## Innovation in the Construction of Mega-Projects

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#### Abstract

Often the construction industry is criticized for a lack of innovation. The same industry designs and builds the largest projects of the world, megaprojects such as bridges, tunnels, dams, harbours, airports and industrial plants. This discrepancy begs the question whether the lack of innovation is a true description of the construction industry. We can distinguish between product (design) and process (construction) innovation. To find an answer, a design/build megaproject can provide the necessary details for a case study as one party becomes responsible for design and implementation. Participant observation was used to detect, define, analyze and categorize innovations at the BangNa Expressway Project in Thailand, with 54 km one of the longest bridges in the world. The result is an impressive list of innovations of product and processes that were new at the time of construction to the world, sector or company. One example is a doubling in the speed of superstructure erection (and another consequent doubling during the project). This process innovation was only possible because of the project size. In a highly competitive industry, process innovation must lead to a decrease in price and therefore only a sufficiently large project can carry the investment cost associated with some innovations. In addition, the analysis shows that many innovations are so small that they hardly can be detected although they are ongoing continuously.

Keywords: Construction innovation, megaprojects, product innovation, process innovation, organisational innovation

## 1. Introduction: a research framework for innovation

Many years ago, in 1798, Malthus published "An Essay on the Principle of Population". Using the idea of diminishing returns in production of agricultural goods, he proved that with time an equilibrium will prevail where the population of a country is sustained at the edge of starvation. In consequence, economics was dubbed as the "dismal science". Malthus used a production function where the output (Y) is based on labour (L) and capital (K), Y = F(L, K). However, starvation is not the standard in many countries and this is due to a factor that Malthus did not consider: technology (T). Technology was then included in the production function, Y = F(L, L)K, T). Taylor (1995: 773) defines technology in economics "... as anything that raises the amount of real GDP that can be produced with a given amount of labor and capital." For technology advance (and survival) we rely on new knowledge brought into application, i.e. we rely on innovation. The construction industry as the largest sector in most countries must contribute to this end. In a more confined sense than it is usual in economics, Tatum (1988: 344) describes construction technology "...as the combination of resources, processes and conditions that produce a constructed product." However, the goal of technology for the construction industry remains also in this context the same, i.e. to provide more output with a fixed input; this is called the economic maximum principle.

Trott (2005) provides a useful definition of innovation as the sum of theoretical conception plus technical invention plus commercial exploitation. The conception of new ideas is the first step, transforming the ideas into something tangible means to implement a technical innovation as second step and for the third and final step many people work hard to convert the invention into products that improve company performance. While Trott focuses in his definition on a process, Freeman and Soete (1997) look at the outcome when defining as innovation the actual use of a nontrivial change and improvement in a process, product, or system that is novel to the institution developing the change. For our purposes the following nominal definition will be applied:

Innovation in construction = (def.) Processes that lead to the implementation of products, technologies, technical and management organisation that are at least new to the performing institution.

A formal process to generate innovation is through research and development (R&D), may the research be basic or applied (Trott, 2005). A less formal process is the search for a solution to an existing problem. This is similar to decision making as described by Cyert and March (1992) and they use the term "problemistic search". A very informal process is an emergent solution to an existing problem, an idea introduced by Mintzberg in the context of strategy formulation (1978).

Based on the work of Henderson and Clark (1990), Slaughter (1998) introduced five models of innovation: incremental, modular, architectural, system and radical innovations. The smallest impact is made by incremental changes which are inherent in all design and construction processes and can also stem from basic research. This could be a reduction in rebar weight relative to concrete volume (kg/m<sup>3</sup>) due to more appropriate computational assumptions. Modular changes exert a broader influence but are still confined in their impact. An improved formwork

system to erect bridge columns may serve as an example. Architectural changes affect other parts of the structure, because of existing interrelations between components. Bridge bearings transfer forces from the superstructure to the columns. Any improvements in the design of the bearings will have effects on both the superstructure and the entire substructure (not only on the columns). System changes cause impacts to the overall system. All construction methods belong to this group. The design of the structure, its cost, quality and time of construction are affected. Radical changes occur seldom and change the overall approach to particular problems. The segmental bridge construction technique was such an innovation several decades ago.

The impact of an innovation can also be measured by its degree of novelty. The above definition demands that the innovation is at least new to the developing company. Of higher impact are of course innovations that are new to the industry or the world.



The ideas presented so far can be summarised to provide a framework for the case study (fig. 1)

Figure 1: Framework for case study research on megaproject innovation

## 2. Research methodology

Laborde /Sanvido (1994) put forth that the construction industry in the U.S spends an "embarrassing" 0.4% of the annual output on R&D. It must be assumed that this is taken from the account books of contractors. Anyhow, similar data are reported for the recent years for Germany. In 2011, external and internal R&D expenditure in the German construction industry amounted officially to 012 % of all innovation expenditure of the German industry. (Stifterverband 2013). Anybody who understands the construction industry is aware of two typical facts: (1) the separation of design and construction and (2) the project-based nature of the industry. Due to the institutional separation between product (engineering firms) and process (contractors), the contractors have often no influence on the development of the product. To have a somewhat fair comparison with other industries, it is necessary to add the cost of product development to the R&D expenses of the construction industry. The project nature of the industry has also consequences: Process or technology development is not booked into an R&D account but into the project account. There seems to be a lot of confusion about innovation in construction when quantifying it from the outside.

Based on the construction investment concept, the construction sector is defined by the input of architects, engineers, contractors as well as construction material and equipment suppliers. In construction almost every building or structure is designed individually. Specific construction processes are designed each time and a new set of plant and equipment is assembled on site. A typical amount budgeted for the design of a project is approximately 7% (Barrie / Paulson, 1992), the amount spent by companies on developing technologies and site layout may be estimated to total another 3%. Finally the amount spend in laboratories might be roughly 0.4 % (Laborde /Sanvido, 1994) of the total construction output. To this we need to add R&D in construction materials and construction equipment. In addition, construction is a highly regulated industry with regard to standards. These are developed based on research sponsored by the public sector at universities and government institutions. The total amount spent on R&D in the construction sector may then be in the magnitude of 12-15% of the sum invested by the owner for any project. Describing the construction industry as non-innovative seems unjustified when comparing it with other industries: The top six spenders in the European automobile industry invested on average 12% in R&D in 2002 and the top two aerospace companies 14.4 %.

These considerations lead to the conclusion that an inside approach using case study research and participant observation is promising to better understand the phenomenon of innovation in construction. The project of choice for the case study is the BangNa Expressway in Thailand that was built from 1995 to 2001. At the time it was the longest bridge in the world (Brockmann / Rogenhofer, 2000). The observation period covers the time from 1995 to 1998. The project was procured using a turnkey design/build/finance approach. Thus, the fragmentation of the supply chain was minimised. The traditional design/bid/build method has often been criticized as being a hindrance to innovation (Walker et al., 2003). For the BangNa Expressway, the contractors were empowered to optimise the product, technology as well as the technical and management organisation. In general, case studies do not allow for hypothesis testing but for generating hypotheses. Hypotheses from this case study are summarized in the last chapter "Conclusions for innovation in megaprojects".

# 3. Institutional determinants for innovation in megaprojects

Most construction projects, large or small, are unique. This is the standard case and a statement could follow that because of the uniqueness all construction is innovative. However, some of the differences are excluded by the chosen definition of innovation as it requires changes to be non-trivial. Megaprojects are defined by their complexity and not by the project size (Brockmann / Kähkönen, 2012). However, in order to simplify the matter, the project budget can serve as a proxy. This has the disadvantage that at the borderline a difference of one dollar will determine whether a project is a megaproject or not – and this does not make sense. All this thoughtfulness set aside, we will set a value of one billion US dollar as a threshold for the definition of a mega-

project for our considerations here. The Gulf Cooperation Council (GCC) countries form a region where many megaprojects are under construction. Meed Projects (2014) lists projects with a project budget from 93 down to 4 billion US dollars in this area for 2011. From this list we can extract information on 97 projects for six sectors (table 1). The point is that megaprojects are not so very special cases and that conclusions based on the study of a megaproject do have importance.

Sector	Number of projects	Average budget	Largest project	Smallest project
Real estate	42	14.8	93.0	4.0
Oil & gas	18	10.6	20.0	4.0
Transport	16	8.9	28.8	4.3
Power	9	7.3	20.0	4.0
Petrochemicals	8	8.1	20.0	4.0
Industry	4	11.3	40.0	5.0

Table 1: Budget for the top 97 projects in GCC countries in 2011

The owners in real estate are most likely large investors, in oil & gas, petrochemicals and industry large multinational companies and in transport and power governments. Industrial and governmental purchasing is conducted by buying centres which show the following characteristics (Kotler/Keller, 2006): (1) few, large buyers, (2) close relationship between buying centre and contractor and numerous negotiations, (3) professional purchasing, (4) several buying influences (senior management and technical experts), (5) derived demand (no personal preferences), (6) inelastic demand (few alternatives), (7) fluctuating demand and (8) direct purchasing.

Combining these characteristics of the buying centre and the high investment cost for megaprojects, contractors are faced with a rather humourless situation where a lot of pressure is exerted on the price. Typical are sealed-bid auctions with strong competition. As a consequence, innovation is required to win the competitive bidding. For design/build procurement, the contractors need to provide a robust product with minimised quantities, a construction technology harmonised with the product design and an efficient organisation. Most likely, the financial benefits of the innovation end up in the hands of the buying centre (Brockmann, 2011): Innovation in megaprojects helps to survive, not to guarantee a large profit. Survival is a strong impetus.

When innovation is used to drive down cost, then the quantity produced must be large enough so that the investment costs can be recovered. A larger amount invested in innovation (often more specific equipment and plant) leads to lower variable production costs (fig. 2).



Figure 2: Investment in innovation for megaprojects

The two discussed institutional influences, buying behaviour and project size, provide for a situation where innovation is required and possible. In this regard megaprojects differ from normal projects that most often are too small to reach the critical quantity  $x^*$ .

### 4. The innovation process

#### 4.1 Short summary of the innovation process

The framework in fig. 1 provides for three different innovation processes: (1) R&D, (2) problemistic search and (3) emergent solutions. It has already been established that R&D is not the way of choice for the construction industry. It remains to be seen whether the two others are more prevalent. A typical innovation process observed numerous times at the BangNa Expressway and other projects is shown in fig. 3. The starting point is simple: there is a new project on the table. This will first be analysed so that it can be understood. Then step by step rules-ofthumb together with solutions from previous experience are applied. The innovation process kicks in when rules-of-thumb and previous experiences do not produce a satisfactory solution. Then, this first unsatisfactory solution is subjected to several what-if questions. The more such questions are asked, the more the solution becomes innovative. This search is carried on until the person or group working on the task feels satisficed with the solution (Simon, 1956). While the satisficing solution is developed, the possibility of implementation is continuously checked. However, at the end of the development process, the question whether the solution can be implemented is again asked: Is the solution part of the technology space of the company? Once this threshold has been passed, the solution can be presented to the decision making group which includes engineers responsible for technical aspects and managers responsible for business aspects. The whole process is iterative and repeated if the engineers are not satisficed, if the solution cannot be implemented or if the group is not convinced of the solution. This is an example of a problemistic search.



Figure 3: Innovation process

#### 4.2 Exemplification of the general process

**Problem analysis:** Prior to the BangNa Expressway project, the same two construction companies (Ch. Karnchang from Thailand and Bilfinger from Germany) had contracted two similar projects with the same client in Bangkok (Expressway and Rapid Transit Authority), Sector A and Sector B of the Second Stage Expressway System. All these expressways in Bangkok were constructed in precast segmental technology. A third joint venture partner – Dywidag from Germany – had built the Don Muang Tollway in Bangkok using a different technology, prestressed AASHTO girders and decks cast in situ.

Compared with the previous projects, there were some notable differences: (1) the size of the BangNa Expressway was four times bigger than any previous project expressed in terms of deck area, (2) the bridge gradient was higher -18 m instead of 12 m, (3) the cross-section comprised six lanes instead of two times three lanes - however the Don Muang Tollway had six lanes, (4) the time for design and construction was with 42 months comparatively much shorter than for the other projects.

**Looking at solutions from previous projects:** In the bidding group, the two basic alternatives (precast segmental construction versus prestressed AASHTO girders) were discussed in depth. In the end, precast segmental construction was chosen because of the predicted lower price and faster construction progress. The design at that stage showed two bridge superstructures side by side on a central pier using D3 segments developed for Sector A and B with a maximum of three lanes (fig. 4, lower part). The solution was not considered satisfactorily with regard to construction speed and price. It was assumed that the price would not be competitive enough and the search for a faster and cheaper solution started.



Figure 4: Comparison of superstructure designs

**Asking what-if questions:** The most important what-if question centred on the idea to develop a single segment for six lanes (D6 segment) with a total width of 27.20m. This would almost double the previous maximum width of the D3 segments (15.60m). Options discussed included designs with three, two or one central web in addition to the inclined outer webs. The final option is depicted in the upper part of fig. 4. It includes two internal struts and two highly inclined webs.

**Generating a new solution:** A comparison of the two options in fig. 4 conveys the idea that the two main objectives – increased construction speed and lower cost – can be achieved with the D6 segments. The D6 segment design was revolutionary as nothing similar had been built before (Podolny / Muller, 1982). Accordingly, this option entailed a number of unresolved problems (see also fig. 5 for illustration):

- Never before such a wide cross-section was precast and there was no experience with time-dependant behaviour, casting doubt over the internal fit of the segments.
- Knowledge at the time about the influence of the bowing effect when match-casting segments indicated that the design would lead to uncontrollable problems.
- The formulas in the codes did not allow for a safe shear transfer at the piers.
- The construction technology had to be adjusted from using tested overhead girders to untested underslung girders.
- The underslung girders influenced the design of the piers.
- The design of the piers changed the design of the bearings. The bearings were now best placed on inclined surfaces. There existed neither experience nor codes for inclined bearings.
- New moulds for precasting the segments needed to be developed.
- New means of transportation needed to be developed (shuttle lifts, trailers and swivel crane).

The savings of material for the superstructure alone are given in table 2. Further savings are in consequence to be found in the substructure (piers, pile caps and piles).

Superstructure	Concrete	Rebars	Post-tensioning
D6 segments	0.49 m <sup>3</sup> / m <sup>2</sup> bridge deck	59.2 kg / m <sup>2</sup> bridge deck	24.0 kg / m <sup>2</sup> bridge deck
2 x D3 segments	0.51 m <sup>3</sup> / m <sup>2</sup> bridge deck	70.6 kg / m <sup>2</sup> bridge deck	24.4 kg / m <sup>2</sup> bridge deck

Table 2: Comparison of quantities between D6 and D3 segments

**Satisficing:** The concept of satisficing was developed by Simon to replace the idea of optimising a solution. It describes a heuristic where the search is stopped once an internal aspiration level with a solution has been reached (Cyert /March, 1992). The development of a design option for the BangNa Expressway was a team process and it stopped when the team's aspiration level was surpassed. The two groups within the team, one favouring precast segmental construction and the other prestressed AASHTO girders did not find an agreement at this stage. It was only reached in the final decision making meeting.

**Technology space:** The answer to the question whether a solution can be implemented is a theoretical one at the time of decision making. It can only be answered through implementation. However, the decision must be taken before submitting an offer and it is a leap of confidence for contractors. Besides questions raised when generating the solution, the most important one was whether one span can be erected in two days because the whole schedule depended on this point. An additional day for each span would have increased production time by 50%. The agreement to the developed solution was based on the experiences with the production and placement of D3 segments. It clearly meant entering unchartered territory.

**Final decision making:** All parties involved took part in the final decision meeting, engineers and managers. After a thorough presentation, the pros and cons were discussed controversially together with the involved risks. In the end the proposed option was adopted as solution (fig. 5). Everything in this picture is innovative, the substructure, the superstructure, the erection equipment, the transportation equipment as well as the organisation.



Figure 5: Innovative features of the BangNa Expressway

The previous discussion leads to the question whether megaprojects are not per se innovative all together because of their evident uniqueness. We believe this to be a valid point of observation. However, to understand innovation in detail more easily, it might be helpful to identify some of the more innovative features of the BangNa Expressway.

A problemistic search was by far the most commonly observed innovation process. Problemistic search is easily detectable as it is a long, laborious process and it is a top-down development. It is more difficult to observe emergent solutions as they just seem to happen. They are emerging from many little steps that are added together, mostly as a bottom-up development. They can only be identified by their end result.

## 5. Innovative features of the BangNa Expressway

A discussion of the innovative features of a project can only be complete, if all of them are thoroughly explained. This is most often – and also in this case – not possible due to space restrictions. The BangNa Expressway is fortunately a well documented project and much information can be found in publication albeit some of them not in English.

For heavy civil engineering projects it is often practically impossible to separate the product design from the process design. Both are developed simultaneously. Despite this fact and in accordance with the framework given in fig. 1, we make firstly use of the theoretical option to differentiate four areas of innovation: product, technology, technical organisation and management organisation. Secondly, we try to indicate at what level an innovation was introduced: world, industry or company level. Attributing an innovation to one of these three levels can only be a best guess, as nobody is aware of all things going on in construction. Thirdly, we refer to the innovation models proposed by Slaughter (1998): incremental, modular, architectural, system-affecting, or radical changes. The identified changes are listed in table 4.

No.	Description	Level	Innovation model		
Product innovation					
1	D 6 segments (Brockmann 2000)		System-affecting		
2	Mainline columns (Brockmann/Rogenhofer, 2000)		System-affecting		
3	Post-tensioning in D6 segment (Brockmann 2000)		Architectural		
4	Bowing effect during match-casting (Brockmann 2001)	World	Architectural		
5	Shear transfer (Brockmann 2000)	World	Architectural		
6	Inclined elastomeric bearings (Krill / Eibl, 1999)	World	Architectural		
7	Piers without crossbeam (Brockmann/Rogenhofer, 2000)	World	Architectural		
8	Mainline portal columns (Brockmann/Rogenhofer, 2000)	World	Architectural		
9	Precast portal beams (Brockmann/Rogenhofer, 2000)		Architectural		
10	Post-tensioned columns (Brockmann/Rogenhofer, 2000)		Modular		
11	Pile foundation with welded spun piles (Brockmann/Rogenh.)	Company	Modular		

Table 3: List of innovations for the BangNa Expressway

12	Reduction of rebars for foundation	Company	Incremental	
Technology innovation				
13	D6 underslung girder (Prade / Surbeck, 1998)		System-affecting	
14	14 Production line in precast yard for D6 segments		System-affecting	
15	15 Construction speed		System-affecting	
16	16 Portal beam erection girder (Prade / Surbeck, 1998)		Architectural	
17	17 Formwork for piers		Architectural	
18	18 Lifting devices for D6 girders (Prade / Surbeck, 1998)		Modular	
19	19 Shuttle lifts in precast yard		Architectural	
20	Transport trailers	Industry	Architectural	
21	Swivel cranes (Prade / Surbeck, 1998)	Company	Modular	
Technical organisation innovation				
22	Longest bridge in the world	World	System-affecting	
23	Full-scale test-span (Fischer / Krill, 1998)	World	System-affecting	
24	Production flow in precast yard	Industry	System-affecting	
25	Design/build megaproject	Company	System-affecting	
Management organization innovation				
26	Voluntary coordination between ETA and DoH	Industry	System-affecting	
27	Financing contract		System-affecting	
28	8 Joint management for all works		System-affecting	
29	Start-up company for spun pile production		Modular	
30	Start-up company for post-tensioning production	Company	Modular	

Throughout the project incremental innovations were implemented almost on a daily basis. When 500 employees and 5,000 workers join their efforts, these incremental innovations cannot be tracked. However, sometimes they add up to a great innovative leap. An example for the BangNa Expressway is the erection speed of the superstructure. One out of five teams achieved after two years over a period of half a year an erection speed of one span per day. This is twice the speed that was planned and achieved by the other teams.

# 6. Conclusions for innovations in megaprojects

There are a number of important observations that can be summarised from the case study:

Firstly, the approach to innovation is through problemistic search and emergence. Specialised R&D departments are not used. Given the project nature and the uniqueness of the construction industry this seems to be a wise approach as people drive the innovation that get feedback from implementation.

Secondly, innovation on the world level is abundant. This seems to suggest a capability and willingness to innovate on the side of the contractors. There was also evidence for much entre-

preneurial courage when betting on the success of innovation at the signature of the multibillion dollar contract.

Thirdly, there are a number of barriers to innovation in construction. Separation of design and construction, project size and the necessity to reduce costs have been discussed above. More barriers can be found in the literature (Blayse / Manley, 2004).

It seems that a deeper understanding of research in construction on the practical level is required before we can make far-reaching statements on the non-innovative character of the construction industry.

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