To Build a Tunnel Boring Machine: Why Assembly on Location is the Next Big Advancement

Lok Home
The Robbins Company, USA

ABSTRACT

Is there a better way to build a Tunnel Boring Machine (TBM) that can benefit all parties involved? For decades TBMs have traditionally been assembled in factories, where the components are assembled and tested, then disassembled and shipped to the jobsite. Delivery of a machine can often be the critical path affecting project schedule, cost, manpower, and other factors. Onsite First Time Assembly (OFTA) has been developed and used on dozens of projects around the world to pass on cost and time benefits to contractors working on fast-paced projects with tight schedules. The use of OFTA is increasing, allowing for TBMs to be initially assembled at the jobsite, and cutting out extra shipping and disassembly steps. This paper will analyze the reasons for shop assembly vs. onsite assembly, determining the ultimate benefits and drawbacks of each. The paper will also draw quantitative comparisons in terms of time and money, as well as differences in carbon emissions, energy, and manpower requirements. The paper will conclude with a discussion on trends in TBM assembly today and where the future is headed when building these complex tunnelling machines.

1 INTRODUCTION

Traditionally, tunnel boring machine components have been shipped to a large assembly hall, assembled, tested, disassembled, transported to the job site and reassembled onsite prior to starting operation. By comparison, other large scale industrial equipment is rarely fully preassembled and tested prior to being installed in the final intended location. As examples, consider small to midsized gas-fired power plants, bucket wheel excavators and specialized small manufacturing factories. Like tunnel boring machines, for all of these examples, time is of the essence. In the period from ordering the equipment to having operational equipment, nothing is being produced and cash flow for the contractor can be negative. While elimination of the first three steps of the process (factory assembly, no-load testing and disassembly) does not result in a 100% equivalent savings in time and labor, it does result in a substantial savings of both. In addition, there are savings in reduced transportation costs.

Given the similarities in complexity and delivery times for industrial equipment and tunnelling equipment, it begs the question: Why have tunnelling machine manufacturers, civil constructors and project owners resisted for so long the direct shipment of components to site for first time assembly? It is easy to understand why machine manufacturers with a large investment in fixed manufacturing facilities would be resistant to Onsite First Time Assembly (OFTA), preferring the status quo, which keeps prices higher and their facilities full of equipment. It is more difficult to understand the motivations of owners and consultants. Even today, in the face of mounting evidence of the benefits of OFTA, many consultants continue to stipulate in tender documents that the tunnelling machine must be fully factory assembled and tested. This resistance to OFTA might be caused by the generally conservative nature of project owners and their consultants; however, it is more likely to be a simple habit from the past. It is now time to break this habit (see Plate 1).

Plate 1: An example of Onsite First Time Assembly, Niagara Tunnel Project, Canada

1.1 Changes in the Industry: The Benefits of OFTA Realized

Thirty years ago tunnelling machines were designed manually, on drawing boards with pencil and paper, with design calculations performed on what are, by today's standards, antique calculators. Project management software was only a dream. Twenty years ago, things improved somewhat with 2D CAD becoming the norm and the first wave of project management software becoming available. Over the past 10 years, the expansion of 3D CAD and improvements in project management software, including links to many enterprise / manufacturing resource planning programs (ERP / MRP), have given manufacturers invaluable tools with which to ensure the quality of design, the fit up of complex parts and the delivery of complex systems.

In a parallel evolution thirty years ago, nearly every tunnel boring machine was unique in its design, custom built and manufactured specifically for each project. Today, that is very rarely the case. Thirty years ago perhaps several dozen tunnelling machines were made annually. Today five to ten times this quantity of tunnelling machines are made annually and, like other heavy machinery, many of them are of a similar make and model. Due in no small part to the sharing of knowledge through professional organizations such as those supporting this conference, today there is much common agreement regarding the "type" of tunnelling machine best suited to certain geological conditions. Standard types are open hard rock, hard rock single shield or double shield, EPB and slurry shield. As a result, the design of each of these machine types have moved from their uniquely designed, custom origins to a vastly superior product today that is mature in design and subject to continuous improvement through incremental changes.

As a result of this maturation and evolution of the tunnelling machine, when a civil contractor receives a machine today the probability is very high that, at a minimum, the core of the machine has been produced many times previously. This provides both a more reliable product and the potential to eliminate the in-factory assembly phase with minimal risk for all involved.

1.2 The OFTA Program Today

The use of 3D CAD software today makes it possible to accurately check the fit up of the component parts of complex machinery in the design phase. A thorough and time-tested quality assurance program ensures that components are made per each drawing, continuing the fit up guarantee through the next step of production. The availability of project management (PM) software, with the capability to plan and monitor resources throughout the design and production process, and the linking of PM software to the ERP software for an entire company, provides a powerful tool for insuring that every component of these complex systems is delivered to the job site when it is needed during the assembly process.

But, it takes humans, experienced humans, as well as software, to make OFTA work. While this is true throughout the design and manufacturing process, it is especially true on the job site, where the complex tunnelling machine must be assembled safely, quickly and correctly to achieve the targeted schedule and cost savings. Fortunately, the widespread global growth in the use of all types of tunnelling machines over the past twenty plus years has resulted in a worldwide pool of highly experienced tunnelling machine professionals. Wherever in the world a project might be, it is possible today to put onsite a team of professionals who can direct the assembly and operation of every type of machine.

2 QUANTIFYING THE BENEFITS

Depending on the size and complexity of the tunnelling machine being produced, and whether the machine is new or refurbished, the savings in both schedule and cost can be substantial. On a small, 3.0 meter simple machine the savings in schedule can be as little as a month or so and perhaps 5,000 man-hours and 100,000 US dollars in transport cost. On a complex 10 meter or larger machine the savings in schedule can be as much as several months and possibly 15,000 man-hours can be saved as well. Eliminating the transport to factory for preassembly of such large machines can reduce transport costs by more than a million US dollars. However, the reduced costs noted here are generally dwarfed by the large commercial gain inherent in delivering a major tunnelling project on a shorter schedule.

These cost savings numbers are generalized based on Robbins' previous project experience. OFTA was first developed and used in 2006 on the world's largest Main Beam TBM, a 14.4 m diameter giant at the Niagara Tunnel Project. It has since been used on all TBM types and in locations around the world, from dense urban areas to remote and mountainous locations. A summary of some time and cost savings on these projects is below (see Table 1).

Table 1. Early Indications of OFTA Benefits

Project	**Machine Type/Diameter**	**Assembly Time**	**Time Savings**
Niagara Tunnel Project	14.4 m Main Beam TBM	17 weeks	3-4 months
AMR Water Tunnel	2 x 10 m Double Shield TBMs	16 weeks	3-4 months
Mexico City Metro	10.2 m EPB TBM	18 weeks	2-3 months

While this data is overwhelmingly positive, and the process of OFTA seems intuitively more cost effective than factory assembly, it is necessary to quantify the benefits more specifically, in part because of industry conservatism. Robbins therefore sought freight, project management and assembly specialists to give quotes based on three parameters where the benefits are concentrated: time savings, cost savings, and carbon footprint differences.

3 QUANTIFICATION STUDY

All estimates for this study were prepared based on an 8 m diameter EPB destined for a jobsite in London. The machine would thus either be assembled at a factory in the central EU, or assembled directly at the jobsite in London. These parameters were set based upon available data for comparison, namely a report on carbon findings from the Lee Tunnel, part of the Thames Tideway Project in London. This project required an 8 m diameter machine, which was factory assembled and shipped to the jobsite from Germany (see Plate 2).

Plate 2: An EPB in the 7-8 m diameter range

3.1 Time Benefits

With regards to time benefits, direct shipping of component parts to the jobsite should save time over the process of shipping to a workshop, assembling the TBM in the shop, disassembling and shipping to the jobsite, and finally reassembling the machine for launch.

Based on past projects, the below timeline (see Plate 3) represents the maximum time savings that could occur based on the two different assembly methods. In this case, the entire process from procurement to manufacturing, assembly, OFTA, testing, and ultimately to TBM launch takes about one year. For a shop-assembled machine that process takes up to four months longer (one year and four months).

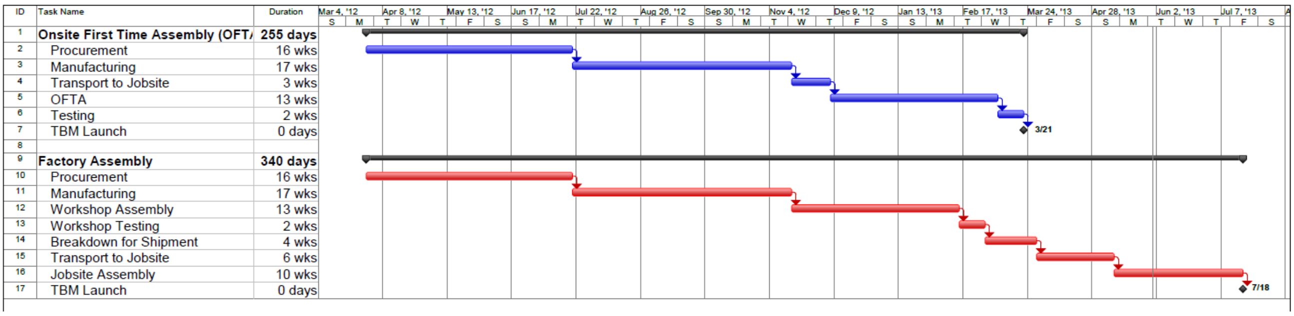

Plate 3: Maximum Time Savings Possible with OFTA

After consultations with logistics, shipping, and assembly experts, average times based on the London project parameters emerged (see Table 2).

Table 2: OFTA vs. Shop Assembly Time Comparison

	OFTA in London	Shop Assembly-Central EU
OFTA		
Time to ship components directly to jobsite	1 day to 30 days depending on supplier location. 1 day for UK-located supplies, up to 30 days for China/USA supplies. Heavy steel from China such as shields, cylinders, cutterhead etc. European shipments could take 1 week. U.S. time for shipments would be about 20 days.	
Time to assemble machine on jobsite for launch	3-4 months	
Shop Assembly		
Time to ship components to Central EU shop		1 day to 30 days depending on supplier location. 1 day for UK to 30 days for China/USA, etc.
Time to assemble machine in shop		3-4 months
Time to disassemble machine in shop		2 weeks
Time to ship components from shop to jobsite		2-3 weeks elapsed time from first shipment to final shipment.
Time to assemble machine at jobsite for launch		2-3 months

As can be seen in the above chart, the average time to ship components does not vary, particularly if the shop is in fairly close proximity to the jobsite. In this case, even locating the shop in the Central EU does not change shipping times as compared to those same components going straight to a jobsite in London. The time to assemble the machine itself will vary somewhat. To assemble a machine for the second time by the same crew will always be a faster assembly. In addition any small interference problems are resolved during the first assembly. However, the difference gain is in the time taken to disassemble the machine in shop (2 weeks), ship the components to site (2-3 weeks) and then reassemble it again for launch (2-3 months). All told, a shop assembly of an 8 m EPB would be at least 3 months longer than a similar OFTA-assembled machine, if not more.

Other factors should also be taken into account. Load testing of components in the factory is very limited and components must be re-tested at the jobsite under actual operating load conditions.

3.2 Cost Benefits

Cost benefits have been shown through previous projects to be on the order of millions in USD given the right parameters, such as large machine diameter. After obtaining quotes from freight forwarders and field service and assembly experts, we once again looked to our example project for cost data (see Table 3).

Table 3. OFTA vs. Shop Assembly Cost Comparison (in USD)

Shop Assembly Europe:		
Local Labor hrs:	12000 hrs at $60/hr	$720,000.00
Expat Supervision:	$12,500 / man-month x 5 people x 3 months	$187,500.00
Shop Rental:	Included in the $60/hr rate	
Misc. shop costs (fluids, consumables, etc):		$100,000.00
Inbound shipping costs to EU shop:	Components for shop assembly via break-bulk and trucks	$ 409,000.00
Outbound Shipping Costs from Shop to London Jobsite:	Disassembled TBM components to jobsite	$595,000.00
FS Labor (estimated for U.K.):	$15,000 / man-month x 15 man-months	$225,000.00
Customer Supplied Labor:	10000 hrs x $75/hr estimated jobsite labor cost U.K.	$ 750,000.00
Tools:	Misc. hand-tools and small equipment	$50,000.00
Misc. fluids, consumables, etc:		$50,000.00
Total Cost:		**$3,086,500.00**
OFTA Assembly in U.K.:		
FS Labor (estimated for U.K.):	$15,000 / man-month x 50 man-months	$750,000.00
Customer Supplied Labor:	15000 hrs x $75/hr estimated jobsite labor cost U.K.	$1,125,000.00
Tools:	Misc. hand-tools and small equipment	$100,000.00
Inbound London OFTA shipping to site:	Shipping of all components via break-bulk, trucks	$797,500.00
Misc. fluids, consumables, etc:		$100,000.00
Total Cost:		**$2,872,500.00**

As can be seen in the above cost comparison, a moderate savings of about $214,000 USD could be expected in this example. The lower margin may be due in part to higher costs for labor in the UK as compared to other construction markets and a large Field Service team required onsite to oversee the assembly. However, the savings in shipping is substantial and telling, being about 20% higher for a shop assembled TBM. Particularly for larger machines with higher shipping costs, this difference in savings in choosing OFTA could in the end become very large.

Other factors should of course be considered—often contracts for major construction projects have both late penalties and early bonuses. Simply by accomplishing assembly earlier, a contractor may be more likely to incur bonus cash and avoid any penalties for missing a project milestone.

3.3 Carbon Benefits

Any carbon benefits realized by OFTA may be the most difficult to quantify, as every project will vary in its unique requirements. As such, we focused on what would be different between the shop assembly and the OFTA method rather than trying to calculate an entire carbon footprint for a TBM project. Equipment to manufacture components would be similar to identical. Equipment required to build the machine was essentially the same (see Table 4).

Table 4. OFTA vs. Shop Assembly Carbon Comparison

	OFTA in London	**Shop Assembly-Central EU**
Number of ships required (8 m EPB) to jobsite	Break Bulk: 1 from China and 1-2 from EU (partial use of those vessels). Containers: 5 or so Container Shipments on Multiple Vessels (Cutterhead support, sub-assemblies, e.g.)	
Trucks directly from port to jobsite in London	25 Break Bulk + 15 Containers (no Conveyor System or Locomotives included). Shipments would include cutterhead, shield, etc.	
To shop in Central EU		2 Ships (USA/China) + 9 Truckloads from EU + 25 LTL Shipments from EU
From shop to jobsite in London		25 Break Bulk + 15 Containers (no Conveyor System or Locomotive)

As can be seen in the above chart, the carbon differences are mainly in the extra shipments of parts that occur in shop assembled TBMs vs. OFTA machines. The average container ship carbon usages are about 150 grams of carbon dioxide per twenty-foot-equivalent unit carried a nautical mile (gCO2/TEU-nm) (World Shipping Council, 2015). While each form of TBM assembly would require at least two ships carrying materials, one from the US/EU, and one from China, the real difference is in the extra truckloads from the shop to the jobsite. Assuming 25 loads of material are traveling from a jobsite in Rome, Italy to London, that represents an extra 32.5 metric tons of CO_2 produced at the very least, per day of operation (calculated via roadnet.com Carbon Emissions Calculator).

When these carbon data are compared to that available for the Lee Tunnel, it is apparent that indeed carbon usage is high for TBM assembly, shipping, and operation at many projects. The Thames Tideway project involves multiple sites, but the site where the TBM launched represented 27% of the entire project's embodied carbon, due to materials shipment and production, as well as machinery diesel and electrical requirements. During tunnel operation, the TBM required about 52% of all of the project's electrical needs. Such numbers reflect a need to reduce carbon footprints during TBM assembly and operation.

That being said, environmental benefits must also be considered. Fewer trucks on the road and fewer resources being used are clear benefits of OFTA. More generally, the use of underground space has a low impact on surrounding neighborhoods and surface streets. As compared to other methods such as drill & blast that utilize explosive materials, TBMs are also safer and produce fewer pollutants.

4 CONCLUSIONS

It cannot be argued that there is no increase in risk with OFTA, but experience has shown that the risk is definable, largely controllable and most important able to be reduced as experience increases. The primary risk is, of course, errors in design or manufacturing which result in a misfit of components during assembly at site. This risk is mitigated through the use of previous designs, 3D CAD, the implementation of proper design procedures and checks, and the implementation of an aggressive quality control program. Finally, as has been shown on the OFTA deliveries to date, when problems are encountered during onsite assembly, the schedule can slip by some days, but techniques are available to recover lost time. Onsite correction can be carried out with the assistance of specialist fabrication and machining companies.

Key components of a successful OFTA program include:

- Use of prior, proven designs where possible
- 3D design and computer aided test fitting of critical components
- 100% dimensional inspection of critical components at the fabricators
- Pre-assembly of subcomponents / modules when schedule allows or is not impacted by pre-assembly
- Aggressive quality control of all components manufactured to ensure proper fit up at site
- Absolute control of the total tunnelling machine system bill-of-materials, to ensure that every part, large and small, which is required for the system is sent to the job site.
- Logistical planning and control, to ensure that every part arrives at the job site, when it is required, in the order that it is required for efficient assembly and use of storage space
- Resource planning, to ensure that all tools and personnel of every type, qualification and quantity required for assembly are onsite when needed
- Advance alternative recovery planning, in order to be ready to react quickly to possible failures in any of the above steps
- A larger than usual team of highly experienced personnel must be provided by the machine manufacturer to supervise and assist with the onsite assembly

Project owners have an obligation to the public to deliver underground infrastructure at competitive prices, on the quickest practical schedule and without undue risk. Contractors need every tool available to meet these demands. It is time for tunnel owners and contractors to move into the new millennium. OFTA offers an opportunity to save both time and cost, as has been shown in our comparison study. Carbon savings may be difficult to quantify but are also apparent in OFTA's streamlined shipping process. Experience to date proves that OFTA can be done with little risk with the use of modern design, quality control and project management tools. The time is fast approaching for all involved in future tunnelling construction contracts to reconsider the requirement for TBMs to be fully shop assembled and tested prior to delivery to site. Onsite, first time assembly is a practical, efficient cost- and schedule-saving alternative.

REFERENCES

Roadnet Technologies, Inc. (2015). Carbon Emissions Calculator. http://www.roadnet.com/pages/products/carbon-emissions/.

Thames Water Utilities Ltd. (2013). Energy and Carbon Footprint Report. Application for Development Consent.

World Shipping Council (2015). Industry Issues: Carbon Emissions. http://www.worldshipping.org/industry-issues/environment/air-emissions/carbon-emissions.