheme without physical separation generally score poor (2 p), apart from the possibilities to prolong under city centre where the score is 3 points.

Not very surprising, the three tube-scheme overall scores higher than the other concepts. This is thanks to the fact that it has one more rail route/50 % more rail infrastructure than the other schemes, which is very beneficial from, for example, capacity and redundancy point of view.

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2.2. Tunnel concept and construction

For the planned Finest link tunnel, expertise, experience and data from large scale tunnelling projects such as Gotthard base tunnel, Brenner Base tunnel or Lyon-Turin Base tunnel is considered.

As construction time is a key parameter for such long tunnels, it is a common practice to use tunnel boring machines (TBMs) for the construction of such large scale tunnelling projects. Compared to common used drill-and-blast technique, the advance rates of TBMs are up to 2.5 times higher than conventional methods.

For this evaluation it is assumed, that a Finest link bored tunnel will be constructed mainly with TBM by using a so-called Shield-TBM with segmental lining (see Figure 1 below). As an advantage of this type of TBM, the tunnel lining is going to be installed few metres behind the tunnel face. Depending on the geology and ground conditions, different modifications of TBM (e.g. face support measures, cutter head equipment) have to be used. For excavation of possible cross passages, drill-and-blast technique will be used.

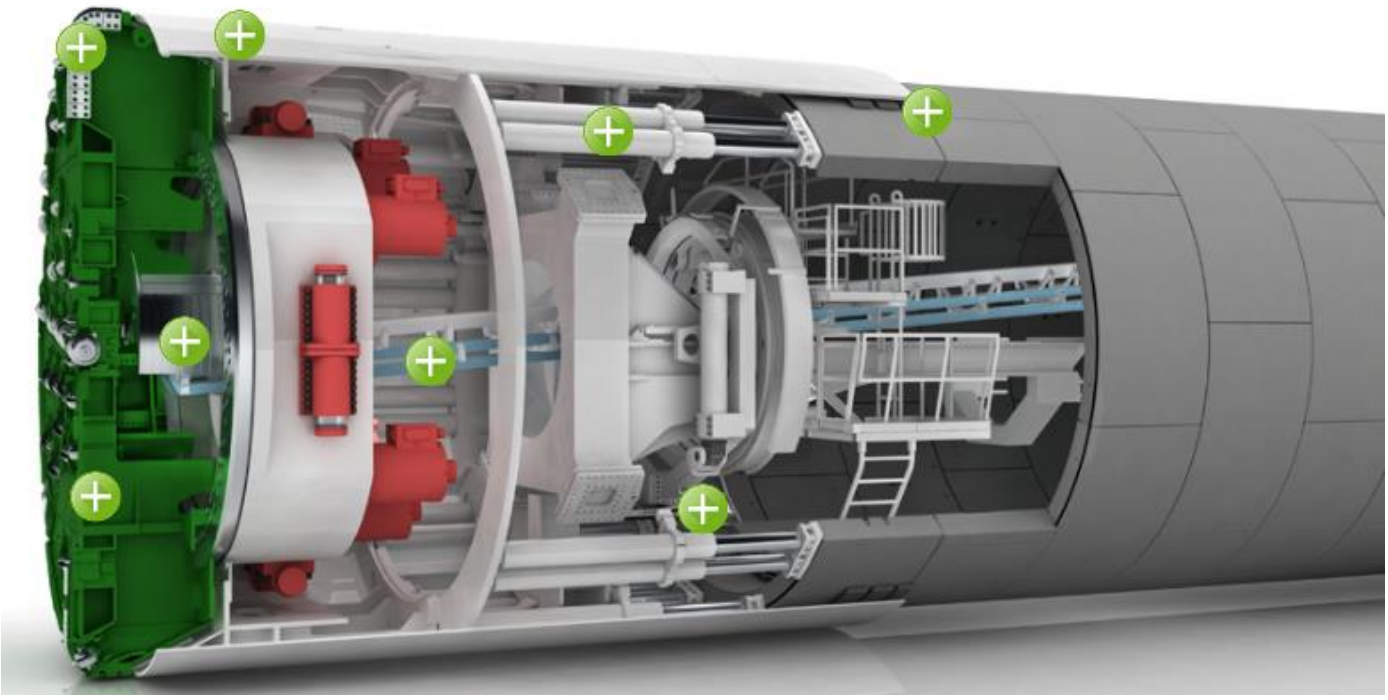

Figure 1 Shield-TBM with segmental lining (source: www.herrenknecht.com)

In the evaluation of the alternative tunnel schemes listed in chapter 1.1 above, the following subordinate criteria were considered under “Tunnel concept and construction” section:

- Construction method suitability
- Logistics and ventilation
- Construction time
- Risk of delay
- Cost risks

Additionally, construction costs are estimated for all tunnel schemes in relation to each other in order to get a first impression of the cost differences between each type. However, these costs were not considered as an evaluation criteria.

Table 2 below summarizes the ratings and the weighting factors for subordinate criteria of “Tunnel concept and construction” section. Tunnel scheme C representing the Gotthard Base Tunnel (GBT) system is considered as common practice solution.

Parameter	weighting factor	Transversal tunnel schemes					
		A	B	C	D	E	F
Construction method suitability	30%	*3*	*3*	*4*	*5*	*4*	*1*
Logistics & ventilation	10%	*2*	*3*	*4*	*4*	*5*	*3*
Construction time	30%	*3*	*3*	*4*	*4*	*4*	*3*
Risk of delay	15%	*2*	*3*	*3*	*4*	*4*	*5*
Cost risks	15%	*2*	*3*	*4*	*4*	*4*	*3*

Table 2 Tunnel scheme scoring for subordinate criteria of “Tunnel concept and construction”

2.2.1. Construction method suitability

From construction point of view, tunnel schemes A to E (bored tunnel solutions) are very similar, as all of them will be built using a TBM and have to go through the same geological zones.

Generally speaking, the larger the tunnel diameter the more construction difficulties it causes. A and B with just one large tunnel tube for train operation are rated slightly lower (3 points), than the standard and reference solution C (4 pt.). Option E is very similar to C, as there are three tunnels with same diameter instead of two.

Tunnel scheme D with 2 tubes of same diameter plus service tunnel is given the highest rating (5 pt.) since the service tunnel can be used for additional geological exploration. Additionally, the service tunnel will be excavated with smaller diameter which is favorable from construction aspects.

Unlike the bored tunnel schemes, concept F “immersed tunnel” uses a different approach for construction. A ditch has to be excavated on the sea floor, in which precast elements will be immersed from the water surface and connected to each other at the sea floor. Consequently, a flat bed is required for the construction under water. According to the longitudinal profile, the sea floor is very uneven with a very steep section at the Estonian side. Additionally, immersing of segments in the expected water depth will be complicated and technically challenging. Therefore, tunnel scheme F is considered as not suitable (1 pt.).

2.2.2. Logistics and ventilation

For ventilation purposes, the dividing wall in tunnel scheme A, is needed to be at least 7 km behind the tunnel face. Consequently, the invert has to be completed together with the advancing of the tunnel. This has large impact on tunnel logistics (muck transport, segmental lining transport), thus a rating of 2 points (poor) is given for variant A. Tunnel scheme B is rated slightly better (medium, 3 pt.) as the tunnel offers more space for logistics without a wall in its center. Negative impact on logistics and ventilation is caused by different concepts and systems, due to different diameters of the running tunnel and the service tunnel.

From logistic point of view Tunnel schemes C, D and E are very similar. A higher number of tunnels (e.g. 3 tubes vs. 2 tubes) results in higher demands concerning logistics and ventilation, but offer more flexibility.

As for Design E the same concept can be used for all three tubes due to the same diameter. Consequently it was rated slightly higher (excellent 5 pt.) than C and D (good, 4 pt.).

For immersed tunnels, different requirements have to be considered as for bored tunnel solutions. The preparation of the flat bed and the segment placing on the sea floor is more complex, with respect to the transport over open sea, placing and connection of segments, but in contrast there is no comparable restrictions of space. Thus tunnel scheme F is assessed to be medium (3 pt.).

2.2.3. Construction time

Similar to the criteria "Construction method suitability" mentioned above, tunnel schemes C, D and E are almost the same regarding construction time, as the excavation of the tubes will be happening more or less parallel. For option E, this can be said under the assumption, that additional TBMs will be used. Therefore, those schemes are considered to be good (4 pt.), regarding construction time.

A larger tunnel diameter results in a smaller excavation rate and consequently a longer construction time. This is taken into account with a rating of 3 points (medium) for single-tube solutions A and B. Additionally, a larger diameter is more difficult to deal with in geological fault zones.

The precast segments, forming the immersed tunnel, can be produced on landside at several construction sites. This leads to a shorter construction time. In contrast, it is assumed that the bed-preparation and the immersing process is very time-consuming, which leads in total to a medium rating (3 pt.) for Tunnel scheme F.

2.2.4. Risk of delays

Compared to the standard solution C, which is assessed as medium (3 pt.) in this case, option A is rated slightly worse (poor, 2 pt.) as there are higher risks connected with larger tunnel diameters. Moreover, there is no possibility for by-passing with the second tunnel in case of difficulties. Variant B scores 3 points (medium) as higher risks due to larger diameter are compensated by additional intervention possibilities through the service tunnel.

Under the assumption that the service tunnel in tunnel scheme D and the third tunnel of E allows geological investigations and counteractions in case of difficult geological zones, both are evaluated as good (4 pt.) regarding the risk of delay.

Due to the fact, that the precast elements of immersed tunnel design F can be built on landsides at several construction sites and there are almost no geological risks, it is assumed to have full flexibility with regard to time scheduling (excellent, 5 p.).

2.2.5. Cost risks

The cost risks for the evaluated tunnel schemes are very similar to the risk of delay as stated above. A larger diameter results in a higher risk of additional costs as it causes more difficulties from construction point of view rather than a smaller tunnel diameter. A solution with more tunnels reduces the risk, as on the one hand geological investigations can be made during excavation of the first tunnel and on the other hand counteractions in case of difficulties are possible. This leads to good ratings for options C, D and E (4 pt.), a medium rating for B (3 pt.) and a poor rating for A (2 pt.).

Considering the immersed tunnel solution F, several risks are related to the immersing process of the precast segments. As for that, professional divers and special equipment are required, the cost risks are evaluated as medium (3 pt.).

2.2.6. Construction costs

At the very beginning of this feasibility study, construction costs for different transversal tunnel schemes cannot be calculated in a serious manner. However, in order to provide a first impression, the costs for all systems are estimated in relation to each other. Design C is considered as a reference to be 100% and all the others are compared to that value. For tunneling projects, as a the first step, construction costs can be taken as a function of the tunnel cross section size. Under this assumption, the construction costs for tunnel scheme A are taken to be 110%, for B 105%, for D 130% and for variant E 150%, provided that the ground is homogenous as schemes have differing cost impact of fault zones. For the immersed tunnel, no estimation of the construction costs could be made at the moment. Consequently, construction costs were not assessed within this section, but only considered for the calculation of the cost benefit ratio at the end (see chapter 3.1).

2.2.7. Conclusion

From a construction point of view, the tunnel schemes D and E with three tunnel tubes, both are favorable as they offer several advantages:

- Cross section size can be reduced compared to double-track tunnel
- More flexibility regarding logistics and ventilation
- Possibility of geological investigation and counteractions in case of difficulties

Taken into account the weighting of subordinate criteria, tunnel scheme E with three tunnel tubes is the best, whereas tunnel scheme B with one double-track tunnel and a service tunnel is the worst.

2.3. Maintenance and operation

Maintenance of tunnel system is mandatory in frequently for keeping tunnel safe and reliable for train operation. Comparison between different tunnel schemes is focused to identify differences between cross sections. For the evaluation of different tunnel schemes the following criteria were taken into account:

- ease of maintenance (track, power, drainage, GMS,…)
- accessibility & safety of operation site
- need of maintenance

Table 3 below summarizes the ratings and the weighting factors for subordinate criteria of “Maintenance and operation” section. Tunnel scheme C representing the Gotthard Base Tunnel (GBT) system is considered as common practice solution.

Parameter	Weighting factor	Transversal tunnel schemes					
		A	B	C	D	E	F
Ease of maintenance	40%	1	2	2	4	3	3
Accessibility & safety of operation site	40%	2	2	3	4	3	4
Need of maintenance	20%	3	3	3	3	2	3

Table 3 Features related to maintenance and operations of different tunnel schemes

2.3.1. Ease of maintenance

In evaluation “ease of maintenance” criteria means how much availability time each tunnel scheme will give for train operation. In other words it’s comparing the differences of how fast maintenance operations could be executed and how short maintenance closure times are for the different tunnel schemes. Scheme D was evaluated 4pt based on separate service tunnel for technical systems. Scheme F can be identical, but immersed concreted structures will need some extra attention. Tunnel scheme E was evaluated 3pt because all maintainable objects are located on running tunnels and can only be accessed on service train. Same reason leads 2pt in scheme C. Scheme B has separate service tunnel but single bi-directional running tunnel which will lead to longer maintenance periods and therefore a score of 2pt was given. Tunnel scheme A was evaluated poorest because of concrete “bridge/wall” structures and difficult access to service gallery below tracks.

2.3.2. Accessibility & safety of operation site

In evaluation “Accessibility & safety of operation” means how easily each maintainable object or tunnel section can be reached. Tunnel schemes D and F were evaluated 4pt cause of easy access via service tunnel and possibility to access via closed running tunnel. In schemes A, C and E there is only access via running tunnel and scheme B by service tunnel and running tunnel, but running tunnel must be totally closed during maintenance.

2.3.3. Need of maintenance

Criteria “need of maintenance” compares differences in maintenance frequency between tunnel schemes. There are no significant differences between tunnels schemes in this because needed equipment and systems are almost of the same extent. Immersed tunnel was evaluated 2pt because of structures and seals which will need special care compared other rock tunnel schemes.

2.3.4. Conclusion

From tunnel maintenance and operations point of view it can be concluded, that variant D is the most favorable transversal tunnel scheme for the Finest link and option A the worst.

2.4. Tunnel safety management

For the evaluation of the different tunnel schemes, the following subordinate criteria were taken into account under “Tunnel safety management” section:

- Working safety during construction

- Operational safety – self-rescue
- Operational safety - intervention

Other aspects of operational safety like evacuation, influence on other trains or prevention are also considered and included in the rating of the two operational safety criteria listed above.

Table 4 below summarizes the ratings and the weighting factors for subordinate criteria of "Tunnel safety management" section. Tunnel scheme C representing the Gotthard Base Tunnel (GBT) system is considered as a common practice solution.

Parameter	**weighting factor**	**Transversal tunnel schemes**					
		A	B	C	D	E	F
Working safety during construction	20%	*2*	*3*	*4*	*4*	*4*	*1*
Operational safety - self-rescue	40%	*1*	*1*	*3*	*5*	*3*	*3*
Operational safety - intervention	40%	*1*	*2*	*3*	*4*	*3*	*3*

Table 4 Tunnel scheme scoring for subordinate criteria of "Tunnel safety management"

2.4.1. Working safety during construction

The working safety for the standard solution C same as built for the Gotthard base tunnel is considered as good (4 points). Tunnel schemes D and E offer more flexibility due to a higher number of tunnels, for instance more means of escape in the event of a fire. In contrast, more tunnel faces lead to higher safety risks, thus D and E also rated as good (4 pt.).

In contrast, option A with just one single tube is considered as poor (2 pt.) regarding working safety as there is no rescue option in parts where the dividing wall is not yet constructed. Scheme B with an additional service tunnel is evaluated as medium (3 pt.) regarding working safety.

The immersed tunnel option is rated as not suitable (1 pt.) considering working safety as the immersing and placing is done by divers at a place, where interaction with sea traffic is possible. Additionally there is a high risk of flooding but no rescue option as the tunnel is only one single box.

2.4.2. Operational safety – self-rescue

When it comes to self-rescue during operation, safe areas for escaping persons are of high importance. Tunnel scheme D is rated as excellent (5 pt.) as the service tunnel can be used as a safe haven, which is easy accessible and not part of operation system. That is why options C and E are evaluated as medium (3 pt.) as there are all tubes under train operation. An immersed tunnel can also provide a safe section but as all parts are combined into one single box, the distances between each sections are very small and therefore not as well shielded as with cross passages. Consequently, variant F is assessed as medium (3 pt.).

Both schemes A and B with larger cross sections offer more space for smoke propagation. However, in case of Design B, the second rail has to be crossed by escaping people in case of an emergency, which is very difficult for persons with reduced mobility, as well as dangerous due to other crossing trains. In scheme A, a buffer zone for escaping persons is missing, which means, people would have to evacuate directly into a tunnel with running traffic. Consequently scheme A and scheme B are rated as not suitable (1 pt.) regarding self-rescue during operation.

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2.4.3. Operational safety – intervention

The evaluation regarding intervention is very similar to the one regarding self-rescue. Tunnel scheme A is considered as not suitable (1 pt.) as intervention has to take place through same compartments as running traffic, which will lead to interactions with escaping people on track. For option B, intervention both through service tunnel and through tube is difficult due to escaping persons, respectively smoke. Therefore, B is assessed as poor (2 pt.).

Tunnel schemes C and E represent the standard and common practice solution and are rated as medium (3 pt.). Option F is very similar to C and E and consequently rated the same (3 pt.). Variant D scores 4 points (good) as the service tunnel can be included into the safety concept and therefore more versatility is offered.

2.4.4. Conclusion

From tunnel safety management point of view it can be concluded, that variant D is the most favorable transversal tunnel scheme for the Finest link and option A the worst.

2.5. Geology, ground and rock engineering

Tunnel schemes with one tube option (A and B) need to have larger tunnel profile (diameter) compared to 2 or 3 tube options (C, D and E). In case of poor rock quality and fracture zones, the larger cross section is more difficult to excavate and support and thus more risky for schedule delays and unpredicted costs. One tube tunnel (A) is also sensitive to changes in geological conditions such as fracture zones which cannot fully be predicted during construction. This could however be solved by constantly drilling a pilot hole and execute reinforcing pressure grouting when needed. In this case the propagation speed of the tunnel construction work is slowed down significantly.

Instead in scheme alternatives (D and E) with a separate service tunnel or three similar tunnels, the service tunnel or one of the three tunnels can advance as a pilot from which eventually needed reinforcement measures, such as pre-grouting, for the other two tunnels can be executed. Thus the tunnel construction work is possible to carry out with fewer delays. Additional geological investigations can be also done from pilot tunnel.

When tunnel cross section is larger it is more difficult to control and make water proof solution. If the pilot tunnel can be used for pre-investigation measures and pre-grouting works, the amount of in leaking water is easier to reduce. However the larger the wall surface area of the excavated tunnel is - the more water leakage can be expected. This has to be taken into account especially in sensitive groundwater areas like the Vimsi area. Therefore tunnel option with 3 tubes (E) is more risky than the two tunnel scheme with a service tunnel.

In the immersed tunnel option (F), sealing the concrete structure and joints to be water proof is critical especially when the water pressure is at the most over 1 MPa. In order to install the tunnel elements the seabed has to be levelled for the tunnel. The topography on the Finnish coast is very variable and the seabed relatively soft on the Estonian coast. This means that large underwater earthworks and subgrade reinforcements are needed.

2.6. Strategic environmental assessment

2.6.1. The use of natural resources

The drilled tunnel variants are with similar environmental consequences as the construction material can be for most part obtained from the excavated material. The excess material can be in principle reused. For instance, the road construction in Estonia has chronical shortage of good building material. That is not the case in Finland, where there is more building materials available for infrastructure projects.

The immersed tunnel option F is least favorable as the building material should be taken from elsewhere and this will cause additional environmental burdens as viable sources could be far from the building site (sand for the concrete in Estonian side, for instance). In addition, immersed tunnel option would not provide any relief on the construction material shortage on Estonian side.

2.6.2. Environmental impacts during construction

The underground excavation process of the bored tunnel variants have some impact to the groundwater quality and availability, especially in Estonian side where geological conditions are more complicated. Impact to the Aegna Landscape reserve Natura 2000 area could be probably avoided by careful lateral alignment of the tunnel. In Finland, there is no Natura areas in the sphere of influence nor other nature reserve areas.

The situation is more complicated with immersed tunnel option where in addition to the groundwater complications and Natura issues there would be considerable impact to the aquatic and benthic habitats and ecosystems as substantial areas of the seabed must be cleaned and sediments relocated. The bored tunnel variants will have same kind of impacts but in smaller scale by establishing intermediate access points in the sea by means of vertical shafts (lesser impacts to seabed but larger by transport of material to the storage places) or artificial islands (more impacts to seabed and lesser by transport of materials to the storage places on land).

Above ground, the building time impacts are due to material relocation and movement of building machinery. Impacts are relatively similar with all the tunnel schemes. All schemes need also huge landfill areas both in Estonia and in Finland. The amount of excavated rock is up to 17-20 million m3. This is a big logistic challenge too.

Large landfill areas accessible to the sea transport (port) and further transport to reuse (railway) could be in principle found in several places in North Estonia. There are quarries close to Muuga port and ports in Paldiski and Sillamäe. Actual usability and capacity is subject to further studies with accompanied EIA-s. In Helsinki Metropolitan Area there is no much landfill capacity to be found at the moment.

Impact to the third parties directs to the shipping mainly by the immersed tunnel option. There will be disturbance even to the on land operations of other parties but here the differences between options is not significant.

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Criteria	Shaft option	Artificial island option
Reuse possibilities of excavated material	Relieves the need of regional shortage of good building material.	Used to form an island
Transportiton need	Large, barges and/or ships	Minimal need
Need of (temporary) material storage places	Need of construction site of shaft structures	Need of large (excess material) storage areas close to the harbours
Impact to the seabed	Limited to the supporting structures of the shaft	Extensive new structure will be built
Possibilities of secondary use	Ventilation?	Windmills, ventilation, recreation, commercial

Table 5 Comparison of mid station variants during construction of bored tunnel variants. Green font stands for positive aspect

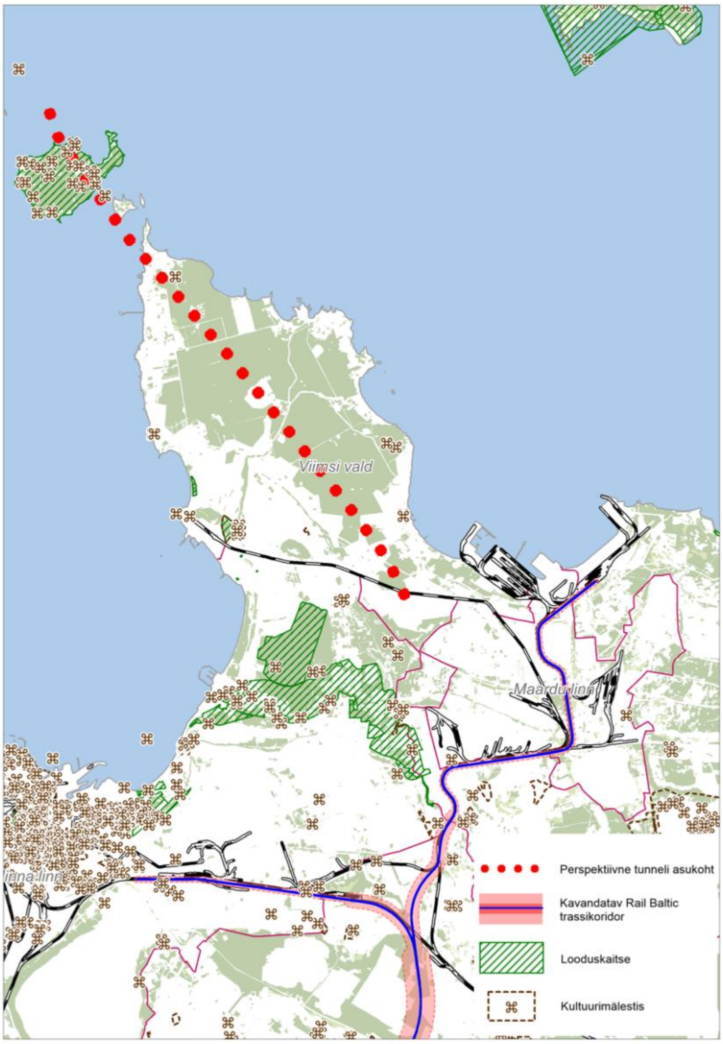

Figure 2 Nature and heritage conservation issues at the Estonian side of the Viimsi-Muuga option of the Finest link

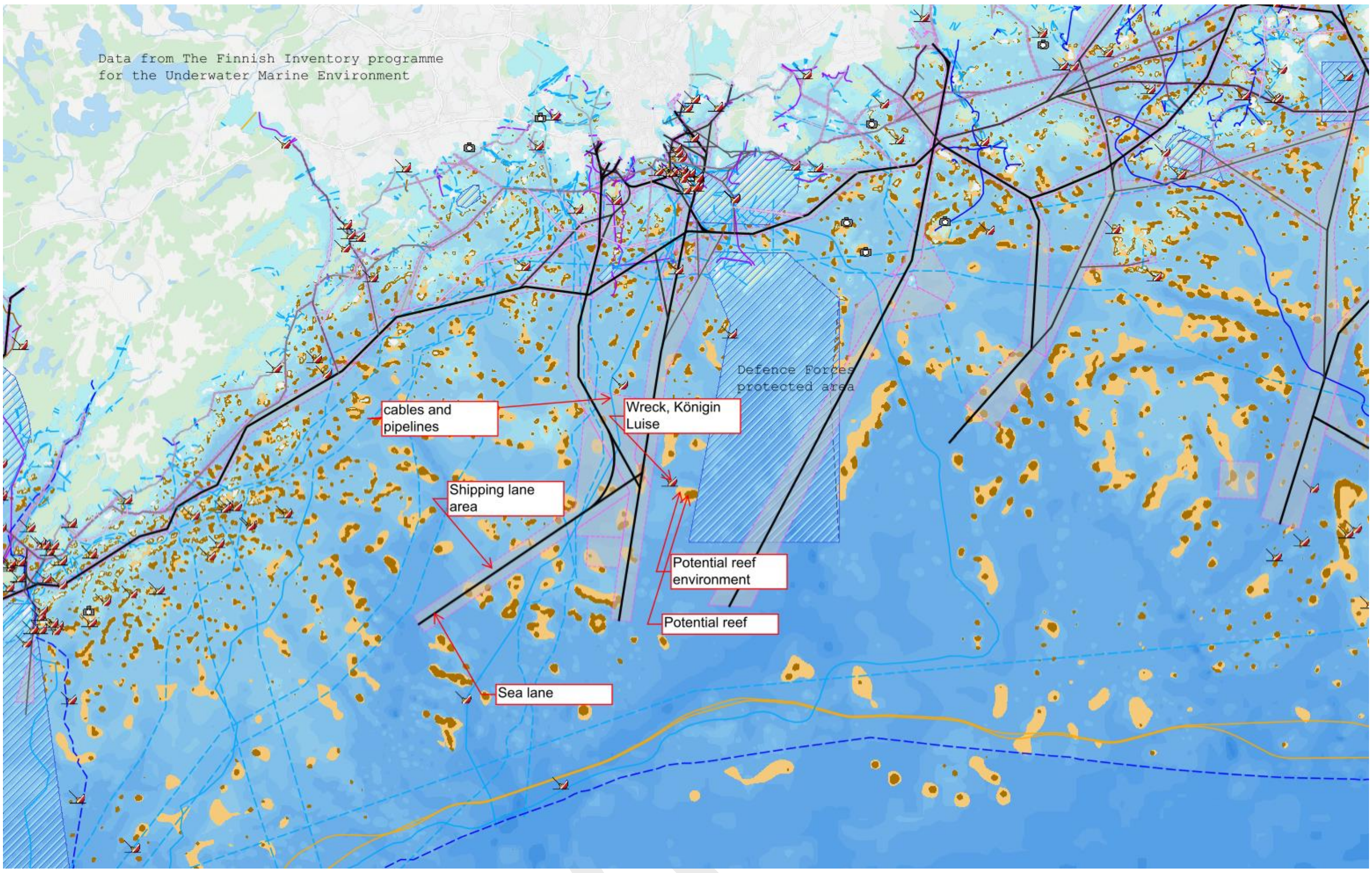

Figure 3 Data from the Finnish Inventory Programme for the Underwater Marine Environment

2.6.3. Impacts after opening to the traffic

Environmental impacts are due to changes in the passenger and freight. Carbon footprint change depends on how big the transition from ship to rails is and how much tunnel increases the total volume of passengers and freight between Tallinn and Helsinki.

2.7. Additional functions of the tunnel

The evaluation of the transversal tunnel schemes with respect to the additional functions concentrates on the future use of additional utilities. In this aspect, it has to be concluded, that for all tunnel options without a service tunnel, the traffic volume cannot be exceeded. Therefore, variants A and C are rated poor (2 points). Scheme E with three tunnel tubes has already more capacity than the others, however one track is needed for occasional service purpose, which also leads to a poor rating (2 pt.).

For tunnel schemes B, D and F, the service tunnel could be oversized for possible future demands. That is why those options scored 4 points (good) regarding additional functions and future use of the finest link.

3. Conclusion

3.1. Results

The total score determined for each tunnel scheme, which is composed of the correspondingly weighted section scores, was definitive in the variant selection decision. Table 6 below shows the applied weighting factors for each criteria as well as the single ratings of each tunnel scheme for different criteria categories. The last column on the very right end presents the best solution for each category. As it can be seen, option D is the best solution for most of the evaluation criteria and also the best overall-solution. Only with respect to the train operation concept, the three tube-scheme E has a higher score than all the other concepts. As stated in chapter 2.1.7, this results out of the fact, that it has 50 % more rail infrastructure, which is very beneficial from operational point of view.

Based on the estimated relative construction costs for each design, the cost benefit ratio was calculated. It turned out, that tunnel schemes C and D are most favorable, which strengthens the decision made for the best-possible system D.

evaluation criteria	weighting factor	A	B	C	D	E	F	best solution
Train operation concept	25.0%	3.0	3.0	3.0	3.0	4.6	2.9	E
Tunnel concept and construction	10.0%	2.6	3.0	3.9	4.3	4.1	2.7	D
Maintenance and operation	23.0%	1.8	2.2	2.6	3.8	2.8	3.4	D
Tunnel safety management	30.0%	1.2	1.8	3.2	4.4	3.2	2.6	D
Geology, ground & rock eng.	5.0%	3.2	3.2	3.8	4.4	3.8	2.4	D
Strategic environmental ass.	5.0%	3.0	3.0	3.0	3.0	3.0	1.0	A - E
Additional functions of tunnel	2.0%	2.0	4.0	2.0	4.0	2.0	4.0	B + D + F
weighted total	100.0%	2.1	2.5	3.1	3.8	3.5	2.8	D
construction costs		110%	105%	100%	130%	150%		
cost benefit ratio		0.515	0.422	0.325	0.340	0.423		

Table 6 Results of evaluation of transversal tunnel scheme for Finest link

3.2. Sensitivity check

In order to make sure, that the decision was made in a stable and robust manner, the weighting of the section scores was varied within a certain bandwidth to simulate the sensitivity of the system decision with reference to the various project requirements.

In the first step, the weighting factor of subordinate criteria within one section was varied. The following Table 7 shows 5 variations of weighting for section “Tunnel concept and construction”. It is apparent for every variation in weightings, that tunnel scheme D in all cases achieves the highest total score and has, overall, an only slightly varying total score.

In the second step, the weighting factors of the main criteria categories were varied. Table 8 and Table 9 show two different weighting possibilities for the seven evaluation criteria categories. As an end result, in both cases, option scheme D remains to be the most suitable solution.

TC	S1	S2	S3	S4	S5		S1	S2	S3	S4	S5	scheme
construction method suitability	30%	20%	50%	30%	20%		2.6	2.4	2.65	2.8	2.6	A
logistics & vent	10%	20%	15%	10%	20%		3	3.0	3	3.0	3.0	B
construction time	30%	20%	15%	50%	40%		3.85	3.8	3.9	4.0	3.9	C
risk of delay	15%	20%	10%	5%	10%		4.3	4.2	4.5	4.3	4.2	D
cost risks	15%	20%	10%	5%	10%		4.1	4.2	4.15	4.1	4.2	E
check	ok	ok	ok	ok	ok		2.7	3.0	2.2	2.5	2.8	F
							D	D	D	D	D	best
							A	A	F	F	A	worst

Table 7 Variation of weighting factor of subordinate criteria of section "Tunnel concept and construction"

evaluation criteria	weighting factor	A	B	C	D	E	F	best solution
Train operation concept	7.1%	3.0	3.0	3.0	3.0	4.6	2.9	E
Tunnel concept and construction	7.1%	2.6	3.0	3.9	4.3	4.1	2.7	D
Maintenance and operation	7.1%	1.8	2.2	2.6	3.8	2.8	3.4	D
Tunnel safety management	50.0%	1.2	1.8	3.2	4.4	3.2	2.6	D
Geology, ground & rock eng.	7.1%	3.2	3.2	3.8	4.4	3.8	2.4	D
Strategic environmental ass.	7.1%	3.0	3.0	3.0	3.0	3.0	1.0	A - E
Additional functions of tunnel	7.1%	2.0	4.0	2.0	4.0	2.0	4.0	B + D + F
weighted total	100.0%	1.7	2.2	2.9	3.8	3.1	2.5	D
construction costs		110%	105%	100%	130%	150%		
cost benefit ratio		0.642	0.474	0.344	0.341	0.492		

Table 8 Variation 1 of weighting factors of criteria categories

evaluation criteria	weighting factor	A	B	C	D	E	F	best solution
Train operation concept	20.0%	3.0	3.0	3.0	3.0	4.6	2.9	E
Tunnel concept and construction	20.0%	2.6	3.0	3.9	4.3	4.1	2.7	D
Maintenance and operation	20.0%	1.8	2.2	2.6	3.8	2.8	3.4	D
Tunnel safety management	20.0%	1.2	1.8	3.2	4.4	3.2	2.6	D
Geology, ground & rock eng.	6.7%	3.2	3.2	3.8	4.4	3.8	2.4	D
Strategic environmental ass.	6.7%	3.0	3.0	3.0	3.0	3.0	1.0	A - E
Additional functions of tunnel	6.7%	2.0	4.0	2.0	4.0	2.0	4.0	B + D + F
weighted total	100.0%	2.3	2.7	3.1	3.9	3.5	2.8	D
construction costs		110%	105%	100%	130%	150%		
cost benefit ratio		0.485	0.391	0.321	0.336	0.425		

Table 9 Variation 2 of weighting factors of criteria categories

It can be concluded, that transversal tunnel scheme D consisting of two single-track tunnels and one service tunnel with cross passages is the most suitable and best-possible tunnel solution for the planned Finest link.

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Appendix:

Evaluation matrix transversal tunnel scheme

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FinEst - WP 3 Rev. 01

06.04.2017

Evaluation of transversal tunnel scheme

responsibility: Amberg; Sweco & Hendrikson; WSP

key:
- TR train operation concept
- TC tunnel concept and construction
- MO maintenance and operation
- TS tunnel safety management
- GGR geology, ground & rock eng.
- ~~EF economic and financial feasibility study~~
- SE strategic environmental ass.
- AF additional functions of tunnel

assessment
1 not suitable
2 poor
3 medium
4 good
5 excellent

key words for construction method (first assumption): *mainly TBM drive, shield TBM with segmental lining, open-shield or mixed-shield TBM (depending on geology), sectionswise grouting works if requiered, conventional excavation of possible cross passages*

task	weighting factor	tunnel schemes & tunnel types / evaluation criteria	weighting factor subtasks	A: 1 tube tunnel with dividing wall (no service tunnel or cross passages)	A	B: 1 tube tunnel with cross passages and service tunnel	B	C: 2 tubes with cross passages	C	D: 2 tubes with cross passages and service tunnel	D	E: 3 tubes with cross passages	E	F: immersed tunnel with separate cross sections and cross passages	F
train operation concept	25%	timetable stability	20%	Normal stability and low influence from meeting trains due to physical separation between train routes	3	Risk for speed reduction, pressure waves and influece due to meeting trains not physically separated	2	Normal stability and low influence from meeting trains due to physical separation between train routes	3	Normal stability and low influence from meeting trains due to physical separation between train routes	3	Highest stability because two tubes permanently (and occationally three) available for operation	5	Normal stability and low influence from meeting trains due to physical separation between train routes	3
		availibility	15%	Normal two track availibilty to be expected because very low influence from meeting trains due to physical separation	3	Disturbance or train failure in tunnel probable to stop both directions	2	Normal two track availibilty to be expected because very low influence from meeting trains due to physical separation	3	Normal two track availibilty to be expected because very low influence from meeting trains due to physical separation	3	Highest availability (permanently two tubes for operation available)	5	Normal two track availibilty to be expected because very low influence from meeting trains due to physical separation	3
		travel time	15%	Travel time in one direction unaffected by traffic in the other because of physical separation	3	Possibly longer travel time due to reduced speed when trains in opposite direction pass eachother	2	Travel time in one direction unaffected by traffic in the other because of physical separation	3	Travel time in one direction unaffected by traffic in the other because of physical separation	3	Enables better separation between goods and passenger trains => higher time table flexibility over 24 h	5	Travel time in one direction unaffected by traffic in the other because of physical separation	3
		Redundance	20%	Accpetable/normal redundancy thanks to track separation and cross over possibilities every 20 km approx	3	Lower redundancy while disturbance or train failure in one train direction probably stops both traffic directions	2	Accpetable/normal redundancy thanks to track separation and cross over possibilities every 20 km approx	3	Accpetable/normal redundancy thanks to track separation and cross over possibilities every 20 km approx	3	Best from redundancy perspective because the third tube gives bigger possibilities for traffic alterations by disturbances	5	Accpetable/normal redundancy thanks to track separation and cross over possibilities every 20 km approx	3
		Possibility to prolong tunnel in under city centre	10%	Concept possible to prolong under city to avoid conflict with city structure and optimize train route. Same technology for drilled tunnel under sea and city and no mouth/joint under sea level	3	Concept possible to prolong under city to avoid conflict with city structure and optimize train route. Same technology for drilled tunnel under sea and city and no mouth/joint under sea level	3	Concept possible to prolong under city to avoid conflict with city structure and optimize train route. Same technology for drilled tunnel under sea and city and no mouth/joint under sea level	3	Concept possible to prolong under city to avoid conflict with city structure and optimize train route. Same technology for drilled tunnel under sea and city and no mouth/joint under sea level	3	Concept possible to prolong under city to avoid conflict with city structure and optimize train route. Same technology for drilled tunnel under sea and city and no mouth/joint under sea level	3	Concept more complex to prolong due to tunnel mouth/tunnel joint between immersed and drilled tunnel under sea level	2
		Capacity	20%	Normal two track capacity to be expected because very low influence from meeting trains due to physical separation	3	Risk for lower capacity due to speed reduction, pressure waves and influece due to meeting trains not physically separated	2	Normal two track capacity to be expected because very low influence from meeting trains due to physical separation	3	Normal two track capacity to be expected because very low influence from meeting trains due to physical separation	3	Highest capacity because two tubes permanently (and occationally three) available for operation	4	Normal two track capacity to be expected because very low influence from meeting trains due to physical separation	3
		train length, oversize load, weight	0%	not influencing		not influencing		not influencing		not influencing		not influencing		not influencing	
tunnel concept and construction	10%	construction method suitability	30%	difficulties due to very large diameter for double track tube, no exploration possible, no supporting from second tunnel possible, no need of cross passages	3	difficulties due to very large diameter for double track tube, geological exploration through service tunnel possible	3	standard and state-of-the art solution , same diameter excavation [Gotthart base tunnel]	4	same diameter excavation, geological exploration through service tunnel possible (smaller diameter favorable) [Brenner base tunnel, Lyon-Turin]	5	TBM excavation, same diameter, one tube can be used for geological exploration	4	precast element production on land, ditch excavation on sea floor, immersing of segments very difficult due to water depth, flat bed is required but sea floor is very uneven, very steep sections in EST (refer to longitudinal profile), more information about bedding conditions required	1
		logistics & ventilation	10%	very difficult, diving wall is needed for ventilation issues at least 7 km behind tunnel face -> impact on tunnel logistic (conveyor belt for muck transp, segmental lining transport) more complex logistics as invert has to be completed together with advance	2	different concepts/systems due to different tunnel diameter, large TBM & tunnel offer more space for logistics	3	parallel excavation process in two tubes, operation equipment is needed in two tunnels, may need cross overs for construction purposes only	4	higher logistics and ventilation needs due to 3 tubes, more flexibility than C, may need cross overs for construction purposes only	4	parallel excavation process in three tube, full flexibility, may need cross overs for construction puposes only, higher logistics and ventilation needs due to 3 tubes	5	different requirements than bored tunnel, logistics to prepare bed for segment placing (transport over the open sea, placing itself, fixing together different segments)	3
		construction time	30%	large diameter construction slower/longer than smaller single track tubes, larger diameter more difficult to deal with in faultzones etc very difficult by-pass possibilities in case of problems	3	large diameter construction slower/longer than smaller single track tubes, larger diameter more difficult to deal with in faultzones etc	3	excavation of both tubes more or less parallel	4	tube excavation more or less parallel more complex to handle in case of intermediate attacks	4	approx. same as for C depending on numbers of TBMs, more complex to handle in case of intermediate attacks	4	no intermediate attacks needed, potentially several construction sites hence short construction time, time-consuming sea bed-preparation and immersing process	3
		construction costs (only homogenous ground conditions are assumed, solution differing cost impact of fault zones etc are considered to be of having no impact)	0%	approx. 10% more expensive than C due to bigger cross section **ref: 110%**		operation equipment required only for 1 tube, same or little bit more expensive than C due to larger tunnel diameter **ref: 105%**		standard solution (Gotthart base tunnel) **ref: 100%**		lower than 3 tubes as service tunnel has less equipment & smaller than 3rd tube, approx. 30 higher than C **ref: 130%**		depending on numbers of TBM, approx. 20% higher than D **ref: 150%**		couldn't be evaluated time given	
		risk of delays	15%	higher risks than option C due to larger diameter and no possibility for by-pass in case of difficulties	2	same as A but ad. Service tunnel	3	standard solution (GBT)	3	slightly lower risk than standard solution under the assumption that service tunnel allows geological investigations and counteractions in case of geological difficult zones	4	same as D	4	lower compared to A-E, more flexibility with regard to time scheduling	5
		cost risks	15%	higher risks due to larger diameter	2	higher risks due to larger diameter, intervention from service tunnel possible	3	standard solution GBT	4	same as C	4	same as C	4	several risks regarding immersing of precast segments	3
maintenance and operation	23%	ease of maintenance (track, power, drainage, GMS,...)	40%	Maintenance on tracks, installations etc always blocks parts of the tunnel in operation -> impact on traffic volume In case of utility / service tunnel underneath the running tunnels easier maintenance mainly of el mech	1	Separate service tunnel + for some equipment, all rail equipment in same running tunnel -> running tunnel must be closed during ma operations -> strong influence to train operations	2	Maintenance on tracks, installations etc always blocks parts of the tunnel in operation -> impact on traffic volume All maintenance to take place in running tunnels -> highest impact on traffic volume	2	Maintenance on tracks, installations etc always blocks parts of the tunnel in operation, some operations via service tunnel -> impact on traffic volume In case of utility / service tunnel easier maintenance mainly of el mech	4	Maintenance on tracks, installations etc never blocks tunnel in operation -> impact on traffic volume smallest However all items are places in running tunnels!	3	Maintenance on tracks, installations etc always blocks parts of the tunnel in operation -> impact on traffic volume In case of utility / service tunnel beneath the running tunnels easier maintenance mainly of el mech	3
		accessibility & safety of operation site	40%	Operation site acces always goes through running tunnels -> considerable restriction	2	access easy for running tunnel - rails next to each other.	2	Operation site access always goes through running tunnels -> considerable restriction	3	Operation site access goes through running tunnels and service tunnel	4	Operation site acces may use tunnel not in operation hence less hinderance	3	Operation site access goes through running tunnels and service tunnel	4
		need of maintainance	20%	no remarkable differences between different schemes	3	no remarkable differences between different schemes	3	no remarkable differences between different schemes	3	no remarkable differences between different schemes	3	no remarkable differences between different schemes	3	no remarkable differences between different schemes in systems, but immersed concrete structures need some maintenance	3

tunnel safety management	30%	working safety during construction	20%	depending on erection location of diving wall, partly only one tunnel and no rescue option Higher risk in case of flooding, gas penetration etc	2	same system as C but one larger and one smaller cross section	3	standard solution (GBT)	4	full flexibility, same as C	4	full flexibility, same as C	4	immersing and placing is done by divers, interaction with sea traffic possible, high risk of flooding, no rescue option as the tunnel is one single box	1
		operational safety - self-rescue	40%	large cross section for smoke, no buffer zone for escaping persons, evacuating persons have to evacuate into a tunnel with running traffic, more connections to "safe tube section" possible	1	large cross sections for smoke, crossing trains, crossing of second rail very difficult for persons reduced mobility	1	standard solution (GBT)	3	safe area for escaping persons	5	same as C	3	same as D, but safe area is very close to point of emergency as the tunnel is one single box	3
		operational safety - intervention	40%	intervention through compartments of running traffic, interaction with escaping people on track	1	intervention through tube difficult (smoke), through safety tunnel difficult due to escaping persons	2	standard solution (GBT)	3	Additional versatility only if servie tunnel is part of the intervention scheme	4	Same as C	3	intervention through compartments of running traffic, doors may be weak point, no buffer zone, evacuation takes place through the same compartment like intervention	3
geology, ground & rock engineering	5%	Geological fault zones/bad rock quality/weak rock	40%	Demanding excavation in difficult geology and hard bed rock due to larger cross section, larger need of reinforcements in fracture zones. By-pass(es) difficult to construct, no additional geological investigation during construction	2	Demanding excavation in difficult geology and hard bed rock due to larger cross section	2	Standard solution	3	Service tunnel may serve as a pilot to investigate quality of rock and allow countermeasures and pre-treatment in weak zones	4	Standard solution/ larger excavation guantity as scheme D	3	Difficult to investigate over the entire length of the tunnel, may cause additional problems during operation. Flattening of the fluctuating topography on the Finnish coast and founding of the tunnel on the Estonian coast very labourous - vast undersea earthworks are needed	3
		Topography structure & bedding conditions on sea floor	40%	Not relevant	5	Not relevant	5	Not relevant	5	Not relevant	5	Not relevant	5	Difficult and costly to evaluate over the entire tunnel length, considerable risk of under - or overestimating ground conditions	2
		Control of inleaking water	20%	Cross section is larger it is more difficult to control and make water proof solutions. Large cross section more difficult to seal.	2	Same as scheme A	2	Standard case	3	Pre-investigations and pre-grouting possible using the service tunnel as a pilot	4	Procedures as in scheme D, but due to more wall surface, more in-leaking water can be expected	3	Sealing of the joints between the tunnel blocks needs to be done very carefully. Water depth possibly too high for this scheme?	2
ee e	~~0%~~														
strategic environmental assessment	5%	material management	20%	least material needed	3	less material needed	3	less material needed	3	less material needed	3	more material needed	3	most material needed, additional material required for backfilling	1
		reuse of excavation material	20%	material can be reused for backfilling and other purposes (eg road construction) in Estonia, Finland or elsewhere	3	material can be reused for backfilling and other purposes (eg road construction) in Estonia, Finland or elsewhere	3	material can be reused for backfilling and other purposes (eg road construction) in Estonia, Finland or elsewhere	3	material can be reused for backfilling and other purposes (eg road construction) in Estonia, Finland or elsewhere	3	material can be reused for backfilling and other purposes (eg road construction) in Estonia, Finland or elsewhere	3	material can be reused for backfilling and other purposes (eg road construction) in greater extent in case consruction of elements is taking part on Estonian side	1
		environmental impacts during construction: Merja Tyynismaa environmental impacts: Heikki Kalle	40%	Excavation vibration weakens affects water quality and aquatic life near ocean floor (fish, aquatic and benthic invertebrates an so on). Transporting and placement/usage of excavated rock? impact to the bentic ecosystems mostly during construction period will be related on establishment of artificial islands	3	Excavation vibration affects water quality and aquatic life near ocean floor (fish, aquatic and benthic invertebrates an so on). Transporting and placement/usage of excavated rock? impact to the bentic ecosystems mostly during construction period will be related on establishment of artificial islands	3	Excavation vibration affects water quality aquatic life near ocean floor (fish, aquatic and benthic invertebrates an so on). Transporting and placement/usage of excavated rock? impact to the bentic ecosystems mostly during construction period will be related on establishment of artificial islands	3	Excavation vibration affects water quality and aquatic life near ocean floor (fish, aquatic and benthic invertebrates an so on). Transporting and placement/usage of excavated rock? impact to the bentic ecosystems mostly during construction period will be related on establishment of artificial islands	3	Excavation vibration affects water quality and aquatic life near ocean floor (fish, aquatic and benthic invertebrates an so on). Transporting and placement/usage of excavated rock? impact to the bentic ecosystems mostly during construction period will be related on establishment of artificial islands	3	Influences negatively to water quality in large areas and releases toxic substances from sediments -> aquatic life (fish, aquatic and benthic invertebrates an so on) impact to the bentic ecosystems mostly during construction period will be related on establishment of artificial islands, more impacts on benthic ecosystems, mainly during construction period	1
		impacts on third parties	20%	negative impacts to the sensitive objects on land (nature objects, residential and social objects) would be the same, building time impacts will be related to the amount of relocated material	3	negative impacts to the sensitive objects on land (nature objects, residential and social objects) would be the same, building time impacts will be related to the amount of relocated material	3	negative impacts to the sensitive objects on land (nature objects, residential and social objects) would be the same, building time impacts will be related to the amount of relocated material	3	negative impacts to the sensitive objects on land (nature objects, residential and social objects) would be the same, building time impacts will be related to the amount of relocated material	3	negative impacts to the sensitive objects on land (nature objects, residential and social objects) would be the same, building time impacts will be related to the amount of relocated material	3	negative impact on ship traffic and recreational use of shores and sea negative impacts to the sensitive objects on land (nature objects, residential and social objects) would be the same, building time impacts will be related to the amount of relocated material as well as additionally negative impact on ship traffic	1
		carbon footprint	0%	?		?		?		?		?		?	
add. Functions of the tunnel	2%	Future use for add. Utilities	100%	Traffic volume can't be exceeded	2	Service tunnel could be oversized for possible future demands	4	Traffic volume can't be exceeded	2	Service tunnel could be oversized for possible future demands	4	More future capacity with 3 railway tubes, however one track is needed for occassional service purposes	2	Service tunnel compartment could be used for possible future demands	4