1. Introduction

Today it is well recognized that underground structures are key to the sustainable development, improving living conditions with the less environmental impact [1]. However, due to high costs, the existing tunnelling techniques are not easily accessible, especially the mechanized methods. The financial obstacles to access Tunnel Boring Machines (TBMs) are especially pronounced for the developing countries, further increasing the already enormous pent-up demand for public utilities and infrastructure in these emerging economies, like Brazil, Russia, India and China [2].

Among the aforementioned countries, Brazil has the least experience with TBMs. In fact, in 2008/2009, the 3 main TBM manufacturers (Robbins, Herrenknecht, Lovat) delivered 45 machines with diameters over 5 m to Russia, India and China, whereas Brazil had only 2 machines. Given the same level of demand for underground structures among the four countries, this difference is particularly significant. Actually, besides the booming growth of the transport sector and of the oil & gas industry, construction of tunnels in Brazil’s main cities has to meet high-pressure deadlines, especially now that the country will host the 2014 World Cup and the 2016 Olympic games.

Attracted by such compelling factors, 3 Brazilian tech companies proposed a novel TBM design which can bring mechanized tunnelling to a new level, reducing costs and increasing productivity. The newly formed group is devoted to launch and settle a new industrial establishment in Santa Catarina State, Southern Brazil (Fig. 1). Due to its well-developed industrial cluster and its strategic economic, political and geographic position, this region emerges as a hub to promote technological innovation in mechanized tunnelling.

Figure 1 – Santa Catarina State, the region to host a new industry of tunnel boring machines.
The present paper is organized as follows. Section 2 outlines some general aspects of tunnelling technology and the relevance of the newly-proposed development. Sections 3 and 4 discuss, respectively, a brief study of the global demand for tunnels and a general overview of the TBM industry framework. Section 5 presents in more depth the proposed technological innovations, the core development group and its strategy to create a new industry. Finally, section 6 presents some conclusions and perspectives to this work.

2. Mechanized tunnelling technology

The origin of the TBMs dates back to nearly 200 years ago [3]. The first shield-like apparatus, built in 1818 in the UK, is due to Sir Brunel (Fig. 2a). However, the first mechanized equipment, built 28 years later in 1846, is attributed to the Belgian engineer Henri-Joseph Maus (Fig. 2b).

In 1952, James Robbins, the founder of The Robbins Company, built what is regarded as the first modern TBM (Fig. 3), whose design is very similar to the existing models. It is noteworthy that, despite their relatively well-established efficacy and applicability, current machines did not undergo significant changes, since they are still based on a more than half-century old design. Furthermore, the question of fully automatic excavation still remains open, with several challenges to be overcome [4]. Undoubtedly, there is plenty of room for innovations.

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3. Brief study of the demand for tunnels

In the last 50 years, tunnelling and microtunnelling activities had a sharp increase both in number of construction projects and contract values. However, due to its high diversity, there is no consolidated report on the status of this market. Most of the available studies normally focus on narrowly defined categories of infrastructure projects.

There are several reports illustrating the potential demand for microtunnelling. For example, a study conducted by Douglas-Westwood [5] forecasts that 232,000 km of oil and gas pipelines are under construction or planned, involving investments of US$ 180 billion for the next five years. In such projects, open-trench excavation is still the prevailing construction method whereas mechanized microtunnelling is barely used. However, although the direct construction costs for open-trench excavation are relatively low, recent studies [6] have demonstrated that its indirect, social and environmental costs largely surpass those incurred by mechanized microtunnelling.

Compared to the demand estimate for microtunnelling projects, there is a lack of data on the status of tunnelling activities. This is partially due to the difficulties in keeping track of the large number of construction projects spread across the world. Besides, a more thorough study should consider the demand by different end uses as for the oil, gas, energy, mining, water, sanitation and transportation sectors. Alternatively, despite their shorter extension compared to long-length pipelines, tunnelling projects normally require much higher investments and financial resources.

Recently, Prof. Noronha’s group at the University of Sao Paulo and at the University of Santa Catarina conducted a research study to measure the potential demand for long-length railway tunnels (> 20 km). According to this research, the list of projects under construction and planned for the next five-year period adds up to a total of 1,580 km and US$ 210 billion.

In contrast to the case of pipeline projects, construction of tunnels has made more frequent use of mechanized methods, with an increasing tendency towards a higher mechanization level in underground excavation. Therefore, this sector offers promising business opportunities and future growth perspectives, which has been mainly limited due to the lack of innovation.

Considering the most relevant applications, like tunnels for transportation and microtunnels for public utilities, a multi-sector evaluation conducted by Prof. Noronha’s group estimates a total investment of US$ 1 trillion for the next five-year time frame (Fig. 4a).

![Figure 4 – Construction of tunnels: a) investments up to 2014; b) usage of TBMs.](image)

It is important to observe that mechanized excavation of tunnels is a relatively unexplored market. Estimates are that 10% to 20% of tunnel projects use TBMs instead of conventional methods (Fig. 4b). Besides, as the next section will show, there is a small number of TBM manufacturers. While all these studies suggest that current TBM technology is not accessible enough, they also indicate that there is a huge market share eager for innovations.
4. The current TBM industry

Today there is about a half dozen of TBM manufacturers (Fig. 5) which supply nearly all of the tunnel construction companies. TBM production remains practically a semi-handicraft enterprise. In fact, each machine is tailored to the specific project requirements, according to the tunnel dimensions and the geological conditions. Many machine types are available, the most notorious difference is between rock and soil type. Due to its big dimensions, the manufacturing process of a TBM is decomposed into separate parts delivered for assembly at construction sites.

One of the most impressive characteristics of TBMs is their over-sized mechanical parts. Actually, the TBM industry is very proud of their brute-force machines, which can easily lift a fully-loaded Boeing 747, weighing 410 tons (Fig. 6a) [7]. However, in this particular case, we should notice that this machine weighs 10 times more (4.364 tons) than the Boeing Aircraft. Another particular characteristic of the TBM usage is that these machines are tailor-made, and most equipments are designed to be used once and then thrown away (Fig. 6b).

However, one of the most important and frequently unnoticed characteristic relates to the business model of this industry. TBM operation normally requires a lot of replacement parts, as the disc cutters [8] [9], for example (Fig. 7).

The constant need of replacement and maintenance of discs represents the main bottleneck of the boring process, causing both increasing costs and reducing advance rates. In many cases, costs of these replacement parts may greatly surpass the total machine cost. This is known in economics as the cross-subsidy model (e.g. razors & blades, printers & ink/toner).

The analysis of the market projections and of the business model suggests that the TBM industry takes a very conservative position, far from meeting the global demand. This reinforces the point that there is a strong need for innovation and improvements in TBM technology.
5. BraBo – A new generation of boring machines

Motivated by the previous analysis herein presented, a group of 3 companies in Brazil (BraBo, Welle and Inovamat) has started a thoroughly search for potential innovations for the current TBM technology. As a result of its R&D activities, this group has devised the concept of an innovative TBM more efficient and rational than the conventional machines. As opposed to the brute-force method, its design philosophy is based on the principles of simplicity and smart-power.

In terms of technological innovation, the expected result from this enterprise is a novel machine named BraBo, an acronym for Brazilian Borer (Fig. 8a). The proposed ideas are relatively simple, elegant, non-high-tech and non-obvious, resulting in a more efficient machine, about 5 times faster and cheaper than existing TBMs (Fig. 8b). Another advantageous aspect of the BraBo machine is that some complicated and expensive parts of conventional TBMs can be removed.

The BraBo machine design is based on 3 innovative ideas (Fig. 9) aimed to achieve performance gains compared to the current TBMs. Whereas the two first and main innovations deal with the excavation process (smart-power concept), the third one is devoted to the concrete lining system.

The first proposed innovation forms a base for supporting and guiding the two other innovations. This development comes from the firm called BraBo Company, Inc., and consists of a two-phase system composed of simple mechanical elements positioned in an innovative way. With this new arrangement, the excavation process of a BraBo machine uses just one fifth of the energy of conventional TBMs, being therefore five times less costly. Due to intellectual property issues, this paper cannot enter into further details of this system.

The second innovation relates to the BraBo machine rate of advance. This development is due to the company Welle, Inc., and consists of a waterjet cutter system replacing the disc cutters. Indeed, this idea was first proposed more than 30 years ago [10], but in an inappropriate manner. However, the first proposed innovation allowed the inclusion of this system into the BraBo design.

Lastly, the third innovation relates to the optimization of the concrete tunnel lining. This development is due to the company Inovamat, Inc., and consists of a new concrete extrusion process. Besides increasing safety, this system properly follows the faster rate of advance.
Apart from the changes in the frontal section, all other systems of conventional TBMs (backup, conveyors, instrumentation, monitoring) have their counterparts in the BraBo machine. However, they also benefit from the simplification and cost reduction of the proposed design philosophy.

Figure 9 – The 3 technological innovations of the BraBo machines.

5.1. The core development group

In the last 4 years, the development group has conducted many studies to validate the new ideas, like numerical and experimental investigations on the key mechanical aspects, the geometric consistency and the functional integrity of the design.

Due to the team work, the core development group (Fig. 10) has now achieved a critical mass and will be able to build the first prototype by the end of 2010. The expected result for this initiative is to present an actual case of a 2 m diameter BraBo machine, which could achieve a daily rate of advance of more than 300m/day in hard rock.

Figure 10 – Part of the core development group.

The project has officially started in November 2009, thanks to Brazilian government stimulus and a new grant to fund a pilot office in Santa Catarina State, Brazil. However, there are still several issues to be addressed, and the development group is currently looking for more partners, investors and a suitable industrial site to develop, test and deploy the BraBo machines. During the last year, the development group has accomplished organizational and administrative actions, promoting the project through a series of round tables in Brazil and China (Table 1 and Fig. 11).

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<thead>
<tr>
<th>Date</th>
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<tr>
<td>March, 2009</td>
<td>Innovation in Mechanized Tunnelling</td>
<td>Shanghai, China</td>
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<tr>
<td>April, 2009</td>
<td>High Performance Tunnel Boring Machines</td>
<td>Sao Paulo, Brazil</td>
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<td>Sept., 2009</td>
<td>3rd-Round of Negotiation China-Brazil on New TBMs</td>
<td>Sao Paulo, Brazil</td>
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<tr>
<td>Oct., 2009</td>
<td>Business Opportunities in Mechanized Tunnelling</td>
<td>Sao Paulo, Brazil</td>
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Table 1: Round tables directed to partners and investors in Brazil and China.
6. Conclusions and perspectives

The analysis herein developed indicates that current TBM technology does not follow a sustainable-based approach. In fact, the brute-force, the high costs and the disposable features only confirm that this business needs alternative approaches, more affordable and accessible.

The main expected result of the proposed project is to build and test a new BraBo machine for hard rock capable of performing a rate of advance of 300m/day in uniform geological conditions. This will represent a significant leap forward in terms of productivity, since the current technology allows a maximum advance rate of 60m/day. For the more realistic case of degraded or changing geological conditions, even considering a reduced gain factor of 2.5 (instead of 5), a single BraBo machine could establish a new record excavating 50km/year in an affordable manner.

Other significant features of the proposed design are the reusability and the possibility to drive tunnels of non-circular cross-section. Since it is still in a very early stage, this development remains open for new contributions and cooperation. Considering all factors together, this new promising machine can allow the construction of essential infrastructure that are currently not viable, opening up new perspectives for tunnelling projects.

With respect to business practices, the most remarkable feature of the new proposed design is the absence of any disc cutters, which is in fact one of its main advantages. Notably, this concept is not consonant with the previously mentioned cross-subsidy policy of the current industry. On the other hand, the BraBo proposal has attracted a growing interest within new emerging markets, specially the Chinese heavy machine industry.

From a benefit-cost perspective, according to the location studies of Prof. Noronha’s group, the Santa Catarina State in Brazil provides practically all resources and infrastructure necessary to accomplish this project.

Conclusively, on the basis of all facts aforementioned, this paper argues that the current TBM technology is still not easily accessible, offering plenty of opportunities for innovation in mechanized tunnelling. In this context, a promising development opportunity lies with the application of mechanized tunnelling in pipeline construction (microtunnelling). This is actually one viable solution which could bring significant improvements for the gas & oil industry [5].

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References


