The optimization potential of alternative crossings for Fehmarn Belt

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ABSTRACT: Constructed strait crossings, whether by bridges or tunnels, have reached lengths of 40-50 km within last decades. At the beginning of project development of each crossing several variants have to to be conceptually developed, investigated and evaluated in order to define the final and most appropriate option. The investigation of different structural options for one crossing is comparing solutions containing : bridge structures, bored tunnels, immersed tubes or their combination using also artificial islands as intermediate connecting parts. In that sense one new approach and methodology for the optimization of strait crossings has been developed in last years. It is based on the implemented design decisions and is already used on several on-going strait crossing projects performed with different structural solutions. The methodology after name "FAUST" uses evaluation of predicted procedures that may happen during project development and construction from conceptual design toward final construction works. It enables the optimization of different structural crossing options after the criteria of lowest overall construction costs.

1 INTRODUCTION

Germany and Denmark have agreed to build an 19-kilometer (11.8-mile) fixed crossing that will connect two countries across the Baltic Sea. The link will cut travel times between Scandinavia and central Europe being at the same time one of the largest infrastructure projects undertaken in Europe. The crossing will link the two countries by road and rail across the Fehmarn strait. This new crossing will be the third link of its kind to be built in the region in recent years. The Great Belt Fixed Link consists of a road suspension bridge and railway tunnel between the Danish islands of Zealand and Funen across the Great Belt and has opened in 1998. The Oresund Bridge opened between Copenhagen and Malmoe, Sweden's third city, in 2000. The new crossing should be constructed as the bridge or as the tunnel, immersed or bored, and will then shorten the way from Hamburg to Copenhagen within an hour and will have a huge impact on communications between Denmark and Germany. The establishment of a fixed Fehmarn Belt link will in fact influence the transport infrastructure and economic development in the entire Baltic Sea Region greatly. The Fehmarn Belt decision will seriously and positively influence the speed of development and integration in the Baltic Sea Region.

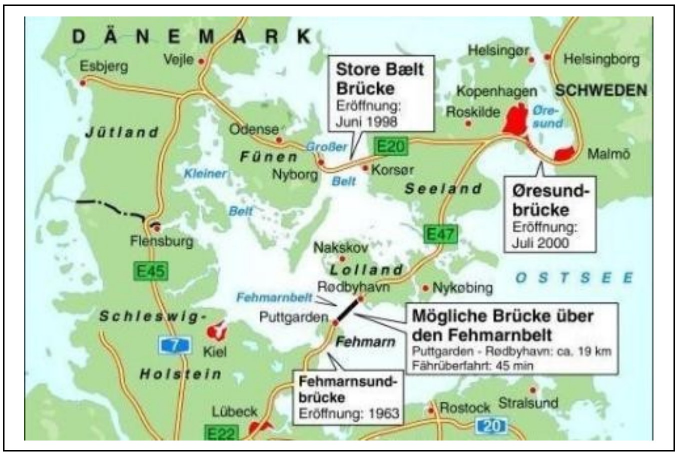

Fig.1 : The layout of Fehmarn Belt crossing.

Construction of the Fehmarn bridge is expected to start in 2012 and to be finished in 2018. It is expected to be built with two railway tracks and a four-lane motorway, taking motorists some 12-15 minutes to cross. At 20 kilometers, it will be Denmark's longest bridge over water, beating the Great Belt Bridge by two kilometers and the bridge across the Sound by four kilometers The current hour-long crossing between Denmark and Germany across the Fehmarnbelt takes place on ferries between the southern Danish ferry terminal at Rødby and the northern German terminal at Puttgarden. The company Femern Bælt A/S that has been established for the purpose of the development of the project. Femern Belt A/S expects to sign contracts with two engineering consultancy groups in early April 2009. While over the next few years these consultants will plan a bridge as well as a tunnel across Fehmarnbelt, only one of the two projects will eventually be executed. The overall crossing costs are expected to be in the range of €4.43 -5.6 billion, depending on the structural system type of the crossing.

2 INVESTIGATED OPTIONS

The feasibility study has analyzed different bridge and tunnel structural options for the Fehmarnbelt crossing. Different crossing options that have been analyzed had to answer to the main traffic requirements but finally developed options had different traffic capacity and different traffic concepts. Options had to enable crossing of the road and rail traffic and this has been provided in 2 main ways : with motorway lanes in combination with rail tracks or using shuttle train concept instead of motorway and rail traffic. Compared structural options have investigated following bridge and tunnel crossing solutions :

- **Variant 1** :double-tube single track bored tunnel for rail traffic
- **Variant 2** : immersed tube with 2 single track cells for rail traffic
- **Variant 3** : cable-stayed bridge option with 4 pylons and 3 main spans and approaching bridges carrying 4 motorway lanes and 2 rail tracks
- **Variant 3.1** : suspension bridge option with 2 pylons and approaching bridges carrying 4 motorway lanes and 2 rail tracks
- **Variant 4** : double-tube and double bored tunnels for road and rail traffic with 4 motorway lanes and 2 rail tracks
- **Variant 4.1** : double-tube bored tunnels with 3 motorway lanes and 1 rail track
- **Variant 5** : immersed tube with 2 double track motorway cells and 2 single track rail cells
- **Variant 5.1** : immersed tube with a 3 lane motorway cell and a single track rail cell

Investigated options have to answer to traffic requirements underneath the crossing enabling enough space for passing of ships through two ship channels. This free space for ship channels have been provided with two spans of a cable-stayed bridge option (var.3) and with the space in the main span of the suspension bridge option (var.3.1). The free space for ship channels have been already provided by the type of the crossing solution when using tunnelling options as in the case of bored tunnels or immersed tubes (var.1, 2, 4, 4.1, 5, 5.1). Considering traffic requirements in the sense of traffic capacity for the traffic along the crossing several basic solutions may be differed:

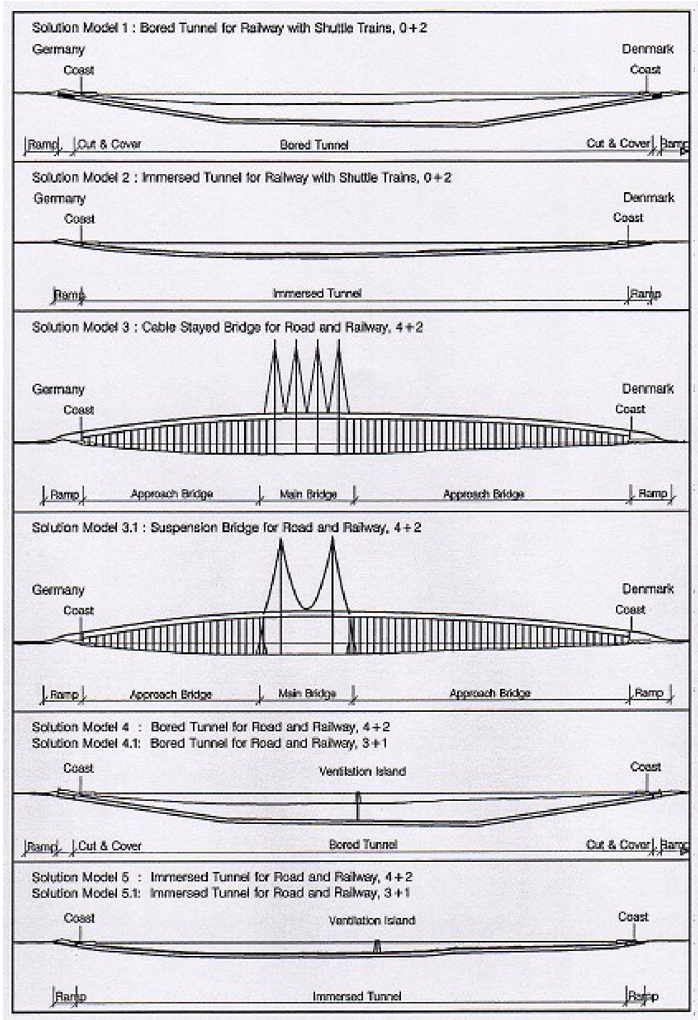

Fig.2 : The *Fehmarn Belt : overview of tunnel and bridge options for a 19 km long crossing(Jensen 2000)*

a) pure rail crossing with 2 rail tracks (0 motorway lanes + 2 rail tracks = 0+2) where only rail passenger and caro traffic has been foreseen, carrying motorvehicles by rail compositions as shuttle system through bored tunnels or immersed tubes (var.1 and 2)

b) bridge crossing with 4 motorway lanes and 2 rail tracks (4+2) on a double deck cross section having motorway traffic on the upper deck and rail traffic on the lower deck of a space truss bridge cross section (var.3 and 3.1)

c) bored tunnels with 4 motorway lanes and 2 rail tracks (4+2) or 3 motorway lanes and 1 rail track (3+1) (var. 5 and 5.1)

d) immersed tubes with 4 motorway lanes and 2 rail tracks (4+2) or with 3 motorway lanes and 1 rail track (var.4 and 4.1)

The conditions on the location of the crossing are showing constant sea depth of about 30 m along the entire crossing length of 19 km. Detailed overview of geological conditions has shown that there is no major differences in geologic formations and no bigger differences in the distribution of geological layers. Horizontal geological layers are having change of layers of sand, peat and gravel with big boulders in upper layers and clay formations in deeper layers.

Option	Type of structure	Overall estimated constr.costs	Relation	No. of road lanes	Road lane width	No. of rail. tracks	Rail track width	Lenght L	Constr.costs per m^2 traff.surface
		[€]	[%]	[-]	[m]	[-]	[m]	[m]	[€/m^2]
1	Bored tunnel 0+2	3.391.000.000	118	0	3,75	2	5,50	23.015	13.394
2	Immersed tube 0+2	3.545.000.000	123	0	3,75	2	5,50	20.210	15.946
3	**Cable stayed bridge 4+2**	**3.040.000.000**	**106**	4	3,75	2	5,50	21.318	**5.485**
3.1	Suspension bridge 4+2	3.573.000.000	124	4	3,75	2	5,50	21.278	**6.458**
4	Bored tunnel 4+2	4.420.000.000	154	4	3,75	2	5,50	22.815	7.451
5	Immersed tube 4+2	3.780.000.000	132	4	3,75	2	5,50	20.380	**7.134**
4.1	**Bored tunnel 3+1**	**2.992.000.000**	**104**	3	3,75	1	5,50	22.815	7.829
5.1	**Immersed tube 3+1**	**2.874.000.000**	**100**	3	3,75	1	5,50	20.380	8.419

Table 1 Fehmarn Belt, Danemark-Germany : predicted construction cost overview [Hommel 2001].

2.1 Bridge vs. Tunnel

Comparing bridge and tunnel type of the structure for the crossing it is convenient to analyze both options and compare their : traffic capacity, price per unit traffic area and overall construction costs per option(tab.1).

Investigations have shown that in the case of one strait crossing it is necessary to investigate all available and real options (Kolic 2008) that answer to the project requirements. In that case all options have to be developed as usable structures that have real element dimensions and cover traffic requirements. This level of project development has to enable making of usable quantities and overall construction costs. Example of the future Fehmarnbelt crossing (Odgard 2002, FDJV 2003, Andersen 2003) will help us to better understand the option investigation and the risk based optimization procedure.

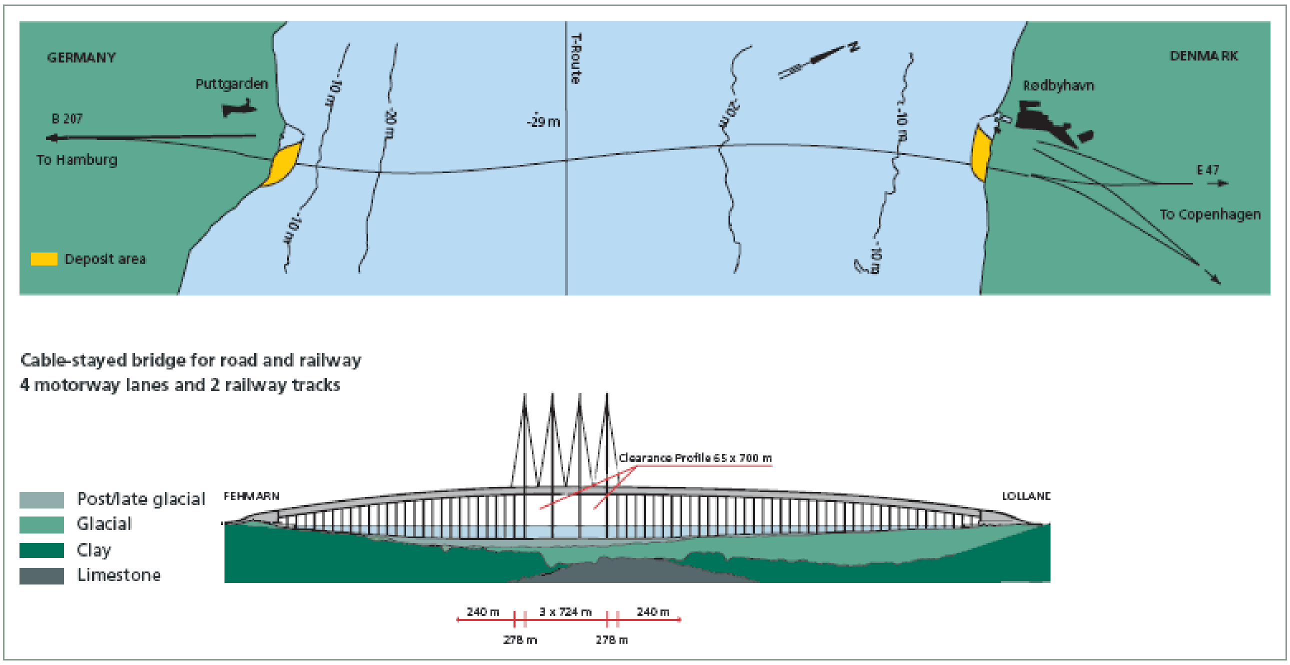

Fig.3 *: Layout and longitudinal section of the cable-stayed bridge option for 4 motorway lanes and 2 railway tracks [www2008].*

When choosing bridge systems or bridge types sometimes is useful to take typical bridge shapes that are known as ridge structure types for some spans. They are graduated according to the main span length and due to their prices for unit traffic area. However overall construction cost estimations based on such diagrams are very unsafe way of defining final overall costs. As detailed investigations have shown each crossing in its shape and costs is very much depending on the location conditions and all other requirements on the crossing that all together finally define the type and the shape of the structure. Therefore the optimization of one strait crossing is possible but within conditions on one location (Kolic 2008).

When choosing tunnel systems for the crossing two main options have been investigated : bored tunnels and immersed tubes. Bored tunnels (var.1., 4. and 4.1) have been foreseen to be constructed using TBMs (Tunnel Boring Machines) of EPBM („Earth-Pressure-Balance-Machine“) or a „slurry“ type that use bentonite support on the tunnel face against the pressure of the water or unstable geological formation at the tunnel face beacuse clayey layers are at the tunnel depth.

Immersed tube solutions (var.2., 5. and 5.1) have been foreseen using prefabricated cell cross section elements of 150 m length. They had to be sunk down on the seabed and later fully covered with boulders for the purpose of : ship traffic, environmental and ecological protection. Both concrete and steel immersed tubes have been evaluated but due to the required free space profiles and necessary traffic widths as well as lower production costs reinforced concrete solution have finally been accepted. Both tunnel types have foreseen the ventilation type using „piston effect“ for rail tunnels. In the case of motorway tunnels semi-cross ventilation have to be used with vertical shaft in the middle of the crossing that requires constructing of one artificial island as well.

When estimating overall construction costs and their unit prices all mentioned crossing solutions have been evaluated for the Fehmarnbelt crossing : bridge, bored tunnel and an immersed tube options providing different traffic capacities (fig.2). Compared predicted construction prices were based on the unit price calculation and have shown two favourite options (tab.1).

2.2 Bored Tunnels vs. Immersed Tubes

Immersed tubes are nowadays in use for lengths between 500 to 4000m and longer solutions would not be applicable because of sure price raise when constructing structures that are beyond maximal performed lengths. As the analysis of usual immersed tube prices show the range of unit prices is between 3 000 to 12000 €/m² of traffic area.

Collected results are not giving stable basis for similar other crossings of different other cross sections and tunnel lengths. Therefore are results calculated for the Fehmarnbelt crossing relatively unsecure or at least not comparable and provable.

Cost estimation in the Fehmarnbelt feasibility study shows that the immersed tube solutions have been interesting in the case of reduced usable traffic area what means also smaller cross section sizes of tubes and reduced amount of construction works. In addition estimating the sources of higher costs by immersed tubes it was obvious that the cost increases with the additional safety measures required for tube cross-sections as escape tunnels as parts of the cross section and additionally constructed artificial islands for the ventilation purpose. Such measures will be necessary in the case of using regular road traffic with vehicles in comparison with shuttle transportation option where no additional ventilation islands are necessary. Anyhow the solution with immersed tubes beyond length of 4000 m represents a world record with different other unknown challenges that could for sure raise the unit price of the immersed tube solutions.

3 STRUCTURAL SOLUTIONS FOR THE PREFERABLE OPTION

The coast-to-coast distance across Fehmarnbelt is 19 km. A range of technical solutions for a fixed link have been examined, but the link’s final design has not yet been determined. On the basis of the investigations so far, a cable-stayed design has emerged as the preferred solution following a general evaluation of construction, financial, traffic, environmental and safety aspects. As an alternative, a solution comprising an immersed tunnel will also be examined further, including the environmental aspects. Both solutions comprise a four lane motorway and a double track electrified rail line, a so-called 4+2 solution.

3.1 Cable Stayed Bridge

The Fehmarnbelt link can be designed as a cable-stayed bridge comprising a main bridge, two approach bridges and two approach ramps. Based on the available studies, the main bridge will be designed as a cable-stayed construction with three main spans of 724 m and two side spans, each of 518 m, giving a total length of 3,208 m. The two approach bridges will be 6,000 m for the southern approach bridge and 9,360 m for the northern approach bridge. It should be noted that the length of the main bridge's navigation span has yet to be determined. This will be decided at a later stage on the basis of the authority's requirements for navigational conditions. Future assessments of navigational safety could also effect the bridge design. However present navigational free space is available width two traffic openings each of 700x60 m size.

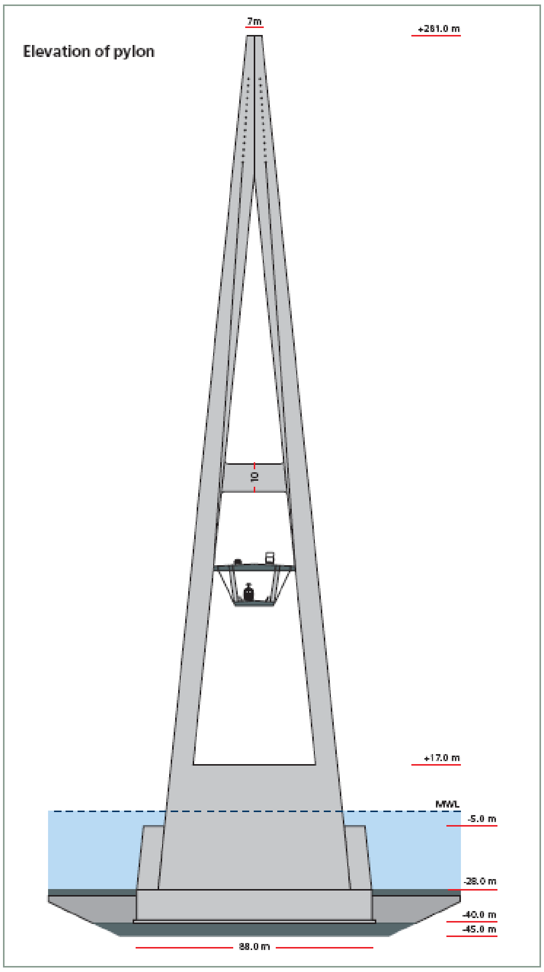

Fig.4 : The c*ross section of the pylon of the cable-stayed bridge [www2008].*

Bridge cross sections (var.3. and 3.1) are designed as one type of the cross section that will be concepted to be performed in two versions. Option with the suspension bridge have investigated the cross section with the space steel truss and with the composite reinforced concrete plate for the upper deck carrying motorway traffic lanes. The cable-stayed bridge option wanted to construct upper deck as steel orthotropic plate. Nowadys is already well known that the suspension bridge option will not be further investigated but both cross-section options are still possible to be used.
All investigated bridge and tunnel options had to take into account geological and hydrological conditions. Because of the stable sea-bed topography and continuous distribution of geological layers both option types, bridges and tunnels have some advantages on such conditions. Bridge structures and immersed tubes could use similar type of the foundation, a and the option of bored tunnel have continuous depth of the overburden along the entire length and similar geological condition along the entire crossing route.

This advantage is especially important when boring longer tunnels because the tunnel boring machine could reach higher boring speed passing only through just one geology type without need to adopt to different geological conditions along the boring length. Final evaluation shows the cable-stayed option as one of most applicable solutions and this decision has been refined after several economical and financial analyses (FDJV 2003, www2008) that have depicted the central cable-stayed bridge with 4 pylons and approaching viaducts on 19 km crossing length. The main advantage of this option in comparison with others and with the immersed tube alternative is lover overall construction costs in the case when the crossing provides the same traffic capacity.

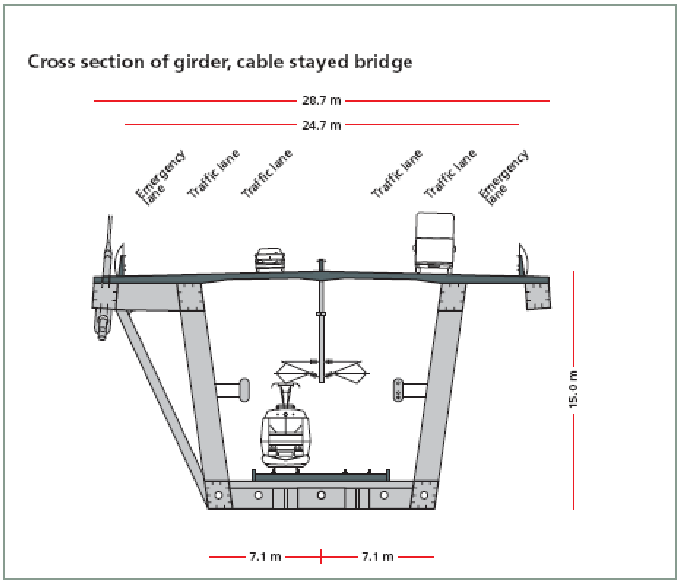

Fig.5 : The *double-deck girder section on the part of cable-stayed bridge [www2008].*

One of important parts of mentioned analysis concerning the feasibility of the option was intensifying ferry-boat traffic on the route of 19 km. Finally the analyses have shown that the construction of the fixed crossing may have be payed-off considering sparing potential that could be established due to the increased speed of the traffic and pertinent costs due to the traffic of passengers and cargo over the time period of next 50 years. Analyses have taken into account some part of unknown or unpredictable costs due to the rough estimation of the project cost in its very early development phase, then costs that could appear due to the project risks concerning investment sources, additional costs due to changes in operational costs and changes of traffic forecasts that may vary over next 50 years by some unknown reasons. Analyses have also presented different advantages and sparing potential due to the activation of this fixed link on the economy and development of Danemark, on further development of the traffic connections between Danemark and Germany and on development of the traffic in the Europe.

3.2 Immersed Tube Option

The link could also be designed as an immersed tunnel which, in addition to the tunnel itself, would comprise two approach ramps and one or two ventilation islands. The concrete tunnel would comprise four tubes carrying traffic lanes. Two tubes would contain two motorway lanes each while the other two tubes would accommodate one rail track each (see fig.7).

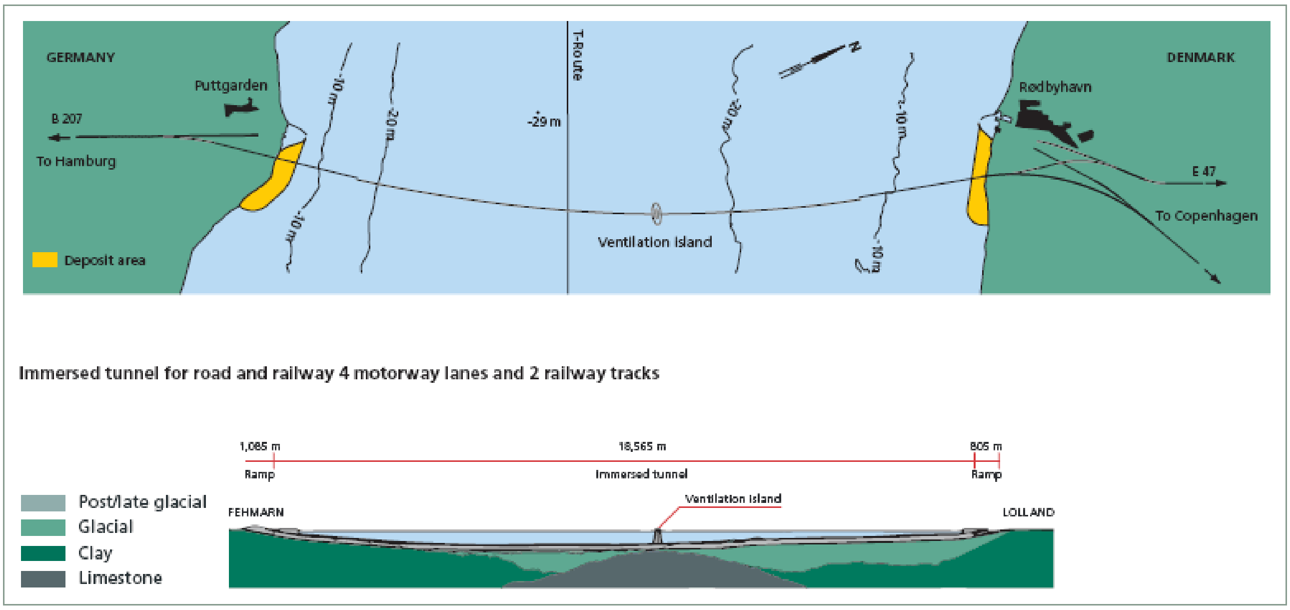

Fig.6 : The *: Layout and longitudinal section of the immersed tube option for 4 motorway lanes and 2 railway tracks [www2008].*

The tunnel's cross section would have a rectangular profile and would be 41 m wide and 10 m high. A 1.5 m wide service gallery would be located between the railway and motorway tubes.

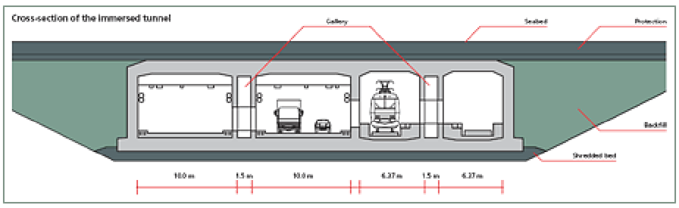

Fig.7 : The *cross section of the immersed tube option of the Fehmarnbelt crossing for 4 motorway lanes and 2 railway tracks [www2008].*

The design of the ventilation system for the approximately 20 km immersed tunnel for road traffic would be a technical challenge. The ventilation system is important for both health and safety reasons. On the basis of the tunnel's overall length, it would be necessary to establish ventilation facilities on at least one artificial island in the Fehmarnbelt.

4 OPTIMIZATION POTENTIAL

The intention to analyse Fehmarnbelt crossing cost estimation results comes from very low dispersion of costs for completely different structural options (see tab.1). It was to be expected that some differences may influence overall construction cost results because the present analysis has been performed in the very early project development phase. The evaluation of known project circumstances has been limited on collected published information but still some of investigation gave relatively clear picture about dominant expected influences on this crossing location. Very important source of information were experiences from other similar large crossing projects on locations in vicinity like Fehmarnsund bridge (1963), Grat Belt (1998) and Oresund (2000) that have been developed and constructed within last 30 years.

The optimization analysis has been performed using newly developed method "FAUST" (Kolic 2008) and has been based on officially published project information (Hommel 2001). The analysis is based on capacity and characteristics of structural elements of crossing options and proposed construction methodology. Structural elements are completely different for different options and therefore there are different influences acting on different options on the same crossing location. The influence of different predicted negative scenarios have been estimated based on design and construction experienced knowledge. Their impact has been analysed and results were shown through overall construction costs (see tab.2).

Opt. Nr.	Type of structure	Overall estimated constr.costs Mill.[€]	Relation [%]	Additonal Costs-Min Mill.[€]	Additonal Costs-Max Mill.[€]	Overall predicted con.costs-Min Mill.[€]	Overall predicted constr.costs -Max Mill.[€]	Relat. Min [%]	Relat. Max [%]	Constr.costs per m² traff.surface min/max[€/m²]
1	Bored tunnel 0+2	3.391,0	118	508,7	644,3	3.899,7	4.035,3	15	19	15.404 / 15.939
2	Immersed tube 0+2	3.545,0	123	602,7	780,0	4.147,7	4.325,0	17	22	18.657 / 19.455
3	**Cable stayed bridge 4+2**	**3.040,0**	**106**	668,8	760,0	3.708,8	3.800,0	22	25	**6.691 / 6.856**
3.1	Suspension bridge 4+2	3.573,0	124	750,3	1.071,9	4.323,3	4.644,9	21	30	**7.815 / 8.396**
4	Bored tunnel 4+2	4.420,0	154	1.060,8	1.326,0	5.480,8	5.746,0	24	30	9.240/ 9.687
5	Immersed tube 4+2	3.780,0	132	907.2	1.209,6	4.687,2	4.989,6	24	32	**8.846 / 9.416**
4.1	**Bored tunnel 3+1**	**2.992,0**	**104**	448,8	568,5	3.440,8	3.560,5	15	19	**9.004 / 9.317**
5.1	**Immersed tube 3+1**	**2.874,0**	**100**	574,8	718,5	3.448,8	3.592,5	20	25	**10.103 / 10.524**

Table 2. : Fehmarnbelt, Danemark-Germany : total predicted construction cost overview.

The results of the analysis have shown that the predicted final overall costs for each option would be higher in the range of 15-30% than previously predicted. Already this analysis has shown that bored tunnel options have far more optimization potential and they could possible be very competitive if not the best option in competition with bridge solutions (Kolic 2005).

After investigation of the influence of negative risk scenarios relations among options have been slightly changed : even though option 3. remained the most favourable regarding price per unit traffic area, followed by the option 3.1, main differences happened within the change of overall construction cost amounts.

Bored option 4.1 is the most favourable regarding estimation of overall predicted construction costs including additional costs because of the stable geological conditions and possibility to bore ahead the smaller diameter tunnel and to investigate eventual unfavourable geological conditions. In addition bored tunnel option will not suffer from the weather influences, especially wind influences as discovered in additional site investigations (Dellwik 2005).

At the same time wind influences have been major reasons to rise estimated total construction prices by the bridge options. Immersed tube options became serious additional costs due to the project length and unexplored additional scenarios that may happen along the project length because the longest tube today is just 4.5 km long in comparison with 19 km of planned Fehmarnbelt crossing length. Required safety equipment for immersed tubes has increased the option prices further and decreased their feasibility.

5 CONCLUSION

Even though the analysis has been performed in a early project development phase the only limiting condition was the limiting source of information. Therefore results are still very rough and their better evaluation in the sense of detailed analysis could be reached in further project phases with additional project investigations and with other details about the project location conditions and option parameters.

Herewith presented capacity of the module "FAUST" shows the ability to predict the total construction project costs of bridge and tunnelling strait crossing options. The method is based on the evaluation of the negative risk scenarios based on the character of the structural solution and on the information about the conditions on the location of the crossing.

Negative risk scenarios have been developed for the specific bridge and tunnel project options but are based on the experience of similar conditions or limitations on other known and available bridge and tunnel projects. The quality of estimation and prediction is based on the range and quality of available project information.

The analysis can seriously change relations among different crossing options and could be a decisive factor in the definition of the most feasible strait crossing option. It can predict serious part of unknown, unpredicted or unexpected projects costs and make project cost estimations far more near to the final required budget size level.

The method has shown good result on the estimation of different strait crossing options when estimating projects analyzed so far. Optimization module "FAUST" covers estimation for the bridge and tunnelling options and is usable for bridge systems, bored and conventional tunnels (SCL/NATM) as well as for immersed tubes.

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