RISK IMPLEMENTED TUNNEL DESIGN USING MODULE “FAUST-T”

Davorin Kolic (*) , Cristopher Kerschbaumer (**)

(*) Dipl.-Ing. Dr.sc., NEURON CONSULT ZT, Pelikanstr.18, 4061 Pasching/Linz, Austria;
e-mail: office@neuron.at
(**) Dipl.-Ing.FH, NEURON CONSULT ZT, Pelikanstr.18, 4061 Pasching/Linz, Austria;
e-mail: office@neuron.at

Keywords: tunnel, NATM, TBM, risk analysis, optimization

INTRODUCTION

Serious intentions to develop experience-based design software tools have been undertaken in different sectors of civil engineering in last decades. None of them is nowadays in active use in that sense as has been foreseen or forecasted. Experience based design knowledge is especially used and applied in early project phases as conceptual and preliminary design. During these two early design phases very important design decisions have to be made that have direct and dominant impact on the final cost estimation and overall project budget of each structure, by underground structures as well. Therefore one new approach and methodology of influence in early design phases has been developed in last years. It is based on the implemented design decisions and is already used on several on-going tunnelling project performed as SCL (NATM) tunnels or TBM driven tunnels. The methodology “FAUST-T” 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 tunnel options and methodologies as well and is based on the final economic evaluation of tunnel variants. The application of the method will be presented over one strait crossing example and evaluation of proposed underground variants.

STRUCTURES FOR STRAIT CROSSINGS

Strait crossings have reached lengths of 40-50 km within last decades (Ponchartrain bridge 38 km, Hangzhou bridge 35.6 km, Donghai bridge 32.5 km, Channel tunnel 50 km, Seikan tunnel 53.9 km). However each crossing had several variants to be conceptually developed, investigated and evaluated in order to define the final and most appropriate structural crossing option. The investigation of different structural options for one crossing is comparing solutions as : bridge structures, bored tunnels, immersed tubes or their combination using also artificial islands as intermediate connecting parts (Kolic 1997).

Comparison of different structural options will usually be performed on few interesting but different crossing locations in micro and/or macro region. The usual approach by such developments is to make several different conceptual solutions and for them to estimate a rough bill of quantity. Based on the average unit prices for different structural parts or entire structures and using volumes depicted in the bill of quantity one rough cost estimate could be established for each structural crossing variant.

Usual problem with such estimates comes from the use of unit prices that are of questionable decent and usually are not coming from some other comparable strait crossing structure. Strait crossings are still rare structures and experience made on one of them could not be fully taken over to another strait crossing. The structure of the final construction price depends very much on the crossing location condition, type and development of the local market of civil engineering services and on the overall quality level of project participants : client, consultants, project management, contractors and suppliers. Beside usual roughly estimated overall construction costs an international phenomena of project budget underestimate appears each time (Flyvbjerg 2003). This follows toward difficulties in the financing project construction or to difficulties in presenting post-construction project feasibility.

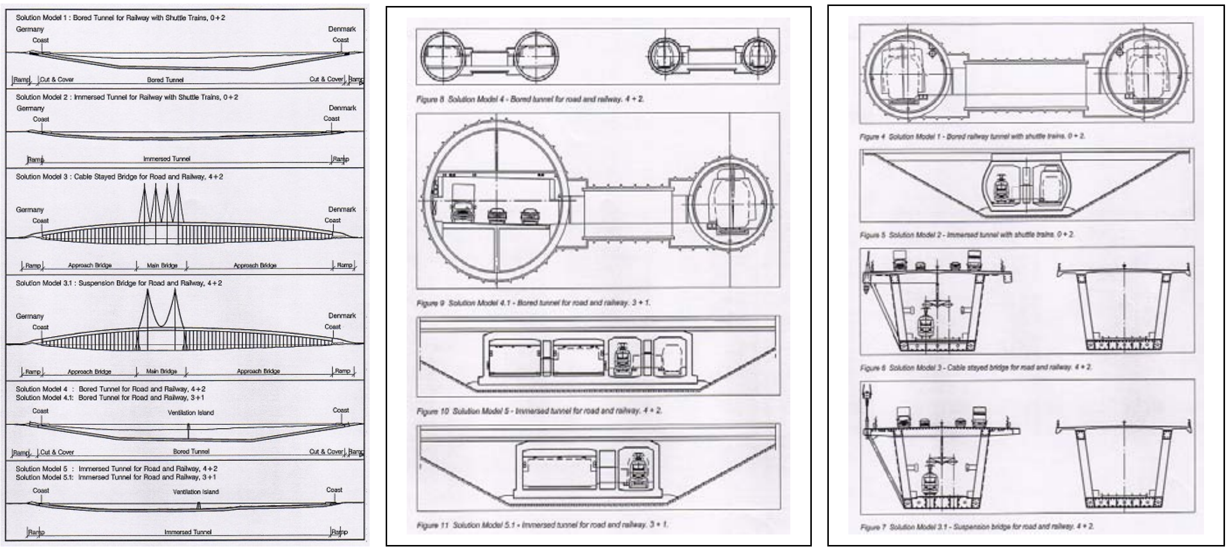

Fig.1 *Fehmarn belt : overview of tunnel and bridge options for a 19 km long crossing(Jensen 2000).*

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 Fehmarn belt crossing (Odgard 2002, FDJV 2003, Andersen 2003) will help us to better understand the option investigation and the risk based optimization procedure.

For the Fehmarn belt crossing different crossing options have been developed comparing basically bridge, bored tunnel and an immersed tube options providing different traffic capacities (fig.1). Compared predicted construction prices were based on the unit price calculation and have shown two favourite options (tab.1).

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 m² traff.surface
		[€]	[%]	[-]	[m]	[-]	[m]	[m]	[€/m²]
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].*

The best option using criteria of smallest overall predicted construction price is the 5.1 option with immersed tube having 3 road lanes and 1 rail track. The other best option using criteria of lowest unit price of the traffic area has shown that the relatively cheapest option is the 3. option for the cable stayed bridge with 4 road lanes and 2 rail tracks (tab.1). Such analysis gives a good overview which traffic capacity is requiring which financial resources and helps the Client to make decision which option is going to be constructed. However, unit price differences are not big even overall construction sums are varying between 100 and 132 % difference what makes a big absolute difference in amounts needed for overall construction costs. Such differences could be also decisive points in when deciding whether to start with some project or not.

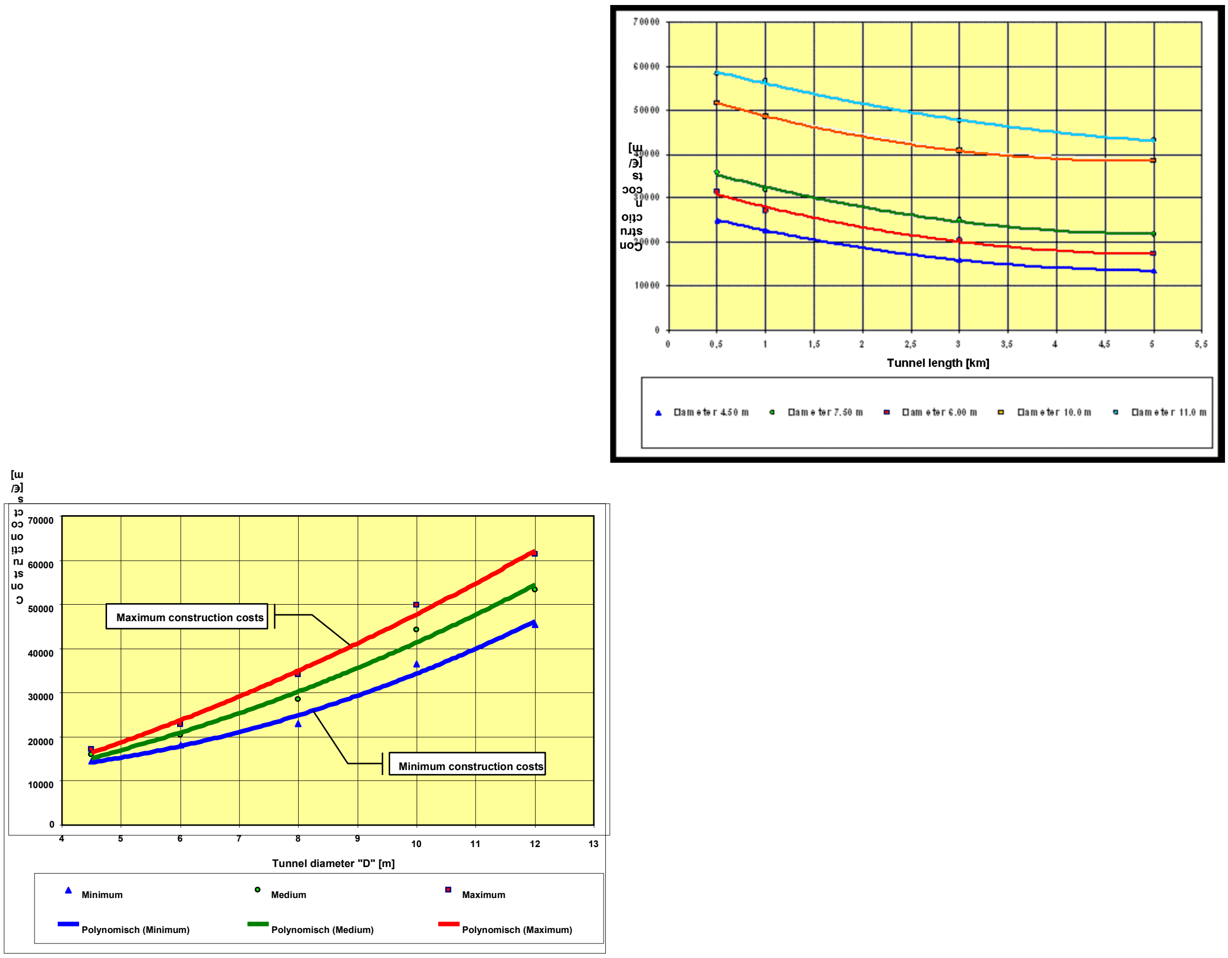

Fig.2 *Unit bored tunnel prices in relation to the tunnel diameter (left) and tunnel length (right)(www2004).*

Estimating bored tunnel options with bridges the analysis has shown that especially bored tunnels require stable overall amount of finances that will be even more stable with the rise of the project length. Previous structural/economical analyses have shown that the broed tunnel unit construction prices rises faster with the increase of the tunnel diameter (fig.2a)(www2004). At the same time the unit price of bored tunnel sinks with the rise of the tunnel length and makes them more competitive in comparison to other structural options.

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 working 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 12 000 €/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 Fehmarn belt crossing relatively unsecure or at least not comparable and provable.

	projekt		**god.**	**Ukupna**	**odnos**	**br.ces.**	**sirina**	**br.zelj.**	**sirina**	**duljina**	**cij.po m²**
Prim.	**potpoljenog tunela**	**zemlja**	**grad.**	**Cijena**	**cijena**	**traka**	**ces.tr.**	**traka**	**zelj.tr.**	**L**	**prom.povr.**
				[€]	**[%]**	**[-]**	**[m]**	**[-]**	**[m]**	**[m]**	**[€/m²]**
1	Ted Williams, Boston	USA	1995	170.000.000	150	4	3,75	0	5,50	2.600	4.359
2	Fort McHenry, Baltimore	USA	1995	620.115.000	547	8	3,75	0	5,50	2.184	9.465
3	Fort Point Ch., Boston	USA	2001	226.250.000	199	11	3,75	0	5,50	465	11.795
4	Texas City Dike, Galveston	USA	*2003*	224.000.000	197	4	3,75	0	5,50	1.325	11.270
5	Piet Hien, Amsterdam	Niz.	1997	113.450.000	100	4	3,75	2	5,50	1.900	**2.297**

Table 2 *Overview of overall costs of constructed immersed tubes [Kolic 2008].*

Cost estimation in the Fehmarn belt feasibility study show 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.

OPTIMIZATION MODULE “FAUST-T”

Knowing all mentioned influences and having results from such examples as Fehmarn belt crossing feasibility study an intention was made to develop one optimization module that could foreseen the range of real construction costs based on structural capacity of the crossing solution. Evaluating the possibility to apply the optimization procedure it was depicted that such procedure can be applied during all project phases (fig.3a). The optimization module will be applied in an iterative procedure that interchanges with the design phase and steps of cost estimation and calculation that are required to define the cost value of chosen structural solutions (fig.3b).

The module FAUST-T is dedicated to tunnel structures. It implies series of negative scenarios that may happen within one tunnelling project concerning surrounding conditions as geology and water, tunnel structural capacity and different design decisions and solutions, influences from construction and hazards during construction procedure. Project risks are implemented over negative scenarios about possible influences that may disturb planned procedure or can have direct influence on the structural elements or construction methodology. This analysis and optimization can be applied in very early project phases.

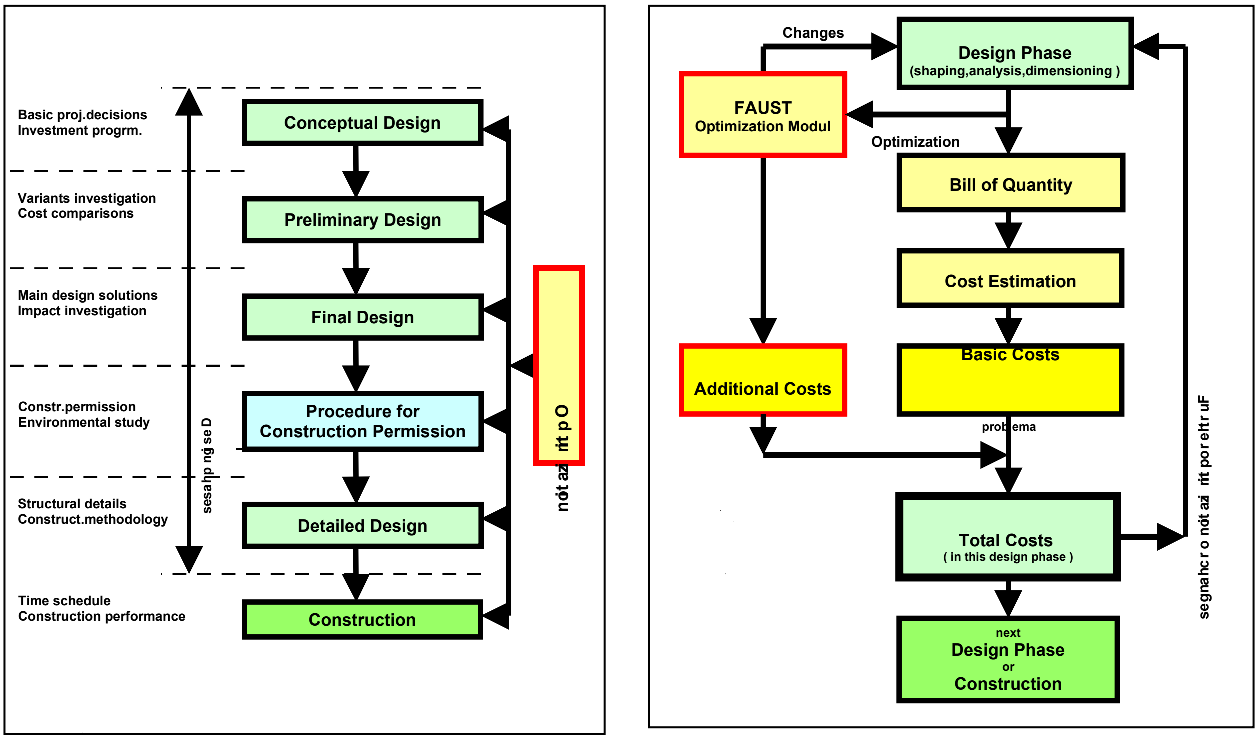

Fig.3 Project phases where the optimization could be applied (left) and flow chart of using FAUST-T module for the optimization of tunnel structures (right) [Kolic2008].

Estimation of Additional Costs

Estimation of overall construction costs is based on the structural concepts and used structural elements and pertinent construction methodology. Regular cost estimation covers the part we know as "basic costs" (fig.3b). There is another amount of costs called "additional costs" that comes from unexpected, undefined or unknown reasons. This part of costs is responsible for massive cost overruns and has its base in : weak project planning, rough estimations in early project phases, unknown project scenarios that come with the higher level of the project size, but also in political decisions, making project more attractive for investors, in giving reasons to start the project and in generally making the project more feasible.

Module "FAUST-T" is implemented in the optimization procedure of tunnelling structures and uses derived negative scenarios that may happen within project phases that are evaluated and that finally form the additional part of the construction costs that was usually before taken unknown. The module consists of qualitative and quantitative part of analysis and uses experienced based knowledge collected on other tunnelling projects for defining negative risk scenarios for analyzed project and pertinent project phase and further they are economical valued as additional costs.

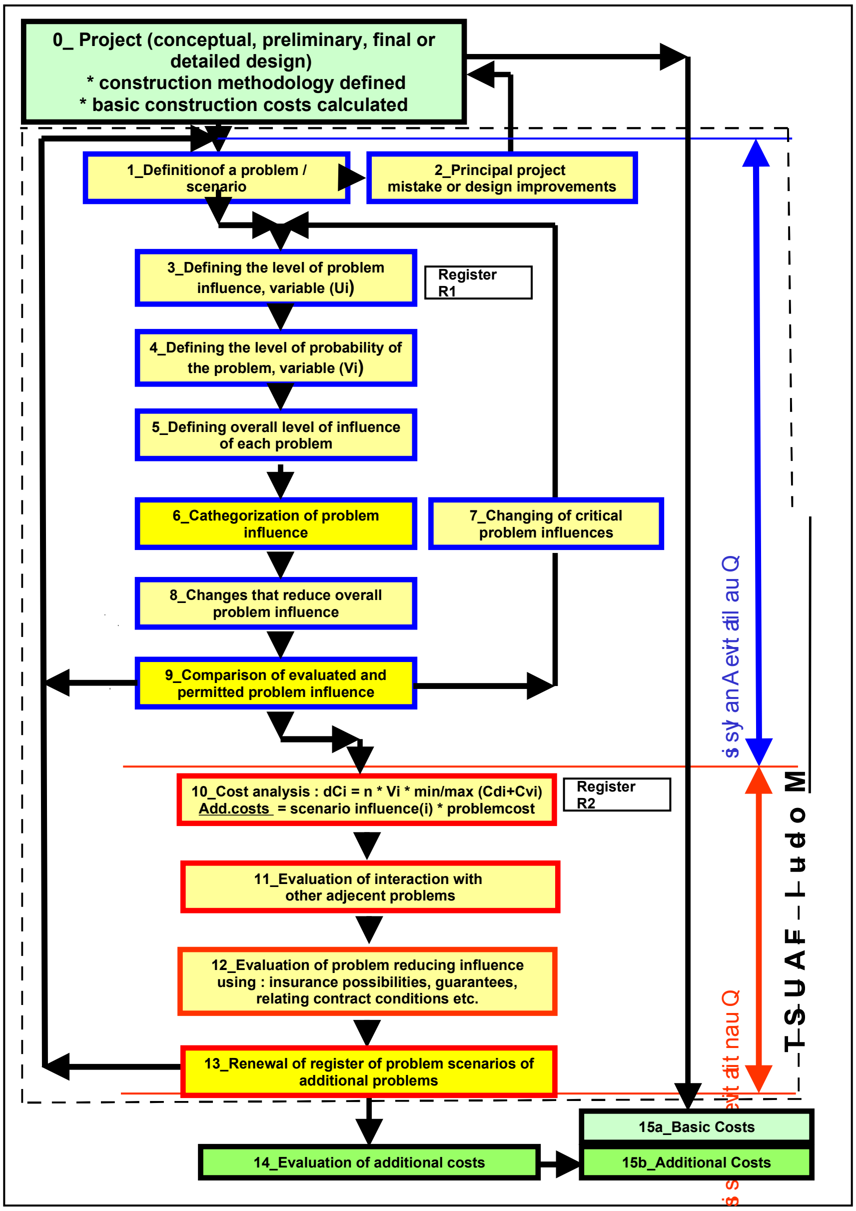

Fig.4   Flow chart of the optimization module FAUST-T using evaluation of negative risk scenarios.

Additional costs are evaluated for each negative risk scenario by the equation :

$$dC_i = n * V_i * min/max\ (Cd_i + Cv_i) \qquad \textit{(Equation 1)}$$

… where separate values are equal to :

dC_i	additional cost for each negative scenario
n	number or repeating one scenario along the project length/duration
V_i	probability that scenario will take place
min/max	min and max value of the calculated amount in brackets
Cd_i	part of direct cost of one scenario
Cv_i	part of time-dependet costs of one scenario
Ac	total additional costs for all negative risk scenarios

The summation of all influences coming form all negative scenarios will give the total amount of additional construction costs :

$$Ac = \Sigma dC_i \qquad \textit{(Equation 2)}$$

Overall Project Construction Costs Including Additional Costs

Therefore total final predicted costs for our future strait crossing structure will consist of two parts. The first one is so called “basic costs” that is the result of each cost calculation that happens by each project in early phases (usually based on unit prices from similar projects) or later on during project phases before the bidding procedure (detailed cost calculation). Second part of overall construction costs are “additional costs “ that cover unexpected parts and are calculated through estimation and evaluation of negative risk scenarios that may happen during the project (fig.4).

RESULTS OF OPTIMIZATION ANALYSIS

When performing optimization module “FAUST-T” on example of Fehmarn belt crossing final overall construction cost results will get some other form. Optimization analysis has been applied on results of feasibility study and has been used within known information about the project gained from other references (www_2003, Dellwik 2005) as well. Risk evaluation procedures as part of the project design and development procedure are in last decade very often used methods for the evaluation of numerous unknown events or are part of the design procedure (Harer 2004, Harer 2007). Some of collected experiences are sometimes tried to be organized in the form of guidelines that could be used on future projects (Kolic 2005). Anyhow none of them have used the entire method through different project phases for different various project parts to predict the amount and probability of influence of unexpected, unknown and unpredicted events on the project in development.

Predicted Final Overall Construction Costs Including Additional Costs

The intention to analyse Fehmarn belt crossing cost estimation results comes from very low dispersion of cost estimation results for completely different structural options. 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 and partly from other similar project locations in vicinity where similar projects have been developed and constructed within last 30 years.

		Overall estimated	**Relation**	**Additonal**	**Additonal**	**Overall predicted**	**Overall predicted**	**Relat.**	**Relat.**	**Constr.costs per m²**
Opt.	**Type of structure**	**constr.costs**		**Costs-Min**	**Costs-Max**	**con.costs-Min**	**constr.costs -Max**	**Min**	**Max**	**traff.surface**
Nr.		**Mill.[€]**	**[%]**	**Mill.[€]**	**Mill.[€]**	**Mill.[€]**	**Mill.[€]**	**[%]**	**[%]**	**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 3 *Fehmarn Belt, Danemark-Germany : total predicted construction cost overview.*

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 total 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 Fehmarn belt crossing length. Required safety equipment for immersed tubes has increased the option prices further and decreased their feasibility.

Optimization Potential

The analysis has been based on available published project information and it was made for the very early project phase. Therefore some of estimations 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.

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. The length of the project crossing presents the possibility to minimize overall bored tunnel construction costs because of the stable geological conditions and possibility to use one of bored tunnels as the exploration tunnel for another one. Bridge options will further be seriously influenced by the wind influence that cause further traffic restrictions within the operation phase as well and possibly additional costs on safety measures that should minimize wind influence.

CONCLUSION

Herewith presented capacity of the module "FAUST-T" shows the ability to predict the total construction project costs of 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 tunnel project options but are based on the experience of similar conditions or limitations on other known and available 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. Tunnel module part "FAUST-T" covers estimation for the tunnelling options only and is usable for bored and conventional tunnels (SCL/NATM) as well as for immersed tubes.

REFERENCES

Kolić D. (1997): *Competitiveness of the New-Age Bridges and Tunnels*, Symposium FIP'97, Johannesburg, March 9-12, 1997, pp.897-906

Jensen O.P., Hommel D. (2000) : *Fehmarn Belt – The Missing Link to Europe*, Proceedings Immersed Tunnel Conference, Copenhagen April 2000, pp. 14

Hommel D., Fagerholt P.B. (2001): *Fehmarn Belt – The Main Results of the Feasibility Study*, Proceedings, Brobyggerdagen, Göteborg 2001, pp. 14

Odgard S.S., Jensen O.P. (2002): *Denmark – A Country with Connections*, NAT2002 (North American Tunnelling 2002 Conference) May 18-22, 2002 Seattle, Washington, U.S.A, pp.13

Flyvbjerg B., Bruzelius N., Rothengatter W. (2003): *Megaprojects and Risk: An Anatomy of Ambition*, Cambridge University Press, Cambridge 2003.

FDJV (2003) : *Fehmarn Belt Fixed Link : Financial Analysis – Main Results*, Femer Belt – a Division of Sund & Baelt Holding, March 2003., pp. 22

Andersen E.Y., Abild J.B., Hvid M.A., Wumpelmann J. (2003): *Feasibility Studies for Major Fixed Links – a Multidisciplinary Challenge in Combining Facts and Experience from Similar Large Infrastructure Projects and Developing New Solutions*, Journal of Indian National Group of IABSE 33/2003 (1), New Delhi , March 22-23,2003, pp. II-1 to II-30

Harer G. (2004) : *Koralm Tunnel – Benefits of a Structured Design and Investigation Process, the Client's View,* 7th Int.Symposium on Tunnel Construction and Underground Structures, Ljubljana , 17.-19. 11.2004, pp.194-199

Dellwik E. (2005), Mann J., Rosenhagen G. : *Traffic Restrictions Due to Wind on the Fehmarn Belt Bridge*, Riso National Laboratory, report No. Riso-R-1521(EN), Roskilde, Denmark, June 2005, pp.25

Kolić D. et al. (2005) : *Kostenermittlung für Projekte der Verkehrsinfrastruktur unter Berücksichtigung relevanter Projektrisiken", ÖGG-Richtlinie*, Oktober 2005, S.47

Harer G. (2007) : *Trassenauswahl und Risikoanalysen am Beispiel des Koralm-Eisenbahntunnels,* General Assembly of Croatian Chamber of Civil Engineers, Opatija, Croatia, June 15,2007, pp.33

Kolić D. (2008) : *Optimization of Bridge Structural Systems for Long Crossings,* PhD thesis, November 2008, pp. 341

www.fdjv.com (2003): *Fehmarnbelt Bridge, Denmark* (15.06.2003)

http://www.ct.tudelft.nl/ogbouw/houston/houston3/ (2004) : *Mainland Connection Tunnel - Texas City Dike Houston*, (25.07.2004)