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Innovations in Tunnel Construction and the Associated Economical Consequences for Supplier, Contractor and the Client

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ABSTRACT
Since the mid-19th century the construction industry – and especially modern-day tunnel construction, which we shall be showcasing here in more detail – has witnessed enormous leaps in development, above all in terms of materials and machinery technology and process engineering.

Although tunnel construction has witnessed an evolution towards automation and industrialization of the production process more than any other field of construction, it has become clear that not all parties involved in the process gain the same level of economic benefit from it. The detailed analysis of developments in the field of highly mechanized tunnel construction clearly shows that, for construction companies – unlike material, plant and equipment suppliers – innovations mostly lead to only a short-lived improvement in a company's competitive positioning and that the economic benefit is very restricted. The reasons for this unsatisfying situation will be highlighted in this paper.

KEYWORDS
Tunnel construction, process engineering, industrialisation, economic benefit
1. INTRODUCTION

1.1 Initial situation

The generally tense situation in the construction industry, both in Europe and worldwide (UBS report 1999), is forcing construction companies to utilize all available possibilities for the optimization of the production process. Thus, in recent decades, new construction methods – as well as optimization of already existing methods – have contributed to an improvement in productivity as well as in quality. If a comparison is made between the different sectors of the construction industry it will become evident that the change in the production process has taken place in varying degrees. While the innovations in the field of structural engineering, apart from a few basic new developments in the field of formwork technology, are essentially restricted to the area of material technology, other areas such as special underground and deep foundation construction and tunnel construction in particular have undergone significant changes in production technology (Girmscheid 2000).

A closer examination of the advances made in modern tunnel construction, beginning with initial efforts at mechanisation in the post-war period up to the highly complex excavation systems in use today (Figure 1), will show the impressive technological development which has taken place in this field of the construction industry. Hardly any other field has experienced such a transformation away from predominantly manual production methods towards a highly mechanized and automated method of construction (Girmscheid 2006). This development was made possible by the consistent implementation of innovative ideas which arose during the course of tackling challenging projects. The impetus for improvements was provided by the most varied needs, including, for example, the safety of the excavation teams, technical complications, the search for cost-effective excavation methods, etc.
1.2 Problem definition and background

Despite ongoing further development in process technology, construction companies are not benefiting from a correspondingly positive influence in the commercial sense – i.e. the balance sheets of construction companies do not demonstrate any significant gains (Girmscheid and Hartmann 2003). In contrast to this, the commercial success of equipment and plant manufacturers and the material suppliers do indeed show gains from product development. It is also notable that many innovations, which arose during the actual construction stage as a response to specific problems, can seldom be profitably evaluated by the construction companies. Far more frequently, utilization of these innovative approaches is carried out by machine manufacturers and material suppliers. This paper will attempt to illustrate the background to this situation which is so unsatisfactory for the construction industry and to analyse the causes of inefficiency which occurred during the implementation of innovations.

1.3 Scientific approach

The unsatisfying situation for the construction industry in regard to the ability to transfer innovative developments to economic success was already well known by the authors of this paper due to their extensive experience as site and project managers of major infrastructure projects. These observations were underlined by an empirical study (Hartmann 2004) in form of semi-structured interviews with key personnel of international construction companies. A case study (Hartmann 2004) of innovation processes in construction companies showed typical analogies in the sequence of activities and the impact on the problem solution of the different parties involved (construction company, material supplier and machine manufacturer). The embedding of the innovation process into its external boundary conditions (contractual situation, economical situation, competitive situation etc.) could clearly demonstrate the existing dependencies for the parties involved. The aim of this research paper is to evaluate the different types of innovations (product and process innovations) in regard to the competitive consequences to the different service provider and user of products in the different phases in the value creation chain.

2. INNOVATIONS IN MODERN TUNNELLING

When it comes to innovative change in companies the main focus of interest is on company performance. Accordingly, two types of innovation, also described as technical innovations, can be differentiated:

- product innovations and
- process innovations.
2.1 Product innovations

Product innovation is to be understood as the creation of new products and the further development of existing products as well as successful marketing. Modifications focus on product functions which are intended to better fulfil new requirements or needs. The goals of product innovation may include, for instance, an increase in earnings or the opening up of new markets (Girmscheid and Hartmann 1999).

The primary product in the building industry is the building itself. In this sense, it is possible to speak of an innovation in the case of a new function or a functional improvement to the building. Essentially, the functions of the building do not change. Instead, some of the building’s properties, such as durability, are modified so that that improved functioning is attained or the construction of the building under certain conditions is made possible at all.

When searching for approaches to the modification of building properties, it is usual to move from the overall view of a building to a more detailed view. The various technical components (structural parts) of a building possess, in their turn, certain functions and properties. Taking a tunnel as an example, the component “tunnel lining” has structural functions and can contribute to an improvement of the total properties of the tunnel on the basis of new and improved properties, such as impermeability.

An even more detailed examination leads then to the basic elements of the building, the materials. New and improved materials or material properties form the starting point of innovative product developments in the construction industry.

Example: Fiber reinforced concrete
Fiber-reinforced concrete is a compound made of normal concrete and high-tensile fibers. Depending on the type of fiber, a distinction is made between fiber-reinforced concrete with steel fibers or with plastic (usually polypropylene) fibers. It is used as fiber-reinforced concrete formwork or as fiber-reinforced shotcrete.

In certain circumstances, the use of fiber-reinforced concrete can completely eliminate the need for reinforcement. In the case of concrete components with pure anticrack reinforcement, for example, this can possible save up to 60% time during the work cycles. Another important aspect is the fire-resistance of fiber-reinforced concrete when plastic fibers are used. By using plastic fibers the tendency for spalling is significantly reduced.

2.2 Process innovations

Process innovations primarily serve the remodelling of the production processes which a company needs to guarantee performance success. In addition, the planning and operating service provision processes can also be the subject of innovative development. Modifications focus on the
production factors which are combined with each other in a novel way or are the subject of original or further development, particularly in the working materials. The goals of process innovation include, for example, a reduction in manufacturing costs or an increase in product quality (Girmscheid and Hartmann 1999).

Innovations in the production processes include, in particular, the broad replacement of human labour force by mechanical equipment. It is possible to find examples of mechanisation and automation in all process classes.

2.2.1 Manufacturing processes

Example: TBM

In addition to the drilling duration of a hub, the driving performance of a gripper TBM, particularly in difficult geology, is primarily determined by the time required for the necessary rock support installations. New and further developments aim at the broad mechanization of supporting works, in order to be able to maintain high driving speeds even in the case of challenging ground conditions. These include, for example, erectors for the relocating of steel arches, roof bolting and roof bolting setting equipment and fully automated spraying machines (Rehm 2001). Furthermore, in order to prevent jamming of the TBM in squeezing ground, the diameter of the cutter head and the cutter head shield (Figure 2) can be adjusted. In addition, flexibility with regard to the possibility of cutting through varying geological formations means that the distinction between TBM and shield machines is blurred. In order to be able to adapt to varying geological conditions and also to be able to mechanically excavate tunnels which have different geological conditions, mix shields, for example, have been developed which can be used as a hydro shield or as a TBM shield machine.
2.2.2 Transport processes

Example: Conveyor belt storage units
When conveyor belts are used to transport cutted or blasted rock out of the tunnel then the belts have to be installed continuously along the conveying route and with as few transfer points as possible, in order to guarantee high performance and low dust levels. Additionally, extension of the belts to keep up with the construction progress has to be possible. The development of conveyor belt storage units (Figure 3), which are placed at the end in front of the dumping area, allowed for continuously high conveying performance, small dust loads and low levels of operation and maintenance. The belt passes through the conveyor belt storage unit in various places. During driving the conveyor belt storage unit is continuously contracted, in the manner of a block and pulley, until the extension belt reaches its end. The extension belt is then opened up and a new one is welded in.
2.2.3 Monitoring processes

Example: seismic exploration
In order to be able to make statements about the composition and the rock-mechanical characteristics of the ground in the driving area, a measuring procedure has been developed which allows the prediction of changes in the immediate and in the surrounding areas of the excavation face and the derivation of rock-mechanical parameters. Acoustic signals are emitted and then reflected by potential ground disturbances and, on the basis of the echo times, the position, angle of intersection with the tunnel axis and distance to the tunnel face are determined (Steidl 2006). The measuring procedure was primarily developed to support the excavation process using TBM’s, in order to guarantee continuous excavation by the timely detection of critical ground areas.

2.2.4 Maintenance processes

Example: Teleservice
As a result of the enormous advances made in telecommunications, machine manufacturers and operators can monitor and maintain their equipment on a worldwide scale. The first machine data acquisition systems for large equipment are already in use today. Data transmission can take place via radio, the mobile telephone network or satellite communication. The current status data of subassemblies, the position data of current movement processes, among other things, can be accumulated using monitoring sensors and then evaluated online. The data give the machine operator timely warning of disturbances. Remote inquiries permit permanent monitoring of the operation status. The term which is
used to describe the equipment which monitors a machine online is Teleservice. With the aid of online monitoring, services can be carried out in a considerably more efficient and cost-effective way, since maintenance periods do not have to be strictly calculated any longer according to a certain number of operational hours, but are determined by technical indicators. This means that downtime and maintenance costs can be reduced (Lenfert 1997).

3. IMPACT AND IMPORTANCE OF INNOVATIONS ON THE PLAYERS IN THE VALUE CREATION CHAIN

3.1 Impact of product innovations

Generally, there is no universally valid answer to the question of whether innovations by material suppliers improve the competitive ability of construction companies or not. Based on the market strategy, the competitive strategy developed by Porter (Porter 1985) illustrates the various ways in which a company can use its own efforts to create competitive advantages and differentiation potential from the client's perspective in the industry environment. Both the behavior vis-à-vis the competition and the resulting impact on the client need to be taken into account.

Although each new material represents a product innovation for its supplier, its impact on the other players in the value creation chain - companies and clients – depends on the type of change it effects to the downstream value creation phases (Figure 4).

Product innovations improve the competitive status of a construction company only when the manufacturing process can be organized in a more cost-effective manner as a result of this innovative product.

For a contractor, fibre-reinforced concrete represents a process innovation only if it eliminates the need for mat reinforcement during the performance process, since the process of producing the reinforcement mat then becomes superfluous.

Clients are interested only in results, and not in processes. If an industrial floor is being produced, the client's only interest is that the floor does not crack or sag, and its durability is ensured. He does not care whether this was achieved by reinforcement mats or fibres in the concrete. Clients will therefore not see fibre-reinforced concrete as an innovation, since it does not change the utilization properties as they perceive them.

If, in contrast, the use of plastic fibres substantially improves the fire-resistant properties of tunnel shells, this would represent a product innovation for clients, since the tunnel shell becomes safer for the users.

When using Self Compacting Concrete SCC certain measures need to be implemented. The formwork has to be stronger, the workers have to be trained, and there is no longer any need for compression using mixers during the actual concreting process. As such, SCC represents a process innovation for contractors.
The new and improved effects of products manufactured using these innovative materials are not apparent to clients. Although they benefit from the possibly improved quality, they do not recognize these benefits at first glance, and as such these products are not genuine innovations for them.

The same applies to the use of high-strength concrete. The suppliers' product innovations do not have a tangible impact on the manufacturing and processing processes. With the exception of a few special circumstances, clients will not notice that an innovative construction material has been used.

If, however, recognizably new properties are generated for the clients' use – irrespective of whether conventional or innovative materials are involved – then this could be seen as a product innovation by clients as well.

### 3.2 Impact of process innovations

The prior goal of process innovations is the attainment of greater profitability through a reduction of manufacturing costs. This cost reduction is to be attained by an increase in the efficiency of the construction methods used or of the manufacturing process, whereby an increase in productivity is achieved. By implementing process innovations (see point 2.2) construction companies are attempting to optimize the production process with regard to construction time and product quality in order to thereby generate competitive advantage.

It is usually the specific problems which arise during excavation works which provide the impetus for process innovations in tunnel construction. This starting point is particularly frequent in tunnel construction since, as a
result of the broad range of possible geological conditions, continuously changing requirements are made on the excavation process. The chronological sequence of the implementation of specific ideas typically takes place as shown in Figure 5.

![Diagram](image)

**Figure 5** Typical chronology of a problem specific innovation process

As a result of its contractual relationship to the client the construction company is obliged, in its role as contractor, to use its complete expertise with regard to problem solving in order to guarantee project success. Practice shows that, particularly in the field of tunnel construction, construction companies are very active in finding solutions whenever unforeseen problems arise during excavation. However, since tunnel construction is a very machine-intensive sector of the construction industry, it is usually necessary to involve a machine manufacturer in order to implement an innovative problem solution. This machine manufacturer now obtains – free of charge, as it were – the expertise of the construction company (principal solution approach) as the basis for its new development. Furthermore, in the prototype stage he has a guaranteed initial purchaser for his development and, simultaneously, is provided with a testing ground for further development as a marketable product. In order to ensure a monopoly in the marketplace the machine manufacturer usually patents every promising idea even in the very early stages of development, whereby a sustained positive economic effect is guaranteed.

In contrast, however, the innovative process know-how, which originally provided the actual impetus for this development, can be regarded as profitable in the short term only, since it is practically impossible to prevent this expertise from being imitated by competitors. In this case, all that is needed is a single change of personnel to provide competitors with access to the complete range of expertise.
4. CONCLUSION

The detailed analysis of development in the field of highly mechanised tunnel construction clearly shows that, in the field of the development of tunnel boring machines and driving equipment, owing to the very high capital expenditure requirements, only a very few, high-capital machine manufacturers are present on the global market. However, due to the clear nature of the competitive situation, they are able to market their products effectively, even, as is the case with key equipment such as tunnel driving machines, exercising influence on the competitive situation in the construction sector.

In marketing their product innovations, the building materials industry profits, on the one hand, from the necessity for construction companies to use qualitatively high-grade, innovative products and, on the other hand, from their largely oligopolistic market position. Product and process innovations usually represent only short- to medium-term competitive advantage for construction companies in the marketplace, since product innovations are also accessible to competitors and process innovations are rather difficult to protect from imitation in the longer term, as is the case in the stationary industry. This therefore means that the differentiation potential for construction companies as a result of product innovations can be categorized as generally rather low.

Usually, process innovations can be used for competitive advantage in the medium term only by correspondingly high-capital construction companies or by company groups who have the opportunity to form strategic alliances with powerful machine manufacturers. In each case, the one to benefit most from innovative developments is the customer, whether due to reduced construction time as a result of process innovations, commercial advantages arising from the competitive climate, or from an increase in quality brought about by innovations in materials.

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