Robofactory: the future of large-scale TBM segments production

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ABSTRACT: Making precast concrete segments is a critical activity for contractors involved in tunnel construction using Tunnel Boring Machine (TBM) technology. However, the global shortage of skilled personnel poses a growing challenge, making it increasingly difficult to maintain the required production capacity and ensure high product quality.

Robofactory addresses this issue by introducing an innovative precast plant where robots and automated systems collaborate with operators to enhance efficiency in a modernised working environment. This approach significantly reduces the risk of injuries while optimising production workflows.

Over the past two years, Robofactory plants have been successfully implemented in Italy, the UK and France, setting a new paradigm for precast production. Robots handle tasks such as mould opening and closing, cleaning and oiling, with the potential to extend their functionality across various stages of the segment production cycle.

By transferring workers from physically demanding tasks to supervisory and control roles, these automated plants improve working conditions while at the same time, significantly boosting efficiency. Current production data indicates a 30% increase in daily output, along with a substantial reduction in segment defects and workplace injuries, thereby enhancing overall production effectiveness.

The precast plant becomes digitally integrated through tracking software monitoring the production schedule, product quality, component stock levels, and logistics management, from initial storage to the installation of segments in the tunnel.

1 INTRODUCTION

The world becoming progressively more urbanised comes with a rising demand for underground transport systems, which are absolutely vital to global connectivity. The invention and implementation of the Tunnel Boring Machine (TBM) has revolutionised mechanised tunnel construction by boosting the excavation of tunnels. In this field, however, a valuable component of the process remains to this day susceptible to production bottlenecks, which can cause significant delays: the manufacture of precast concrete segments. As the TBM advances, it installs the tunnel lining, which is composed of high-precision precast concrete segments. These segments need to be produced rapidly, precisely and safely, a challenging undertaking to achieve in an era where we are subjected to skilled labour shortages and rising quality demands.

Traditional precast production methods, which are considerably reliant on manual labour, have struggled to keep up with the ever-growing demand and associated standards. This has increased general interest in automation and its endless possibilities. In this context, Robofactory proves itself to be a fresh, novel approach to precast production, reimagining production plants as hybrid environments where the human workforce and robotic applications can work together to enhance efficiency and quality.

The production of these concrete blocks offers the chance to provide the tunnelling industry with recent innovations, shifting this part of the project from a construction site to an industrial plant, thereby enhancing safety standards, the quality of the process and the digitalisation of information.

This paper examines the Robofactory model and its implementation in several European contexts. It explores how automation can enhance not only productivity but also workplace safety and product consistency. It will aim to lay out the lessons and information learnt from this technology-driven alteration in the precast segment industry in Europe in view of a future application on Australian projects.

2 THE VERY FIRST APPROACH: STATIONARY PRODUCTION

2.1 *General overview*

The production of TBM segments has been performed using traditional methods since the 60s. As a matter of fact, for decades, the only production concept in use was made up of stationary moulds.

This type of production plant, as seen in Figure 1, involves having the different moulds fixed on the ground, with the different operations needed for the production being performed at every station. This means that the production crew move from one mould to the other while repeating the following steps:

1. Mould preparation (spraying of release agent, installation of gasket, cast-in items and rebar)
2. Pouring and vibration
3. Extrados smoothing
4. Mould covering for proper curing
5. Mould opening
6. Segment demoulding
7. Mould cleaning and closing

The same process has to be applied for all the moulds in the factory, relying on a concrete truck for the discharge of concrete and on an overhead crane for the demoulding of the segments.

Figure 1. Stationary plant.

2.2 *Recurring issues*

There are some commonly encountered issues experienced by contractors and factory workers when adopting a stationary production, some of which we will take a look at below.

It can sometimes be difficult to find manpower for the production. Segment production plants are often located in rural areas. Moreover, it’s a demanding job and isn’t always appealing to the workforce, who are often drawn towards other opportunities.

Different tasks in the segment production process are performed manually and can be source of injuries. This can be seen through the bolting and unbolting of moulds’ locking screws as they are performed by using heavy bolting guns, which transmit heavy stress and vibrations to the arms of the workers. Extensive use of these tools can cause a whole range of long-term, irreversible and debilitating effects on their health, thereby preventing them from performing their job properly and affecting their overall quality of life.

The opening of the moulds is done manually and pulling down the heavy side panels of the mould poses the risk of being hit by a metal panel weighing 600 kg. Lid opening is also a manual-based task that involves pulling and pushing a 500 kg metal panel. Performing a repetitive task such as this one, eight hours a day, can lead to back pain and strain injuries. Segments are stored in stacks, where these concrete pieces are separated using timber dunnage. As the positioning of the timber blocks is done manually, lifting these 20 or so kilogramme, heavy components over multiple hours can also lead to injuries.

It should also be said that, seeing as though many tasks are performed manually, there are few guarantees on the quality of the segment. In fact, they often need to be adjusted after being demoulded to correct any eventual defects.

The production capacity is constrained to the layout of the plant as only two pours per day can be done, due to the length of the curing cycle. Higher demands of segments cannot be fulfilled if not planned at the beginning of the project. Logistics must be carefully planned, as concrete trucks and lifting equipment need to be able to access every mould. Dedicated lanes must be foreseen for the passage of vehicles and clear paths for suspended loads.

3 A STEP FORWARD: CAROUSEL PLANTS

3.1 *General overview*

Thanks to the ever-increasing use of TBMs as a main excavation method for medium-long tunnels, and to the rise of industrial plants in other sectors, the so-called carousel plants started to appear in specific markets.

A carousel plant is a sort of automated production line, in which the plant is divided into two main areas:

– A working line, where all the production activities are performed
– A curing chamber, where poured segments are cured for several hours to reach the requested strength.

In these factories, it’s no longer up to the production team to move from one mould to another to perform the different tasks, but instead, it is the moulds that move along the production line, like in an assembly line.

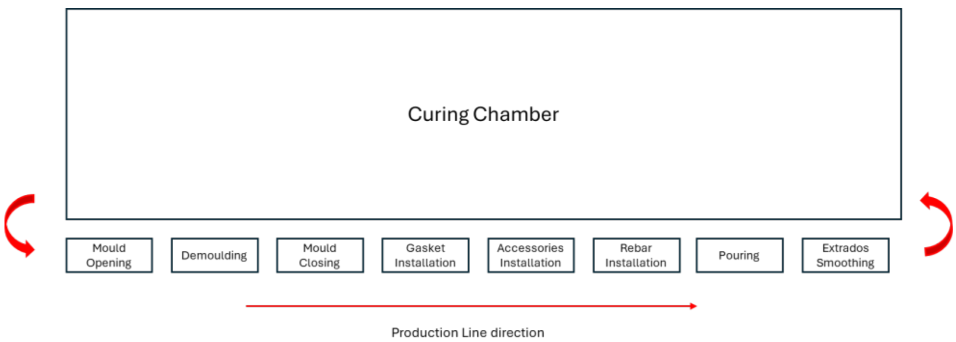


Figure 2. Carousel plant schematic layout.

3.2 *Advantages vs. recurring issues*

Compared to stationary plants, implementing a carousel allows for an optimisation of logistics, the flow of raw materials, vehicles, finished production as well as the required workforce. Production capacity is not bound anymore by the number of moulds in the factory, which encourages flexibility and facilitates managing demand peaks. Furthermore, by being responsible for specific tasks, operators can focus on single activities, thus increasing the quality of the production process. Carousel plants demonstrate an increase in productivity over time of around 30%, thereby reducing cycle times. This means that one segment is usually produced every 7 to 10 minutes. The quality of the segments also turns out better as there are fewer parameters in play that could jeopardise it. There is also less need for manual workforce which could lead to possible cost savings. As the moulds are in an isolated chamber during the pouring process, overall noise levels in the plant are lessened. This is advantageous not only from a technical standpoint, but also in terms of creating a safer working environment and reducing the risk of accidents and injuries among workers.

That being said, carousel plants can still be far from the safety standards and quality processes applied in other sectors, such as automotive or food production factories. More specifically, we will look at some aspects of this production method that could be improved. Although the number of workers needed is lower compared to stationary plants, in some areas, manpower can be difficult to find, especially for plants which must run on night shifts. Some quality aspects remain aleatory; by this, it’s meant that they still rely on human workers. Examples can be tightening moulds at the correct torque, segment defects identification, release agent spraying, etc.

Being an automated production line comes with the limitation that the fault of a single component affects the overall production cycle. This can cause delays and further problems when trying to resolve the initial one.

Compared to other sectors where automated plants have represented the basic production concept for decades, the precast industry is still behind in that matter, with contractors sometimes opting for a direct production of segments, thus venturing outside their core business and having to set up new factories as well as rapidly gain skills. This leads to a neglect of running costs with the only focus being on the investment cost, as the key objective is to produce segments at the right pace, rather than slowing down the TBM.

Focusing on repetitive tasks such as the ones presented in Figure 2 can be alienating, leading to high staff turnover. Despite many improvements from previous production plant types, fatigue-intensive and incident-prone activities are still present in the production process. Accidents may also happen due to moving machines and insufficient safety standards.

4 ROBOFACTORY: THE NEW PRODUCTION PARADIGM

4.1 *Robotics and automation implementation*

Stemming from the need of different precast plants and construction sites all around the world, CP Technology has spent the last few years developing a new and innovative carousel plant concept: Robofactory, as depicted in Figure 3. This concept involves robots, digital solutions and automated equipment working alongside operators.

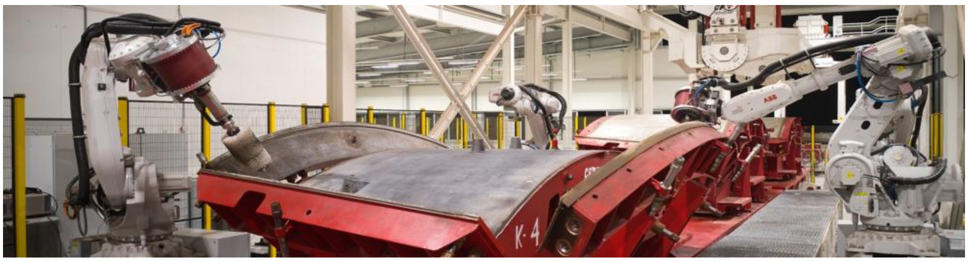


Figure 3. Robofactory in Italy.

While the production sequences remain the same as those of a carousel plant, some stations have been improved by adding robotic solutions in order to bring benefits to both the people working in the plant and the quality of the process.

Concerning mould opening, robots are responsible for unbolting the locking screw by applying the correct torque. The moulds are opened and closed automatically by a hydraulic system. Similarly, when preparing to close the moulds, robots are responsible for cleaning the internal surfaces of the moulds by using specific brushes. They are also in charge of spraying the release agent before the moulds exit from the robotic enclosed area.

When demoulding the segment from the mould, an automated machine as seen in Figure 4 is used to demould, turn the segments as shown in Figure 4(a) and move them towards the storage location. While the segment is being flipped, safety bars that can also be seen in Figure 4(a) are used to “catch” the segment in case of any kind of slipping malfunction. This way, it acts as a sort of safety net for the precast elements. The demoulding machine itself uses friction to keep the segment in place, reducing the stress on the segment extrados compared to the traditional vacuum solution. The contact pads that hold on to the segment can be seen in Figure 4(b). This equipment is particularly useful as it limits the different handling phases and the quantity of manpower needed for these operations.

(a) Device holding a concrete segment. (b) Empty device with exposed contact pads.

Figure 4. Demoulding and tilting machine in France.

Once the concrete starts being poured in the mould, load cells and automation work as support for the workers when controlling concrete pouring. Another improvement is the adoption of electrical vibrators instead of the traditional pneumatic vibrators used in stationary plants and in most carousel plants. This is advantageous as there is the possibility of adjusting the sequence and the frequency of each vibrator, while the pneumatic ones only work on an on/off basis. Vibration processes can be memorised based on the type of mould or the type of concrete which contributes to improving overall simplicity and efficiency within the casting chamber.

When exiting the casting station, the segments’ extrados usually needs to be smoothed out. For this particular step, robots can likewise be used to optimise the finishing of segments, without the need for operators. Robotic arms can also be used for the positioning of dunnage on the segments before stacking them in storage and in printing traceability labels that can be stuck on the segment in order to keep track of its specificities and whereabouts.

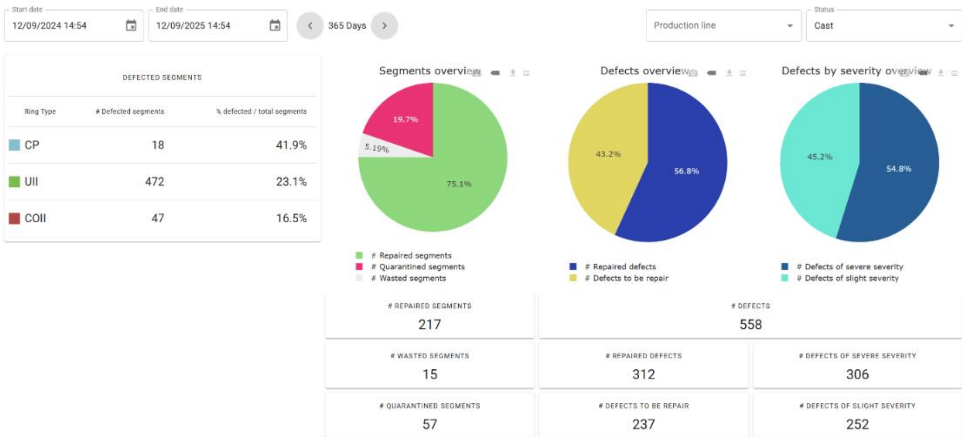
The utilisation of robots and automated technologies has resulted in a transition of workers from manual and repetitive tasks to roles involving control and supervision. This pushes the workforce towards more value-added tasks, and it can lead to the formation of new and useful competences. These skills can be applicable to different sectors, seeing as though in some areas, a tunnelling project or segment production may just be a temporary venture. Additional improvements have been made to the production process that don’t involve robotics but other kinds of equipment and tools.

4.2 *Other improvements of the Robofactory*

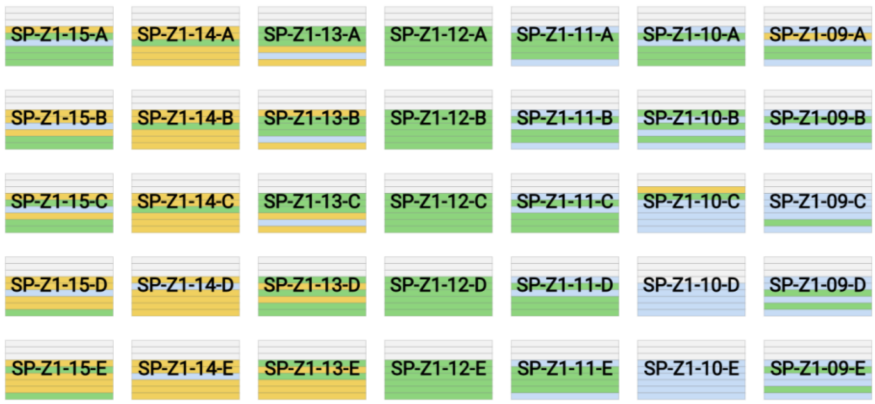
Production surveillance using traceability methods is a smarter way to track segments and related equipment. Thanks to self-developed software, production managers have access to a real-time dashboard, as seen in Figure 5(a), to control the status and the performance of the production. This includes information like the number of segments produced, an overview of the production trend, the percentage of different types of segments cast, etc. Other dashboard interfaces can contain indications of the defects rate, as shown in Figure 5(b), of the bottlenecks and of the storage yard mapping, as shown in Figure 5(c), with the aim of always optimising the production process and pouring time.

All the data regarding the production of the segments is collected in a smart and digitalised way, without the need to compare delivery notes, dispatching bills and serial numbers. Gaskets, rebar, cast-in items and concrete batches are scanned before the installation, such as to link their production lot to the specific segment being poured. This also considers all the process-related parameters (such as pouring time, demoulding time, etc) with the goal of providing a complete record of information that is crucial for the owner of the tunnel for the future maintenance.

(a) Display of production performance.



(b) Defects overview.



(c) Storage yard layout representation.

Figure 5. Example of dashboard interface.

Special temperature probes based on a Long Range (LoRa) connection are installed on the moulds' erector cones in order to measure the temperature at the centre of the segments. By doing so, it is possible to correlate the temperature of the concrete to its maturity, with the aim of spotting in advance if a segment has not yet reached the necessary strength for demoulding. Each mould inside the curing chamber is represented digitally and the temperature is visible to the plant operators.

A set of sensors, paired with a connection between the Robofactory's different pieces of equipment, allows the operating parameters of the machines to be monitored. The aim is to reduce power consumption if it is not necessary for production while also offering a general overview and the ability to control equipment consumption levels. For instance, the curing system power can be adjusted using temperature probes placed inside the curing chamber, which modulate the curing system if temperature increases aren't required.

The vapour control system enables the operator to adjust the vapour's temperature and humidity using a proportional-integral-derivative (PID) control system, thereby optimising response time, stability and adaptability. This system controls the valves for each of the curing chamber zones individually. It automatically keeps track of the curing environment. It also provides a user-friendly interface, giving operators all the necessary data. This display allows them to measure, control and record the different phases of a complete curing cycle. The temperature shows up at the bottom of the screen, providing an easy overview of the conditions to which the concrete elements are being subjected.

To assist electricians and fitters, specific maintenance scheduling and routines can be drafted to minimise the downtime of the equipment. Real-time data monitoring can also allow us to spot unexpected behaviours or changes of running parameters, suggesting preventive maintenance interventions.

In order to promote a safer working environment, alarmed gates and fences as well as 3D laser scanners are just a few examples of new-generation safety devices that are adopted in Robofactories to verify the absence of workers from hazardous areas and contribute to the reduction of injuries. 3D laser scanners are easily programmable and adjustable to survey specific areas and differentiate between relevant disturbances, such as those caused by the light reflected by people, or non-relevant ones, like ones by light reflected by dust. They have a detection range of up to 8.4 metres with a scanning area of 190°. Entering an area when the carousel is about to move or already in motion automatically stops the carousel and the Programmable Logic Controller (PLC) will generate an alert. The various information related to the event is recorded, such as the position, when it occurred and how long it lasted. This way, there's a possibility to check the logs for any past detection history, with up to 500 events that can be saved. This is useful in determining why a specific machine encountered a stop.

These developments aren't limited to process improvements. In fact, new spacers made of recycled plastic have been developed by CP Technology, under the name Green Spacers. Not only is their durability greater than timber spacers, but their weight is one fourth of the previously used timber ones. This tremendously benefits the people whose job it is to lift them every day as part of their tasks on precast sites.

5 CASE STUDIES

5.1 *Implementation in Europe*

Robofactories from CP Technology have been operating for 3 years in Europe, with plants serving the following projects:

- Messina-Catania Railway (Catania, Italy)
- Naples-Bari, Hirpinia-Orsara & Orsara-Bovino High-Speed Railway (Foggia, Italy)
- Turin-Lyon Tunnel (La Chapelle, France)
- HS2 – Northolt Tunnel East & Euston Tunnel High-Speed Railway (Hartlepool, UK)

5.2 *Plant overall efficiency*

The main improvements that have been achieved thanks to the adoption of Robofactories are the following:

- 50% reduction of manpower needed by going from 12 to 15 workers, like on a traditional carousel plant, down to 7 workers
- 30% reduction of cycle times by going from ten minutes per segment like on a traditional carousel plant to 6 to 7 minutes per segment, with a potential production of up to 170 segments

per day
– 40% decrease in segment defects.

Let's refer to Figure 6 and Table 1 to take the example of a carousel in Australia and a Robofactory in Italy. Based on data extracted from the production tracking system over the course of two months, it's clear that the Naples-Bari production plant showed better results, with an overall production increase of around 18% and a daily production increase of around 31% in comparison with the carousel plant.

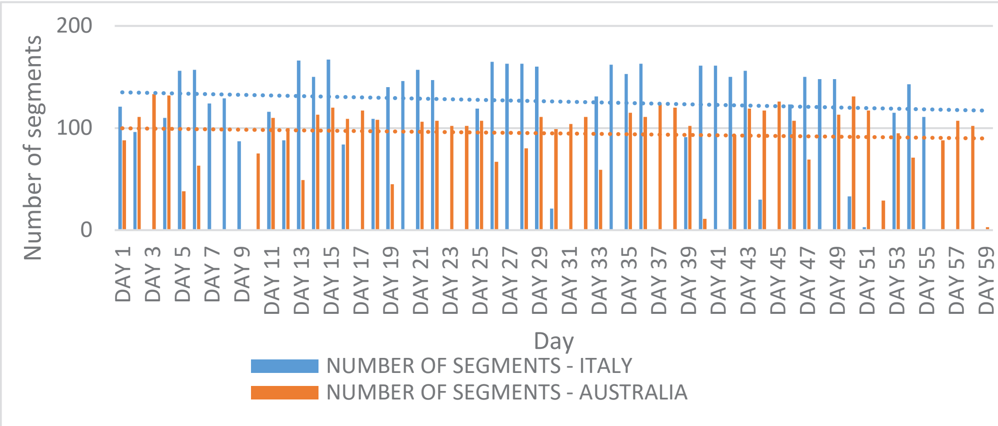


Figure 6. Graph comparing segment production in Italy and Australia

Table 1. Australia and Italy production comparison.

Country	Daily average production	Lowest daily production	Highest daily production	Total production
Australia	96.57	3	133	4732
Italy	126.66	3	167	5573

5.3 Conditions and suggestions for the Robofactory

Although the Robofactory is crucial to cut the operating costs of segment production, the initial investment is higher than a traditional carousel. For this reason, they are more often suggested when the following conditions are met:
– High cost of local manpower
– Long tunnels to be excavated, meaning large-scale and/or rapid segment production
– Universal factory, with the ability to produce segments for different projects over the years.

Analysis conducted with our clients shows the break-even is reached for tunnels of 10 km in length in Italy and tunnels of 5 km in length in Australia.

6 CONCLUSIONS

Long-standing challenges related to workforce shortages, workplace safety concerns, and production inefficiencies are in dire need of being addressed and worked on.

By integrating robotics, automation, and digital monitoring systems, the innovative Robofactory plant model is a revolutionary development in TBM segment production, which enhances operational reliability, reduces the need for manual labour, and significantly lowers defect rates. Its effectiveness is highlighted by the results observed across various European infrastructure projects, such as increased output, improved quality, and safer working environments, which truly highlight its effectiveness.

Although the initial investment is greater than that required for traditional carousel systems, the long-term benefits in terms of cost savings, scalability and sustainability make the Robofactory a compelling solution for modern tunnelling projects, particularly those with high production demands and strict quality requirements. This renders it a compelling option that should not be overlooked for future tunnelling projects in Australia.