ON-DEMAND GENERATION OF AS-BUILT INFRASTRUCTURE INFORMATION MODELS FOR MECHANISED TUNNELLING FROM TBM DATA: A COMPUTATIONAL DESIGN APPROACH

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Abstract

When dealing with complex curved geometries and massive datasets linked to linear infrastructures, manual generation and maintenance of related multidisciplinary BIM models and documentation are yet to be fully automated. This research focused on the integration of BIM and computational design into an intuitive approach for the generation of as-built models of mechanised tunnelling projects, leveraging the use of the real-time data collected by TBM. A preliminary study of the parameters was conducted to describe the curved geometry of the tunnel, then their mutual alignment was followed by the identification of additional relevant information. To automate the tunnel's BIM-based modelling process, a system of four coupled algorithms was developed and tested with a sample TBM dataset. The results demonstrate how the adoption of computational design methods drastically enhances the modelling process for infrastructure projects, allowing for the on-demand generation of as-built BIM models, reducing time and errors.

Keywords:

As-built; on-demand modelling; BIM; computational design; TBM Tunnelling.

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1 Introduction

The built environment has been perennially caught up in low productivity conundrum for a long time. This is despite its significant impact on industrial employment (i.e. over 6.6% contribution) and representation of 9.8% of the UK's Gross Domestic Product [1]. Poor collaborative processes and lack of productive information exchanges have been identified as primary reasons for this [2][3]. Besides, the technical and theoretical gap for the integration of design and construction has also been cited as a significant contributor to this discontinuity [4–10]. For instance, in the European context, concerning the non-residential sector, this implies a potential annual global cost savings of 10% to 21% throughout the all the project phases from design to construction and operation [11].

Over the years, leading experts from industry and academia [12][13] have contributed to the dissection of the drivers behind this and suggest solutions to address these issues. However, it has taken major developments in digital technologies like the internet, project extranets, building information modelling (BIM), IoT among others to generate the kind of optimism that the industry has never experienced before. The built environment is not alone in sharing the excitement around these technologies. These technologies have captured the imagination of just about every industrial sector. Of course, no technology can result in addressing the challenges of any industry on its own. A set of complementary processes [3][8] need to be developed in tandem for the technologies to be effective enablers of change. Quite encouragingly, such processes have been developed recently, particularly concerning information management and collaborative working in the built environment sector. These are positive developments and whose integrity and effectiveness will be tested over the next few years.

In case of the built environment sector, the nine pillars of the industry 4.0 revolution are somehow underpinned by BIM, widely regarded as the tool of choice to address key issues as industry fragmentation, value-driven solutions, decision making, client engagement, and design/process flow to name but a few. Therefore, it could be argued that Construction 4.0 has ten pillars which include the nine Industry 4.0 pillars and BIM. Exemplars from other industries such as automotive, aerospace and oil and gas currently demonstrate the power and application of these technologies. However, the built environment has only just started to recognise terms such as "golden key" and "golden thread" as part of BIM processes and workflows. Construction 4.0 offers a portfolio of potential solutions to bridge the knowledge and information gaps between design, construction and operations [14].

This has led to the emergence of a series of cutting edge technologies in the AEC realm including but not limited to virtual reality-based collaboration technologies [15], artificial intelligence-based optimisation [16], data-driven decision support [17], smart data modelling [18][19], blockchain and distributed ledger technologies [20], and computer vision and graphics [21][22]. Where, for example, these advancements are now able to assist decision-making in predicting the cost and performance of optimal design proposals [23].

Advancements in cryptography and read-only data management optimisation are paving the way for fully-fledged distributed ledger technologies for digital twinning and asset lifecycle management. Previous research has demonstrated real-time centralised solutions for openBIM [15]. Collectively, these developments are forcing a paradigm shift in design from asynchronous to real-time data exchanges which are impervious to repudiation, ultimately improving inter-organisational perceptions of social presence [24] and imbuing confidence in the design shift expected of openBIM.

As a means of the digital transformation of the sector, or in other words "a digital representation of a building's characteristics in its whole lifecycle", BIM plays the role of the frontrunner promising to provide large efficiency gains shared among all the stakeholders [25]. For this reason, many countries have promoted BIM adoption with both top-down and bottom-up approaches, especially concerning strategic infrastructure sector, where a growing interest in BIM implementation is evident [26]. However, the innovative methods and tools of BIM are often conceived to address the traditional design processes at a "building scale", thus not comprising the challenges posed from the design, construction and operation of infrastructure projects. Nonetheless, the recent growing recognition of BIM as the frontrunner in the digital transformation of the construction sector due to the provided efficiency gains has laid the ground for its expansion to the full-scale of the built environment.

Several works have explored the field of BIM application to the infrastructure sector, focusing on different aspects. Abdal Noor and Yi [27] conducted a meta-analysis on the studies related to the adoption of BIM in civil engineering construction projects. They reported a significant growth in the research interest in the past five years, especially in the development of new synergies and BIM-based tools to automate most of the processes. Cheng *et al.* [28] defined nine categories for the evaluation of the use of BIM in civil infrastructure facilities. They identified vigorous activity related to bridge, road or tunnel projects but also research gaps and a fundamental lack of efforts for the development of data schemas for other infrastructure facilities (e.g. airports, ports, harbours, recreational facilities, water management infrastructure). Costin *et al.* [29] focused on BIM for transportation infrastructure, contributing to define the current trends, emerging uses and technologies, challenges and limitations. They highlighted the need for standardisation to address interoperability issues related to highly heterogeneous data types. Bradley *et al.* [30] approached the implementation of BIM processes in infrastructure projects also from a constructor perspective, pointing out and discussing additional research gaps related to the need for alignment of business process with BIM process and a framework for information governance.

Furthermore, a survey study conducted on practitioners and professional association in the UK [31] evaluated the impact of BIM adoption in the design, building and management of transport infrastructure projects. It confirmed a significant disposition over the subject. It also advocated that if correctly implemented, BIM can have repercussion in the overall project cost, transition and the initial investment. This tendency is also aligned with the results of another recent report [32] on the general BIM adoption in the UK that marks a new record share of 73% of the surveyed professionals who declare BIM use in their work. However, when dealing with the potential benefits of BIM introduction in the infrastructure sector, issues related to the information governance and contracts restrictions are often overlooked, although their crucial impact on the process performance is well-known [33]. In this regard, a study related to the Japan context [33] stressed the importance of public sector leadership to overcome contract issues and to improve construction and fabrication knowledge availability in the design phase to frustrate efficiency gains offered by the digitisation of the sector. Likewise, but in a different context (Finland), Gerbov *et al.* [34] argued that there is a need to improve the level of assessment of the performance of BIM adoption in infrastructure projects. They stressed the distinction between measuring the benefits of using BIM in the design process and how designers perceive those benefits. Nonetheless, numerous works documented the widespread diffusion of BIM in the infrastructure sector beyond the research domain and further confirmed the direction taken by industry professionals and stakeholders [35][36][37][38].

This paper reveals how BIM adoption is changing the way tunnel and linear infrastructure are procured, designed built and managed. It does this by developing a framework and working prototype for the integration of BIM and computational design for tunnelling projects. The developed prototype leverages the data collected by the TBM during operation to generate the tunnel's as-built BIM model automatically. This study is motivated by the growing demand for BIM to support better information and documentation management during the whole lifecycle of massive construction and infrastructure projects. It is funded in the understanding that even in the presence of the complex curved geometries and massive datasets linked to linear infrastructures, such as roads, railways, and tunnels, the modelling and documentation extraction are still mostly manual and yet to be fully automated. This makes them time-consuming, error-prone and expensive processes. As such, this research has focused on the integration of BIM and computational design into an intuitive approach for the generation of as-built models of mechanised tunnelling projects, leveraging the real-time data collected by the Tunnel Boring Machine (TBM). In this regard, a preliminary study of parameters was carried out to describe the components of the curved geometry of the tunnel. Subsequently, their mutual alignment was followed by the identification of additional relevant information (e.g. components' installation time, anomalies). Therefore, to automate the tunnel's BIM-based modelling process, a system of four coupled algorithms were developed and tested with a sample TBM dataset.

This paper comprises of four sections. Section 1 sets up the background and identifies the gaps and motivations of the study. Section 2 presents the relevant studies to this work, covering three main areas of BIM implementation in the infrastructure sector, computational design for AEC processes automation and acquisition and modelling of as-built data. Section 3 presents the approach to the research and showcases the development framework of the proposed system. It then shows how the proposed system prototype works using a real case study. Section 4 outlines the main findings and highlights the main contributions and impacts of the research making clear proposals for future works.

2 Study Background

For the development of the proposed automated system for the generation of as-built BIM of mechanised tunnelling projects, the investigation of three main research lines has been carried out, related to BIM implementation in the infrastructure sector, computational design for AEC processes automation and acquisition and modelling of as-built data. The presented state-of-art is therefore organised according to three dedicated subsections and eventually followed by the discussion of the emerged open issues that motivated the present work.

2.1 Computational design for AEC processes automation

In the last decades the growing adoption in the AEC sector of computational design methods, mostly groupable under the definitions of parametric, generative and algorithmic design, contributed to the enhancement of the traditional process supporting the designers especially in the tedious and time-consuming tasks [39][40][41]. Moreover, the ever-growing number of variables, information and the better computational power allow for the development and implementation of powerful artificial-intelligence based tools helping the optimisation of several processes and serving as a basis for future advancements [42][43].

In this regard, to better understand the opportunities offered by the application of computational design approaches in the construction sector, the following studies regarding their application to the building energetic and structural performance simulation and optimisation deserve to be cited. Some research [44][45] achieved promising results related to building form and envelope design in the function of incident solar radiation and thermal performance. Furthermore, the benefits of the implementation of advanced computational approaches in this field are confirmed by the work of Dino et al. [46] where they are used to develop an image-based 3D reconstruction pipeline for the semi-automated generation of 3D models and to build energy models. Other studies [47][48][49] showed the feasibility of optimisation processes for design, prefabrication and assembly of building components and systems comprising the use of construction robots [50]. Some further works [51][52][53] were carried out to investigate BIM-based computational design methods for the evaluation of different design option of buildings with reinforced concrete structures for life cycle assessment (LCA) purposes and structural performance optimisation [54].

2.1.1 Advanced BIM-based applications for tunnel projects

Studies related the application of advanced BIM tools in tunnel projects were reviewed, especially those integrating computational design approaches in support of design, construction and management processes. Koch *et al.* [55] investigated the potential of interactive data visualisation and advanced numerical simulation. They proposed a framework for tunnel information modelling using an open industry Foundation Classes (IFC) schema, integrating a ground model, a TBM model, a tunnel lining model, and a built environment model. However, the advantages related to an enhanced understanding of their complex mutual interaction are somewhat lost due to the applied dispersed and heterogeneous data format. This issue was addressed by Ninić *et al.* [56] who developed an integrated platform for enabling automatic parametric information modelling, structural analysis and visualisation of mechanised tunnelling projects. They adopted a multilevel approach related to the different scales and level of details (LoD) required from the early design stages to construction detailing phases. Moreover, further works explored and demonstrated the feasibility of the cited integrated approaches and the advantages in terms of simulation efficiency and multidisciplinary information management [57][58]. Yet, research interest in such BIM-based applications is even growing beyond the academic research field among the industry stakeholders [59].

Furthermore, other several studies focused on addressing specific issues and showed the advantages provided by the implementation of computational approaches and process automation even though related to more limited aspects. Erharter and Marcher [60] presented a refined data-driven approach for the rock mass classification based on the processing of TBM operational data, improving previous systems. Zhou *et al.* [61] developed and validated a proposal IFC extension to enable the information transfer from tunnel's parametric design models to shield segment assembly system, to enhance the management and to control the performance of the construction process. Chen *et al.* [62] tackled the issue related to the safe and reliable operation of an ever-growing number of highway tunnels constructed in China with the proposal and application a novel BIM-based facility management system framework divided into five modules for the management of project documentation, personnel and contractors, safety and emergency and maintenance planning and execution and technical performance evaluation.

2.2 Acquisition and modelling of as-built data

When dealing with a built asset or a system of assets comprising their surrounding environment, the definition of "Digital Twin", though likely destined to undergo an evolutive expansion in terms of scope, capabilities and application domains [63], has become popular to refer to a digital model, that automatically and bi-directionally exchanges data with its physical twin [64] mirroring and simulating its functioning and characteristics in order to optimise the asset management and the decision-making process through the whole project lifecycle. Considering the significant uncertainties that intrinsically affects the design of the most considerable built assets, especially concerning transport infrastructure and tunnel projects, the production of accurate as-built models is crucial to driving the decision-making process during the construction phase. It plays a pivotal role in the later asset management process.

The automation of the digital modelling process of buildings, whether existing (as-is) or under construction (as-built), has represented especially in recent times a challenging issue that has been addressed with several different approaches depending on the building typology and the modelling process. In this regard, most of the efforts have been spent in the geometric modelling side of the process [65] and on the implementation of various visual recognition methods for shapes and objects from point clouds or laser scanning data [66][67]. Still, few constructed facilities have complete as-built information models which gather relevant data besides 3D representations of building components. As such, various proposals aimed to provide a framework for the integration of BIM, computer vision, image processing and laser scanning technologies for geometric building data acquisition and automatic generation of the related building information models [68][69][21]. In the same direction, many works, although differing in terms of adopted methods and technologies depending on the sector's specific applications, showed interesting results. Xiong *et al.* [70] focused on the creation and information enrichment of 3D building models from scanned data. Some other studies [71][72][73][74] investigated the automatic generation of parametric BIM from point cloud data focusing on structural components recognition. From a different point of view, other scholars [75][76][77][78] showed the automation opportunities provided by computer vision-based interpretation of scanned as-built data for several purposes, from construction progress monitoring to production monitoring and on-site inspections.

2.2.1 As-built modelling of tunnel projects

Looking further into the matter and limiting to the scope of the present work, tunnel projects, most research efforts have focused on the integration of advanced modelling systems with data capturing technologies. Methods for the automatic creation of as-built tunnel information models or 3D reconstructions from data acquired with different technologies have been proposed and tested for different scopes (e.g. production monitoring, deformation monitoring, defects detection). These projects achieved promising results in terms of accuracy (millimetric level), yet presenting issues related to the limitations of the algorithms developed for the data processing that fails to interpret and model objects with complex or occluded geometries [79][80][81].

The discussed approaches seem to represent the most viable solutions, especially for built tunnels which don't have an as-designed BIM and for which construction data are not available or are stored in a non-processable form. However, in a new-build tunnel project, a different approach is needed to enable constant collection and processing machine data for supporting the quasi-real-time production of accurate as-built information models. This could play a game-changer role and help to avoid additional data acquisition works and costs. In this sense, several studies advocated the effectiveness of the implementation of photogrammetric and laser scanning technologies for the automation of inspection activities [82][83][84] which are functional to structural assessment, deformation and damage detection, before maintenance operations [85][86].

2.3 Open issues

The literature review confirmed a strong research interest in the adoption of BIM and computational design approaches in civil engineering and especially for transport infrastructures. Despite the relevant results achieved in terms of automation of design processes and as-built modelling, along with enhanced information management throughout all the project lifecycle, this paper has identified two main issues related to the generation of as-built BIM of tunnel projects.

The first issue is that there is a need for the definition of a standard approach for the BIM modelling of tunnel projects both in the design and construction (as-built) phases. Despite the growing adoption of information modelling in several fields of the infrastructure sector, the potential of computational design tools integrated with BIM has not yet been fully applied for the automatic generation of the complex geometries of tunnels. Especially regarding the as-built BIM generation, the automation of tedious, repetitive tasks could provide considerable benefits in terms of efficiency and accuracy for a process known as critically time-consuming and error-prone. Even limiting the as-built modelling scope to the tunnel lining, basic operations are nothing but trivial if they are carried out manually. This can include the correct generation and positioning of thousand of elements (rings and segments) that could present a minor deviation from the design alignment. I can also involve the model population with heterogeneous data collected during the lining installation, and the extraction of plenty of as-built sheets reporting both elements' geometries and data along the tunnel alignment.

The second issue is that in mechanised tunnelling, the vast amount of data produced during the construction phase from the machine (TBM) is usually ignored after its operation or not considered in the as-built modelling process. Among this data, relevant information related to the overall tunnel geometry and components' assembly properties (e.g. forces, pressures, anomalies, defects) cannot be known for certain in the design phase and are recorded and available almost real-time just under construction. This information, especially related to eventual defects, is crucial to driving the decision-making process for the later equipment installation and finishings execution and can equally have relevance in the asset operation phase. Despite this fact, the most adopted solution for the BIM modelling process of existing tunnels, whether carried out under construction (as-built) or later (as-is), comprise the integration of computer vision, image processing and data capturing technologies (e.g. photogrammetry, laser scanning), implying additional survey campaigns and the following interpretation of the collected data. For this reason, an automatic modelling system for the data-driven generation of as-built BIM of mechanised tunnel projects could provide a new perspective in the field. The implementation of the dedicated algorithms for the exploitation of available construction data could drastically cut as-built modelling and documentation time while neutralising the human factor. It can also allow the models' enrichment with the cited components' assembly data that are usually neglected due to the lack of viable processes for their integration.

3 Proposed automated system for as-built modelling of mechanised tunnels

The goal of this research was to demonstrate the feasibility and the advantages offered by the integration of computational design methods and BIM for the automation of the as-built modelling process in large and highly standardised (repetitive) infrastructure projects such as mechanised tunnelling. As stated in the previous section, the main concerns of this study consisted of the lack of a standard approach for design and as-built modelling of tunnel projects. This research was grounded on developing a methodology for capturing and modelling as-built information about the geometry of the tunnels from the boring machine. This entails tackling the following issues:

- Defining a consistent approach that could be suitable and easily adjusted for the most mechanised tunnelling projects regardless of design constraints (e.g. tunnel diameter, typology and dimensions of ring and segments, etc.) or projects characteristics (e.g. tunnel length, alignments, curvatures, etc.)
- Addressing the issues related both to the geometrical and informational modelling of the tunnel (the as-built model won't be just the actual reproduction of the tunnel's geometry, but a model containing all and only data collected from the TBM)
- Developing a universal system that is not restricted to a specific typology of TBM
- Leveraging the full potential of data-driven modelling, allowing for the on-demand generation of a portion of the tunnel just filtering the available data
- Using a case study to validate the developed methodology for converting the TBM's data to BIM models
- Using a simulated dataset to assess the automated as-built modelling system's functioning

A preliminary analysis concerning the TBM operational principles has been carried out to define a consistent strategy for the automation of the as-built BIM modelling process of mechanised tunnelling projects. In this respect, an overview regarding the main aspects that influence mechanised tunnelling is reported before the detailed description of the proposed automated modelling system (see Section 3.2).

3.1 Mechanised tunnelling overview

In the field of tunnelling works, "mechanised tunnelling" refers to those highly automated tunnelling processes that make use of dedicated Tunnel Boring Machines (TBMs) to reduce construction time and costs when projects' characteristics permit. TBMs provide the progressive construction of the tunnel's prefabricated segmental lining, assembling its segments in consecutive adjacent rings while proceeding with the excavation. Nonetheless, since TBMs cost, comprising transport, assembly and dismantle is high, they are usually chosen over other tunnelling methods (e.g. drilling and blasting) after considering different factors, most significant of which is the tunnel length. For projects longer than 2-3 km, the tunnelling time reduction is usually worth TBMs adoption.

Furthermore, depending on the soil characteristic attended for the project, three TBMs typologies can be adopted, each applying specific tunnelling procedures, namely: open; single shield and double shield. For this work, the overview here presented focuses only on the aspects related to the double shield TBMs, on whose operational procedures the proposed automated as-built modelling system has been developed. In this regard, in the following subsections, the characteristics of the double shield TBMs are described, along with all the information regarding the tunnel's segmental lining geometry, composition and construction, that is relevant for the modelling system understanding.

3.1.1 Double-shield TBMs

Full face tunnelling machines allow for the complete mechanisation of tunnelling and the simultaneous construction of the related segmental lining. The essential functioning of a double-shield TBM is based on the alternate movement of its main head's section: front and tail. As shown in Figure 1 (a), with the lateral grippers extended, the tail section is blocked. It provides a contrast to the cutterheads' jacks that pushes the main bearing and the attached rotating cutterhead forward. At the same time, on the back, the lining's segments are positioned by mean of a dedicated erector. Meanwhile, according to Figure 1 (b), with the grippers retracted, the head's tail section moves forward pushing with other jacks on the last set lining ring.

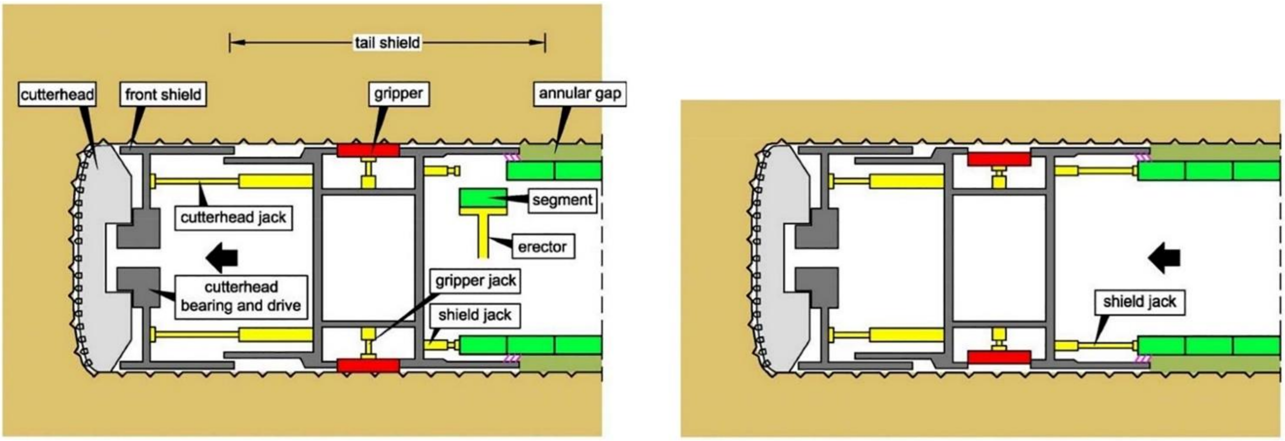


Figure 1: *Boring cycle of a double-shield TBM: a) Stroke and installation of segmental lining, grippers extended; b) pushing forward of the tail shield, grippers retracted. Source:* [87]

The simultaneous application of normal force and torque to the front causes the rocks to fracture in small pieces (chips). The crushed stone is mechanically removed from behind the cutterhead. Passing through the TBM's back-up out, it is conveyed out of the tunnel, to an external site. In the opposite direction, a constant supply of lining segments feeds the TBM's head. Compared to the other typologies, the main benefit of a double-shield TBM consists of the greater productivity that it provides when the soil characteristics are suitable for the use of the grippers' system. The front's excavation progresses at once with the erection and positioning of the lining segments in the tail section.

Nonetheless, if the characteristics of the encountered rock are low, the gripper system is not used, and the excavation proceeds with the lower productivity of a single-shield TBM. In this case, there must be an alternation between the lining segments installation and the sequent propulsion of the head. The capability of dynamically adapt to the soil characteristic, adjusting the excavation's procedures, gives to the double-shield TBMs greater versatility.

3.1.2 Segmental lining design

The lining of circular cross-section tunnels bored with the use of TBMs consists of prefabricated curved elements – segments - made of reinforced concrete which are positioned and joined to form a series of subsequent rings arranged in a continuous cylindrical structure (see Figure 2).

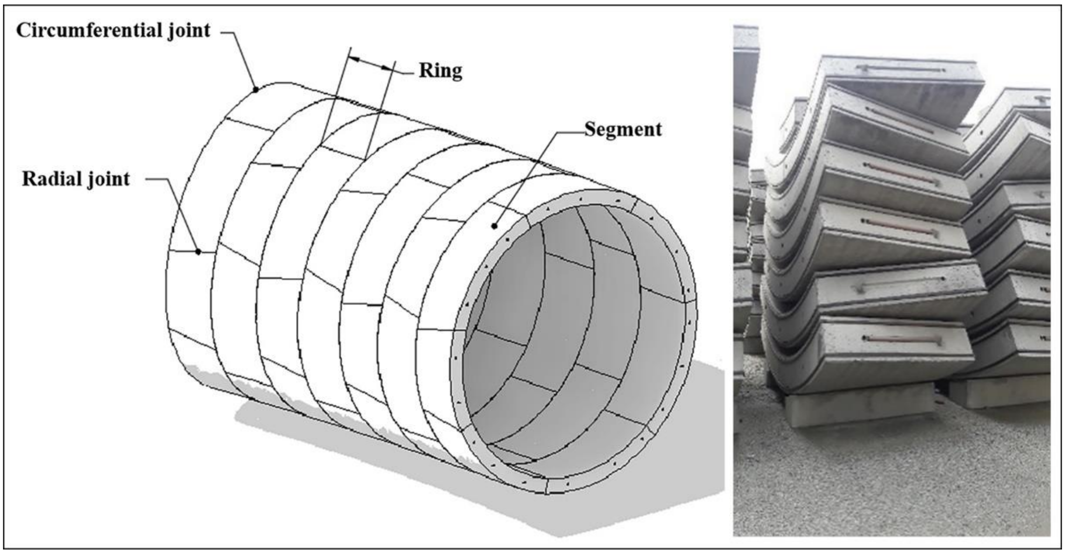


Figure 2: *Segmental lining elements (left); a pile of prefabricated ring segments ready for TBM feeding (right)*

A broad distinction of the lining segment typologies must be made on their possible forms and mutual orientations of their trailing and leading edge's faces to understand the tunnel's modelling procedure later proposed. For what concerns the edge faces direction, three-segment typologies can be identified along with the related ring typologies (see Figure 3):

- Segments with *parallel faces* form *straight rings* (parallel rings) – limited to straight tunnel's sections;
- Segments *tapered on one side* form *left/right tapered rings* - curved tunnel's sections;
- Segments *tapered on both sides* form *universal tapered rings* - straight and curved tunnel's sections.

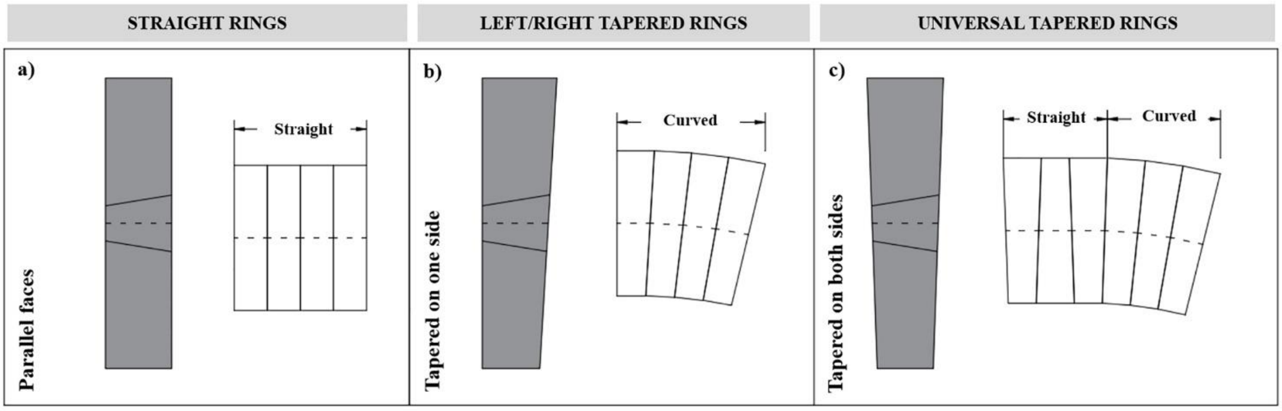


Figure 3: *Segment and ring typologies: a) segments with parallel faces – straight rings; b) segments tapered on one side – left-right tapered rings; c) segments tapered on both sides – universal tapered rings.*

Considering this main distinction, the design of the segments takes into account many other factors (e.g. tunnel's diameter; curve radius of the tunnel's bends) that eventually concur to define their final length (0.75 m ÷ 2.50 m) and thickness (0.15 m ÷ 0.75 m) to optimise the tunnelling process. Besides, for what concerns the segment's possible forms, three shapes can be identified: *rectangular* (R), *trapezoidal* (T) and *rhomboidal* (P). However, regardless of the different ring's configurations determined by the chosen segments' shapes, each ring finishes with the positioning of a particular trapezoidal segment named key block (see Figure 4). Furthermore, the assembly procedure requires the connection of every segment with the adjacent segments, both on its lateral edges (same ring) and its trailing edge. For this purpose, depending on the different bolting systems, several designs can be adopted for the longitudinal (or radial) joints and the circumferential (or circle) joints, whose primary function, after the structural resistance to the soil loads, is to provide the correct operation of the lateral EPDM gaskets. The automatic modelling procedure developed in this work has considered only the *rectangular lining* of *universal tapered rings*, made of seven segments (4 rectangular + 2 trapezoidal + 1 key block).

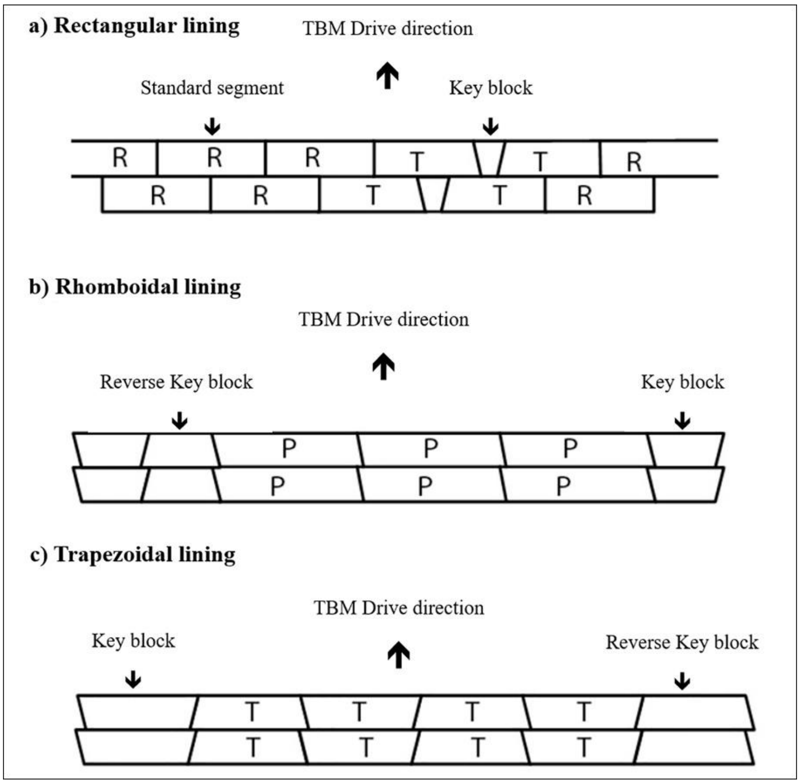


Figure 4: *Lining typologies: a) Rectangular lining; b) Rhomboidal lining; c) Trapezoidal lining.*

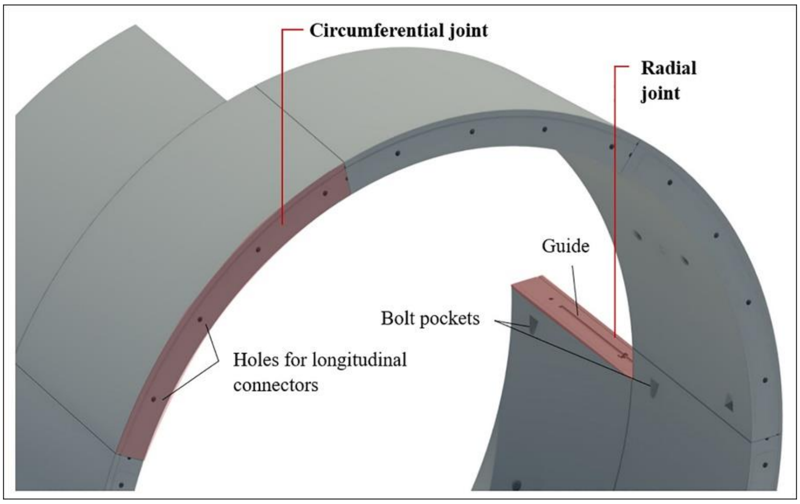


Figure 5: *Details of the segment's connections.*

Figure 6: *Auxiliary jacks pushing on the lining segments under the tail shield; erector in the foreground. (Brenner Base Tunnel; "Mules 2-3" block; double-shield TBM "Virginia")*

3.1.3 Tunnelling procedure

In normal operating conditions, propulsion jacks push forward the main bearing which supports the rotating cutterhead and hence making the TBM proceed. The TBM's driving system constantly provide information regarding the deviation of the cutterhead's centre from the designed tunnel's axis and allows for the adjustment of the propulsion jacks' pressure to correct the TBM's direction dynamically. The use of universal tapered rings, which provide the most freedom in terms of segments positioning, allows for greater versatility in following the different plano-altimetric track's variations. As described in detail in the following paragraph 4.1.4, because of its shape the universal tapered ring can be assembled in several different positions in respect of its predecessor, allowing for the dynamic adjustment of the proceeding direction just by choosing the optimal rings' configuration.

Figure 7: *Positioning of a standard segment (left) and the key block (right).*

For this reason, it is to be noticed that it is impossible to know in advance the exact as-built configuration of the various components of such tunnelling projects. It is also not possible just knowing a few variables (e.g. rings' subsequent rotations and joint arrangements) for each tunnel's rings is possible to solve the whole tunnel's geometry definition.

Furthermore, the TBM driving system notifies and records the anomalies which could be encountered and eventually arrest the operation in the case that control parameters are exceeded. Among these anomalies can be listed: sudden variations of the cutterhead's torque, cutterhead's block, unexpected variations in the soil density, insufficient pressure of the grout pumped to fill the annulus between the extrados of the lining and the tunnel profile. All these data were not taken into account in this paper but, if considered relevant, could be automatically added to the as-built model with the adoption of the same proposed approach.

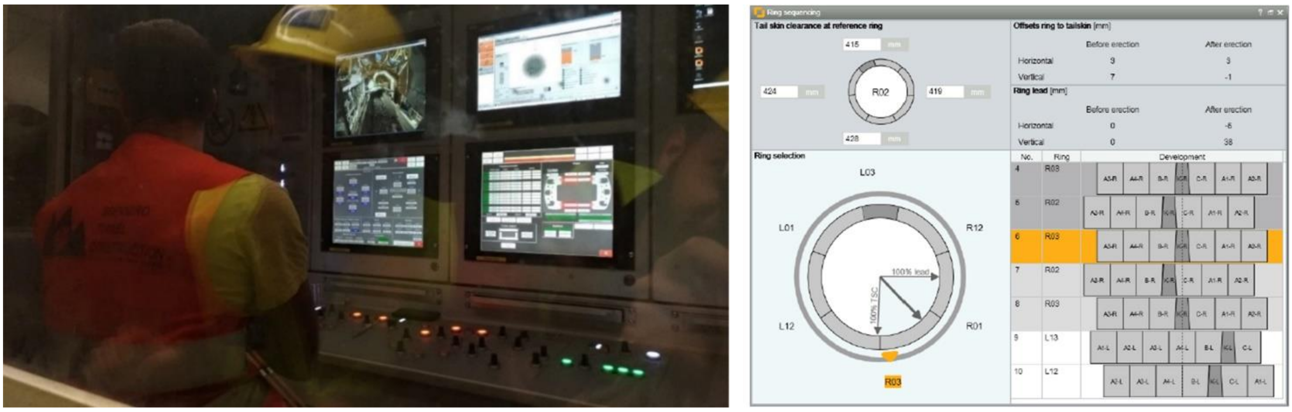


Figure 8: *TBM driving supervisor (left); TBM driving software's screen with the ring sequencing suggestion (right).*

3.1.4 Analysis of the lining component's geometry

The preliminary study of the geometry of the tapered ring is key for the development of the algorithm which provides the automatic tunnel's model generation. Furthermore, this study allowed for the definition of the test dataset for the simulation of the automated modelling system. It also facilitated later assessment of functionality the dataset, in terms of positioning and orientation of the lining's rings.

The lateral profile of the universal tapered ring has a trapezoidal shape (equal oblique sides). Both the trailing and leading edge of the ring present circular shape to allow a consistent connection with the previous and following ring, regardless of their mutual rotation. The rings can be positioned accordingly to a set of predefined configurations (rotations about the longitudinal axis) in a way that prevents the alignment the sequent radial joints. Furthermore, due to their tapered trailing and leading edges, different rings' configurations allow following all the tunnel track's Plano-altimetric variations with just the use of a single type o ring, speeding up the production and supply of ring's segments and reducing the errors. Figure 7 reports the main variables which run the universal tapered ring's geometry.

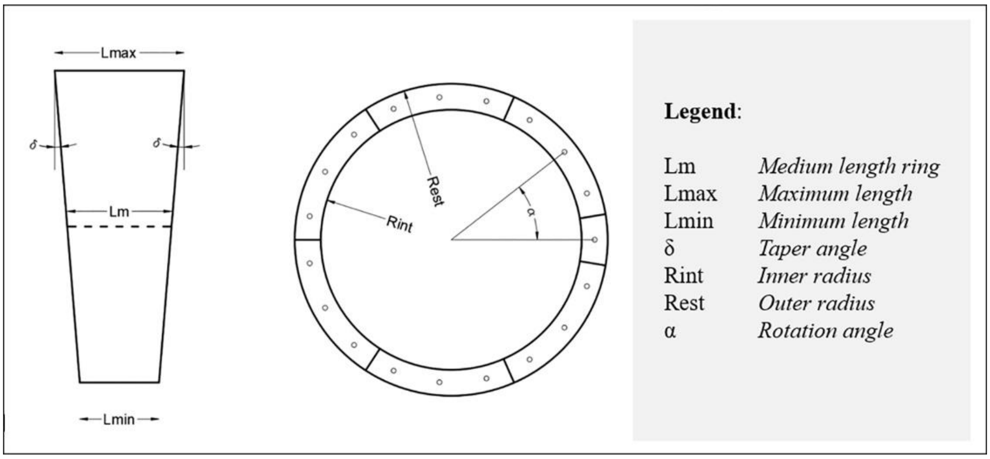


Figure 9: *Universal tapered ring: lateral and front profiles with variables.*

The capability of following the designed tunnel's track depends on three parameters: **Lm**, **δ** e **α**. The TBM's driving system dynamically adjust and solve the lining segments positioning, determining first the location of the key block, which is the last to be erected and installed for each ring. As shown in Figure 10, the position of the key block is defined with rotation concerning a reference position. The longitudinal ring rotation occurs about the orthogonal axis of the plane determined by the leading edge of the previous ring. The movement determined from this rotation can be geometrically described with the support of a right triangle **ABC**. As shown in Figure 11, **AB** is the side that equals the mean length of the ring (**Lm**) and connects the centres of the trailing and leading-edge faces. Similarly, **AC** and **CB** are determined from the parameter **δ.** This triangle, rotating about the **AC** side, describes a cone, on whose base circle can be determined all the possible positions of the centres of the leading face of the considered ring (point **B'**).

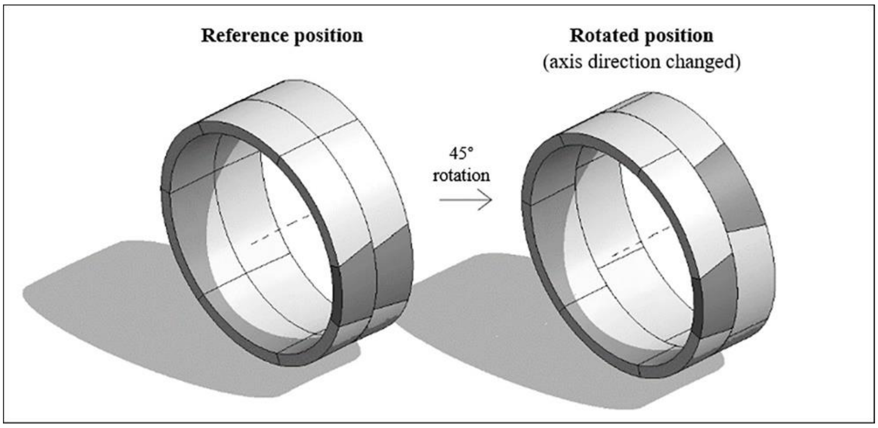


Figure 10: *Universal tapered ring: rotation.*

The longitudinal axis of the ring, which for each ring corresponds to the actual tunnel's axis, changes direction for new position chosen for the key block. The tunnel's axis orientation can vary discretely, considering the discrete number of positions permitted accordingly to a predefined number of connections on the ring's edges. For this reason, it can be assumed that every ring configuration determines a predefined "progress direction" for the tunnel which depends on the ring's: the mean length (**Lm**), taper (**δ**) and (**α**) rotation in the function of the number of the predefined edge connections.

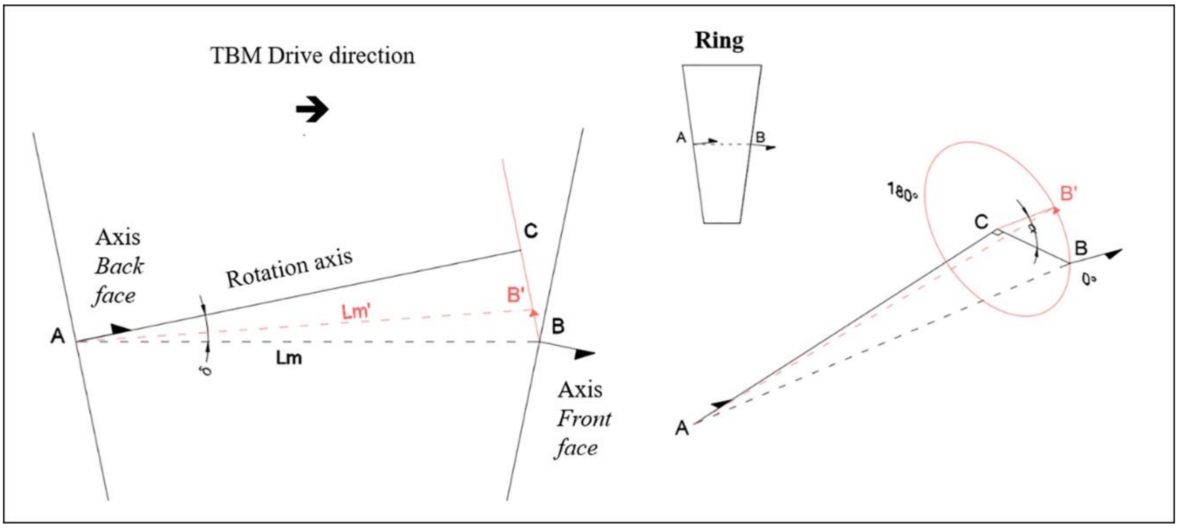


Figure 11: *Universal tapered ring: rotation geometrical representation.*

Figure 12 reports a sequence of four rings, rotated in different configurations to clarify the influence that the ring's rotation has on the tunnel's track deviation.

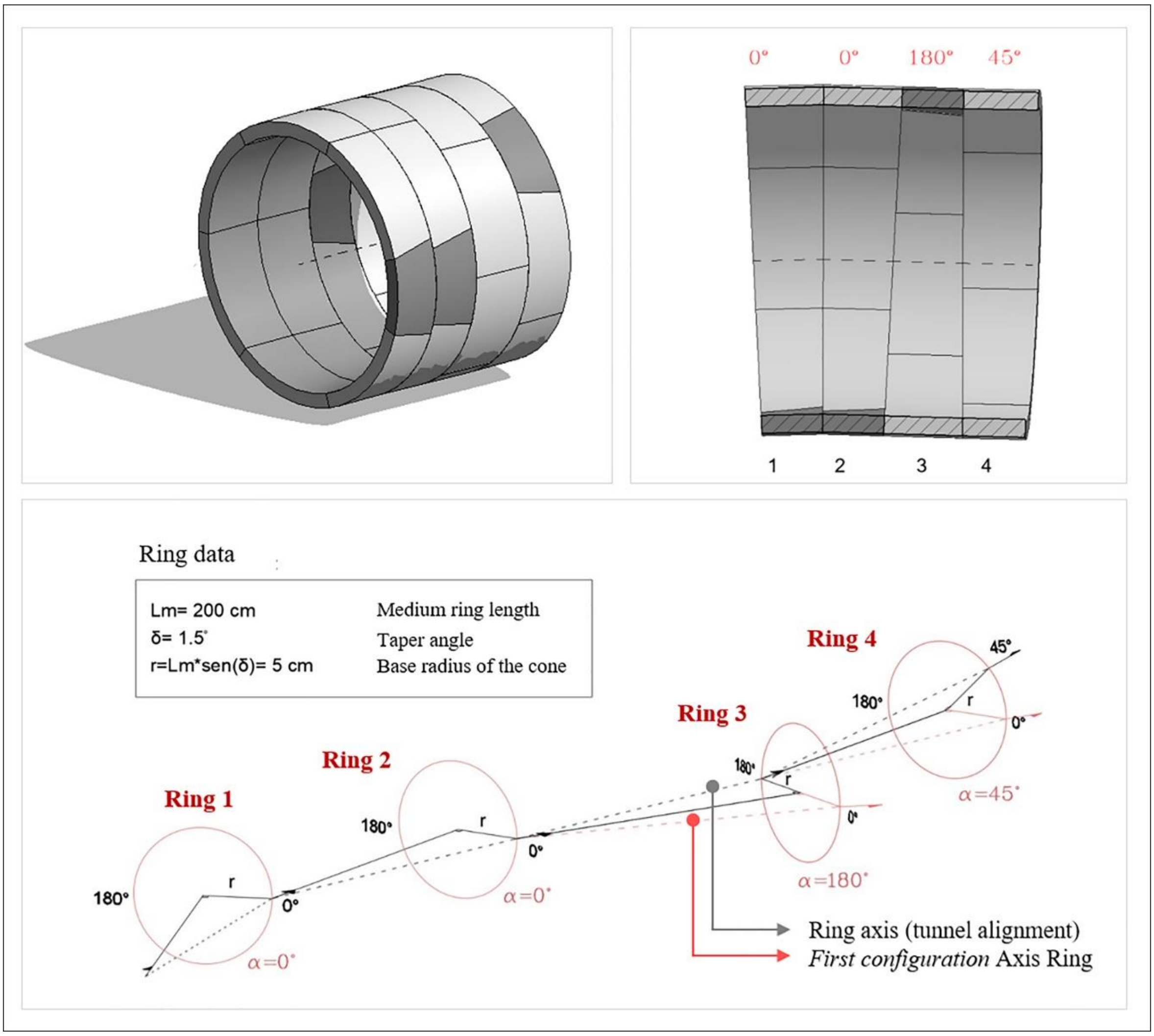


Figure 12: *Sequence of four rings with different rotations.*

Following Figures (13-15) report the possible configuration for a universal tapered ring with the addition of a compatibility matrix for the installation position (depending on the position of the connection).

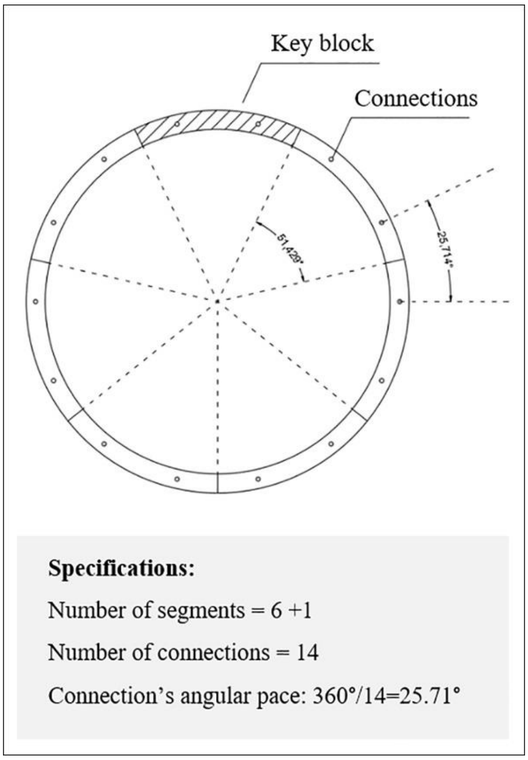


Figure 13: *Universal tapered ring.*

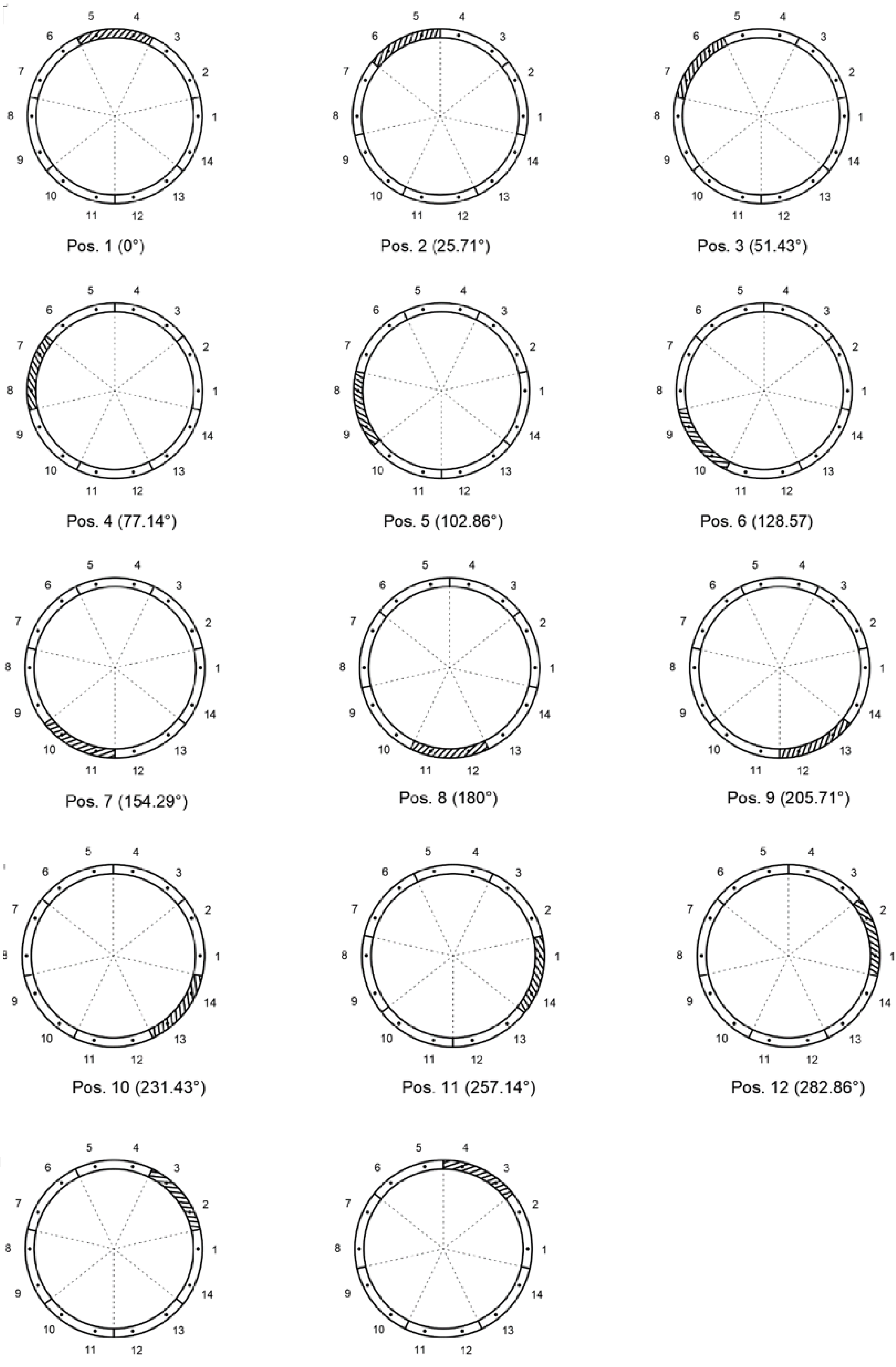


Figure 14: *Universal tapered ring's rotations.*

		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
	Angles	0.00	25.71	51.43	77.14	102.86	128.57	154.29	180.00	205.71	231.43	257.14	282.86	308.57	334.29
P1	0.00		●		●		●		●		●		●		●
P2	25.71	●		●		●		●		●		●		●	
P3	51.43		●		●		●		●		●		●		●
P4	77.14	●		●		●		●		●		●		●	
P5	102.86		●		●		●		●		●		●		●
P6	128.57	●		●		●		●		●		●		●	
P7	154.29		●		●		●		●		●		●		●
P8	180.00	●		●		●		●		●		●		●	
P9	205.71		●		●		●		●		●		●		●
P10	231.43	●		●		●		●		●		●		●	
P11	257.14		●		●		●		●		●		●		●
P12	282.86	●		●		●		●		●		●		●	
P13	308.57		●		●		●		●		●		●		●
P14	334.29	●		●		●		●		●		●		●	
	●	Permitted position													

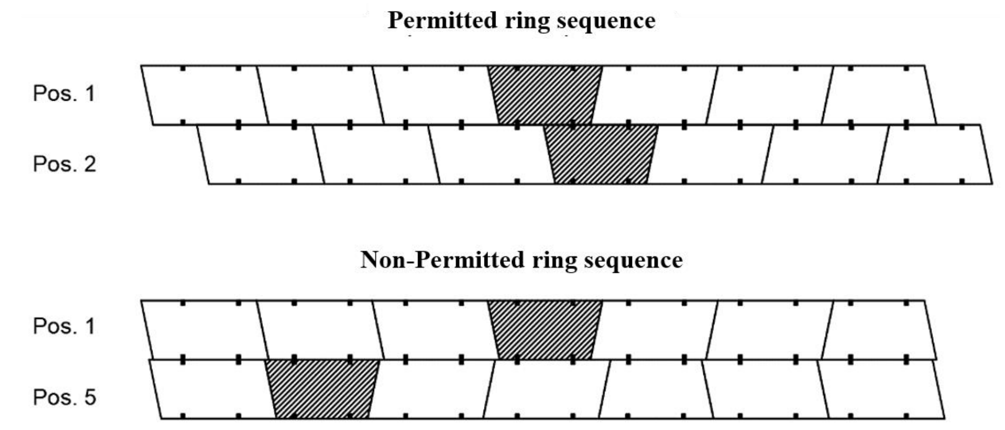


Figure 15: *Ring mutual configuration permitted: compatibility matrix (**top**) and example (**bottom**). The alignment of the radial joints that does not occur in the permitted configuration is clear in the non-permitted configuration.*

3.2 The automated as-built modelling system

Regarding the mechanised tunnelling process described previously, an approach which integrates BIM and computational design methods has been adopted to develop a system that leverages the data collected by the TBM during operation to generate the tunnel's as-built BIM model automatically. The proposed approach and system, although still in a prototypical phase, have been studied, developed and tested on the case study of the mechanised tunnelling project Brenner Base Tunnel (Italy) currently under construction with the adoption of double shield TBM technology. In Figure 16, the system's flowchart presents three main phases that will be later discussed in detail: 1) *Data study and acquisition*; 2) *Parametric components creation*; 3)

Automated as-built model generation. The system functioning and data flow are based on the adoption of commercial software and standard data formats, as expressed by the use of icons and described below:

- *Input data*, respectively related to both as-built information collected during TBM's operation and lining segments' geometry specified in the project design, are organised and provided in spreadsheets in the *.xls file format. Microsoft Excel is used, though any other software which handles this format could be suitable.
- *BIM objects for tunnel's rings and segments, comprising their assembly in a comprehensive tunnel model*, are authored via Autodesk Revit. As detailed below, this means making use of certain platform-specific parametric objects, so-called "families", for the creation and assembly of the segments and rings of the tunnel lining (simple families, nested families, adoptive families). The set of geometric and non-geometric parameters necessary for the automated modelling process is, in turn, generated as a formatted *.txt file, as required to work in the selected authoring environment.
- *Algorithms for the computational design-based generation of the as-built BIM of the tunnel* are developed and run as a series of scripts for the visual-programming environment Autodesk Dynamo.

The system is conceived to suit different mechanised tunnelling projects. In the initial phase, the tunnel design characteristics and the available information depending on the TBM are studied to calibrate the input data that will drive the BIM components generation (Section 2) and feed the automatic as-built BIM generation algorithms (Section 3).

3.2.1 Section 1 – Input data definition and acquisition

Given a mechanised tunnelling project, to make the automated modelling system operate, a preliminary calibration of the input data is required. In this regard, two sources are considered: (1) the recorded TBM's operational data and (2) the lining components' design characteristics.
From the first source and the study of the execution procedure of TBMs themselves, the authors identified the following set of information necessary to generate an as-built model with the data collected from the machine. Briefly recalling the lining positioning process carried out from a TBM together with the excavation progress, it can be reduced to the what the machine knows and records during the operations, namely: its position, geo-located and referred to the designed tunnel's alignment in terms of spatial coordinates; the mutual rotation of the ring that is currently being installed referred to the previous one and, therefore, the position each segment along with the related installation information and eventually occurred anomalies.

All the mentioned data, collected by the driving system of the TBM, is filtered to fit just the parameters that are considered necessary or relevant for the as-built model generation, in particular:

- *Coordinates* - the coordinates of the center of each plane considered to position the ring component in the project model togheter with the related nested segments. It consists of three values for the three-axis global reference system (x-y-z) of the final as-built model, derived from the geo-located data provided from the TBM. The tunnel tridimensional as-built alignment passes through the spatial points defined by these coordinates.

- *Rotations* – the sequence of the rotation value of each ring in respect of the one that has been installed before, expressed in degrees.
- *Installation parameters* – the parameters that consider any further non-geometric information that is assumed relevant to be stored in the as-built model. In this respect, for the tested dataset, this research considered: the installation *date* and *time* both for each ring and segments; the installation *pressure* expressed in kPa and, finally, the occurrence of an eventual *anomaly* for each installed segment, expressed as a boolean value and not further specified.

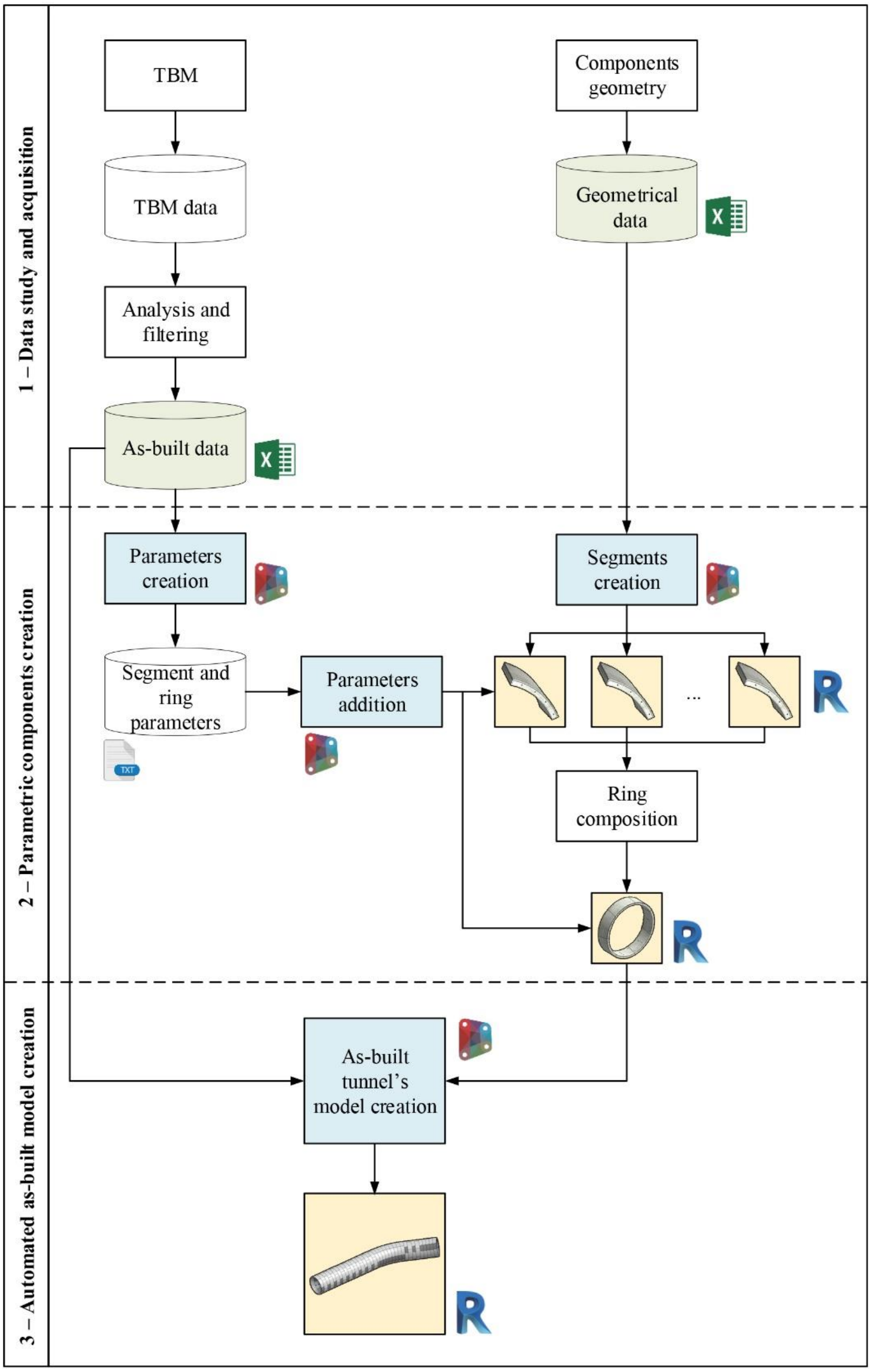


Figure 16: *Automated as-built modelling system: flowchart.*

This distinction is reflected in the structure of the "as-built database" spreadsheet. Each record or line in the sheet correspond to an installed ring and its related segments and is associated with unique alphanumerical codes. Single sheets comprise the above-cited groups of information, plus a "Master" sheet that automatically collects data from the others, associates them to the present records and provide them in a suitable form to be later read from the as-built model generation algorithm (see Section 3). Figure 17 reports a sample of the master sheet of the tested dataset. The rings assumed to be installed in this system are composed of seven segments.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	
1	Ring										Segment 1					Segment 2	
2	ID RING	Number	x	y	z	Rotation	Mileage	Instalaltion day	Srat time	End time	ID	Start time	End time	Pressure (Kpa)	Anomaly	ID	Iniz
3	A1	1	185,320	537,225	0,000	0	0	04/07/2019	4/7/19 6:12	4/7/19 7:12	c1-A1	4/7/19 6:12	4/7/19 6:18	80	no	c2-A1	4/
4	A2	2	187,295	537,536	0,000	180	2	04/07/2019	4/7/19 7:12	4/7/19 8:12	c1-A2	4/7/19 7:12	4/7/19 7:18	80	no	c2-A2	4/
5	A3	3	189,271	537,846	0,000	0	4	04/07/2019	4/7/19 8:12	4/7/19 9:12	c1-A3	4/7/19 8:12	4/7/19 8:18	80	no	c2-A3	4/
6	A4	4	191,247	538,157	0,000	180	6	04/07/2019	4/7/19 9:12	4/7/19 10:12	c1-A4	4/7/19 9:12	4/7/19 9:18	80	no	c2-A4	4/
7	A5	5	193,223	538,468	0,000	0	8	04/07/2019	4/7/19 10:12	4/7/19 11:12	c1-A5	4/7/19 10:12	4/7/19 10:18	80	no	c2-A5	4/7/
8	A6	6	195,198	538,779	0,000	180	10	04/07/2019	4/7/19 11:12	4/7/19 12:12	c1-A6	4/7/19 11:12	4/7/19 11:18	80	no	c2-A6	4/7/
9	A7	7	197,174	539,090	0,000	0	12	04/07/2019	4/7/19 12:12	4/7/19 13:12	c1-A7	4/7/19 12:12	4/7/19 12:18	80	no	c2-A7	4/7/
10	A8	8	199,150	539,401	0,000	180	14	04/07/2019	4/7/19 13:12	4/7/19 14:12	c1-A8	4/7/19 13:12	4/7/19 13:18	80	no	c2-A8	4/7/
11	A9	9	201,125	539,712	0,000	0	16	04/07/2019	4/7/19 14:12	4/7/19 15:12	c1-A9	4/7/19 14:12	4/7/19 14:18	80	no	c2-A9	4/7/
12	A10	10	203,101	540,022	0,000	180	18	04/07/2019	4/7/19 15:12	4/7/19 16:12	c1-A10	4/7/19 15:12	4/7/19 15:18	80	no	c2-A10	4/7/
13	A11	11	205,077	540,333	0,000	0	20	04/07/2019	4/7/19 16:12	4/7/19 17:12	c1-A11	4/7/19 16:12	4/7/19 16:18	85	no	c2-A11	4/7/
14	A12	12	207,052	540,644	0,000	180	22	04/07/2019	4/7/19 17:12	4/7/19 18:12	c1-A12	4/7/19 17:12	4/7/19 17:18	80	no	c2-A12	4/7/
15	A13	13	209,028	540,955	0,000	0	24	04/07/2019	4/7/19 18:12	4/7/19 19:12	c1-A13	4/7/19 18:12	4/7/19 18:18	80	no	c2-A13	4/7/
16	A14	14	211,004	541,266	0,000	180	26	04/07/2019	4/7/19 19:12	4/7/19 20:12	c1-A14	4/7/19 19:12	4/7/19 19:18	120	si	c2-A14	4/7/
17	A15	15	212,979	541,577	0,000	0	28	04/07/2019	4/7/19 20:12	4/7/19 21:12	c1-A15	4/7/19 20:12	4/7/19 20:18	80	no	c2-A15	4/7/
18	A16	16	214,955	541,887	0,000	180	30	04/07/2019	4/7/19 21:12	4/7/19 22:12	c1-A16	4/7/19 21:12	4/7/19 21:18	80	no	c2-A16	4/7/
19	A17	17	216,931	542,198	0,000	0	32	04/07/2019	4/7/19 22:12	4/7/19 23:12	c1-A17	4/7/19 22:12	4/7/19 22:18	80	no	c2-A17	4/7/
20	A18	18	218,907	542,509	0,000	180	34	04/07/2019	4/7/19 23:12	5/7/19 0:12	c1-A18	4/7/19 23:12	4/7/19 23:18	80	no	c2-A18	4/7/
21	A19	19	220,882	542,820	0,000	0	36	05/07/2019	5/7/19 0:12	5/7/19 1:12	c1-A19	5/7/19 0:12	5/7/19 0:18	99	no	c2-A19	5/
22	A20	20	222,858	543,131	0,000	0	38	05/07/2019	5/7/19 1:12	5/7/19 2:12	c1-A20	5/7/19 1:12	5/7/19 1:18	80	no	c2-A20	5/
23	A21	21	224,847	543,338	0,000	0	40	05/07/2019	5/7/19 2:12	5/7/19 3:12	c1-A21	5/7/19 2:12	5/7/19 2:18	80	no	c2-A21	5/
24	A22	22	226,845	543,440	0,000	0	42	05/07/2019	5/7/19 3:12	5/7/19 4:12	c1-A22	5/7/19 3:12	5/7/19 3:18	80	no	c2-A22	5/
25	A23	23	228,845	543,438	0,000	0	44	05/07/2019	5/7/19 4:12	5/7/19 5:12	c1-A23	5/7/19 4:12	5/7/19 4:18	80	no	c2-A23	5/
26	A24	24	230,842	543,332	0,000	0	46	05/07/2019	5/7/19 5:12	5/7/19 6:12	c1-A24	5/7/19 5:12	5/7/19 5:18	80	no	c2-A24	5/
27	A25	25	232,831	543,121	0,000	0	48	05/07/2019	5/7/19 6:12	5/7/19 7:12	c1-A25	5/7/19 6:12	5/7/19 6:18	88	no	c2-A25	5/
28	A26	26	234,806	542,806	0,000	0	50	05/07/2019	5/7/19 7:12	5/7/19 8:12	c1-A26	5/7/19 7:12	5/7/19 7:18	80	no	c2-A26	5/
29	A27	27	236,761	542,388	0,000	0	52	05/07/2019	5/7/19 8:12	5/7/19 9:12	c1-A27	5/7/19 8:12	5/7/19 8:18	80	no	c2-A27	5/
30	A28	28	238,693	541,868	0,000	45	54	05/07/2019	5/7/19 9:12	5/7/19 10:12	c1-A28	5/7/19 9:12	5/7/19 9:18	80	no	c2-A28	5/
31	A29	29	240,599	541,263	0,037	225	56	05/07/2019	5/7/19 10:12	5/7/19 11:12	c1-A29	5/7/19 10:12	5/7/19 10:18	80	no	c2-A29	5/7/
32	A30	30	242,504	540,658	0,074	45	58	05/07/2019	5/7/19 11:12	5/7/19 12:12	c1-A30	5/7/19 11:12	5/7/19 11:18	80	no	c2-A30	5/7/

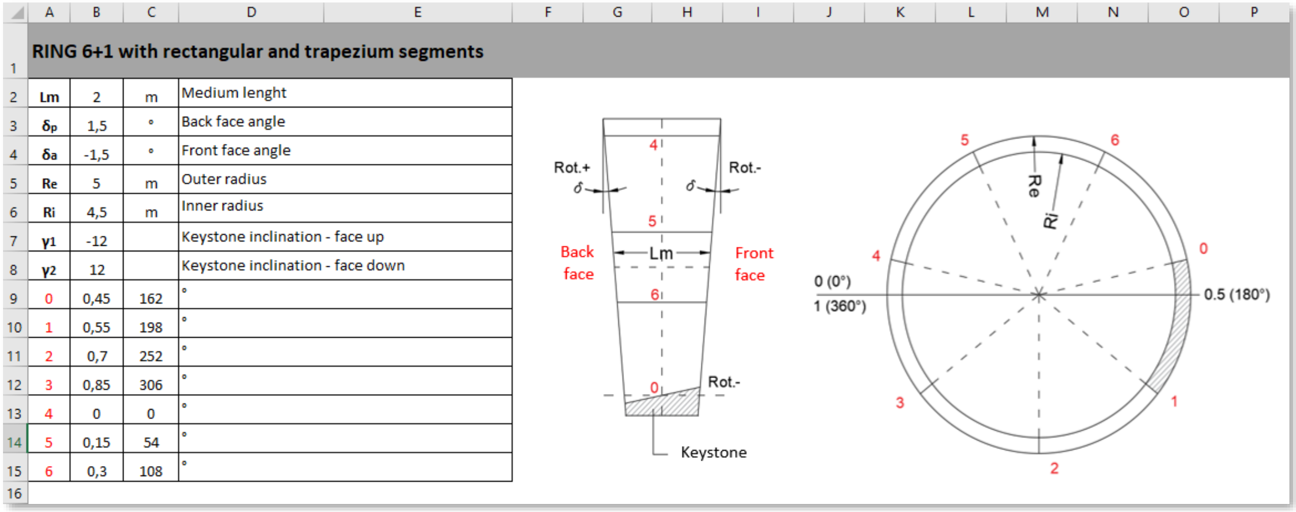
MAIN SHEET | COORDINATES | ROTATION | RING PARAMETERS | SEGMENT PARAMETERS | Par

Figure 17: *As-built information database (configurated spreadsheet).*

Other sheets are included in the "as-built database" to drive the later generation of the "shared parameters" for rings and segments via the dedicated Dynamo script (see Section 2). This helped the authors to store parameters, table, and data in the same database, leading to enhance the consistency of the input data structure.

The tunnel lining design represents the second source of information that has to be considered in this initial system setup phase in terms of the geometrical definition of its components, i.e. rings and segments. To speed up the generation of the related parametric objects and to reduce the chances for likely human errors, mainly due to their curved geometries, a dedicated algorithm takes charge of this operation (as detailed in Section 2). For further reliability, the algorithms read the values of a set of predefined geometrical parameters from a reliable additional spreadsheet (Figure 18).

The mentioned spreadsheet is conceived for the double-tapered ring typology with seven segments and support the user in the values input with figures that specify their meaning. The requested parameters for the definition of the ring geometry are namely: *Lm*, mean depth; δ_p and δ_a, tapering angle for both the front and rear faces; *Re* and *Ri*, the external and internal radius of the ring; *y1* and *y2*, tilt angles for both the lateral faces of the key segment. The proposed sheet that collects the "geometrical data" for the parametric generation of the BIM objects to be used in the model could be customised and modified to match the requirements of different ring typologies and characteristics. It is worthwhile to notice that, at the development stage, the inserted parameters and tunnel's ring components are enough to achieve their overall correct geometric representation, but lack the details comprised in proper "as-built" models (bolts, holes, reinforcement, gaskets and so forth). Nonetheless, despite the main purpose of this research, i.e. the automatic creation of an "as-built" model in line with the data provided from a TBM, further developments could be explored in producing more detailed objects in a dedicated modelling environment. These models could be further enhanced by training new algorithms based on the models that are correctly positioned in the model.

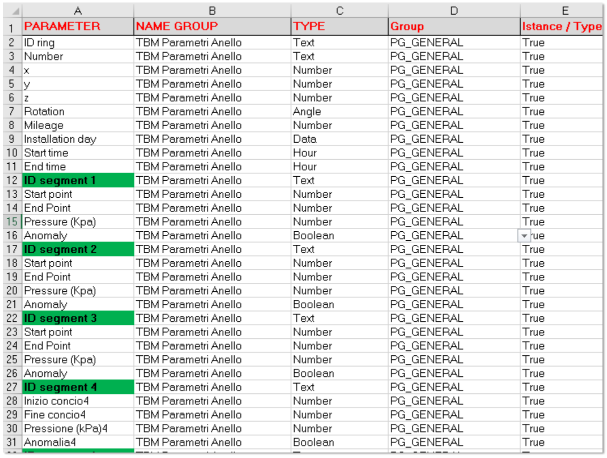


RING 6+1 with rectangular and trapezium segments			
Lm	2	m	Medium lenght
δp	1,5	°	Back face angle
δa	-1,5	°	Front face angle
Re	5	m	Outer radius
Ri	4,5	m	Inner radius
γ1	-12		Keystone inclination - face up
γ2	12		Keystone inclination - face down
0	0,45	162	°
1	0,55	198	°
2	0,7	252	°
3	0,85	306	°
4	0	0	°
5	0,15	54	°
6	0,3	108	°

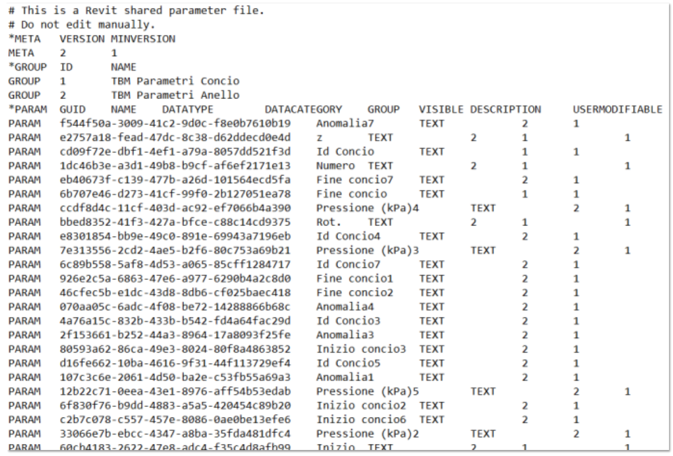
Figure 18: *Geometrical data (configurated spreadsheet).*

3.2.2 Section 2 – Parametric components creation

Once identified the main design elements of the tunnel project and studied the available TBM's data, the system is set for the automatic parametric generation of the lining components. Breaking down the as-built BIM of the tunnel it can be stated in the brief that it is modelled similarly to how it is built: a series of sub-components, ring segments, are modelled one by one starting from a target ring geometry and then put together to form a single ring component; this, in turn, is positioned in its correct location on the tunnel alignment and then oriented and rotated to respect the tunnel assembly constraints. Therefore, the automatic model generation is based on the proper definition of the parametric ring component and the segments sub-components. Due to the characteristics of the adopted authoring environment, this process has been split into two parts, both driven by a dedicated algorithm (Dynamo Scripts) for the generation of BIM components geometries and parameters definition. From the "geometrical data" spreadsheet discussed above, an algorithm generates the ring segments reading the cited design constraints values (Figure 19 and Figure 20). These components are now ready from a geometrical point of view. Still, they must be completed attaching to them all the parameters necessary for the related non-geometrical relevant information that will be stored in the as-built model. Parameters, in turn, are first automatically defined as a list in a formatted *.txt file running an algorithm that reads the "as-built database" spreadsheet discussed above (Figure 19). Then, a second algorithm attaches the listed parameters to the segments families that are then put together to form the ring family (Figure 21). This is the one that will be positioned, oriented and rotated on the tunnel alignment to fit the as-built correct tunnel geometry. However, a final step is required consisting of the attachment to the ring family of the parameters for the related non-geometrical information by mean of the same algorithm discussed above. In conclusion, from this point on, there is no further need for modelling the tunnel components. This is because the ring families are set to be not only geometrically correct but also to store all the non-geometrical information both at a ring scale and at a single segment scale.



	A	B	C	D	E
1	PARAMETER	NAME GROUP	TYPE	Group	Istance / Type
2	ID ring	TBM Parametri Anello	Text	PG_GENERAL	True
3	Number	TBM Parametri Anello	Text	PG_GENERAL	True
4	x	TBM Parametri Anello	Number	PG_GENERAL	True
5	y	TBM Parametri Anello	Number	PG_GENERAL	True
6	z	TBM Parametri Anello	Number	PG_GENERAL	True
7	Rotation	TBM Parametri Anello	Angle	PG_GENERAL	True
8	Mileage	TBM Parametri Anello	Number	PG_GENERAL	True
9	Installation day	TBM Parametri Anello	Data	PG_GENERAL	True
10	Start time	TBM Parametri Anello	Hour	PG_GENERAL	True
11	End time	TBM Parametri Anello	Hour	PG_GENERAL	True
12	ID segment 1	TBM Parametri Anello	Text	PG_GENERAL	True
13	Start point	TBM Parametri Anello	Number	PG_GENERAL	True
14	End Point	TBM Parametri Anello	Number	PG_GENERAL	True
15	Pressure (Kpa)	TBM Parametri Anello	Number	PG_GENERAL	True
16	Anomaly	TBM Parametri Anello	Boolean	PG_GENERAL	rue
17	ID segment 2	TBM Parametri Anello	Text	PG_GENERAL	True
18	Start point	TBM Parametri Anello	Number	PG_GENERAL	True
19	End Point	TBM Parametri Anello	Number	PG_GENERAL	True
20	Pressure (Kpa)	TBM Parametri Anello	Number	PG_GENERAL	True
21	Anomaly	TBM Parametri Anello	Boolean	PG_GENERAL	True
22	ID segment 3	TBM Parametri Anello	Text	PG_GENERAL	True
23	Start point	TBM Parametri Anello	Number	PG_GENERAL	True
24	End Point	TBM Parametri Anello	Number	PG_GENERAL	True
25	Pressure (Kpa)	TBM Parametri Anello	Number	PG_GENERAL	True
26	Anomaly	TBM Parametri Anello	Boolean	PG_GENERAL	True
27	ID segment 4	TBM Parametri Anello	Text	PG_GENERAL	True
28	Inizio concio4	TBM Parametri Anello	Number	PG_GENERAL	True
29	Fine concio4	TBM Parametri Anello	Number	PG_GENERAL	True
30	Pressione (kPa)4	TBM Parametri Anello	Number	PG_GENERAL	True
31	Anomalia4	TBM Parametri Anello	Boolean	PG_GENERAL	True



```
# This is a Revit shared parameter file.
# Do not edit manually.
*META	VERSION	MINVERSION
META	2	1
*GROUP	ID	NAME
GROUP	1	TBM Parametri Concio
GROUP	2	TBM Parametri Anello
*PARAM	GUID	NAME	DATATYPE	DATACATEGORY	GROUP	VISIBLE	DESCRIPTION	USERMODIFIABLE
PARAM	f544f50a-3009-41c2-9d0c-f8e0b7610b19	Anomalia7	TEXT		2	1
PARAM	e2757a18-fead-47dc-8c38-d62ddecd0e4d	z	TEXT		2	1		1
PARAM	cd09f72e-dbf1-4ef1-a79a-8057dd521f3d	Id Concio	TEXT		1	1
PARAM	1dc46b3e-a3d1-49b8-b9cf-af6ef2171e13	Numero	TEXT		2	1		1
PARAM	eb40673f-c139-477b-a26d-101564ecd5fa	Fine concio7	TEXT		2	1
PARAM	6b707e46-d273-41cf-99f0-2b127051ea78	Fine concio	TEXT		1	1
PARAM	ccdf8d4c-11cf-403d-ac92-ef7066b4a390	Pressione (kPa)4	TEXT		2	1
PARAM	bbed8352-41f3-427a-bfce-c88c14cd9375	Rot.	TEXT		2	1		1
PARAM	e8301854-bb9e-49c0-891e-69943a7196eb	Id Concio4	TEXT		2	1
PARAM	7e313556-2cd2-4ae5-b2f6-80c753a69b21	Pressione (kPa)3	TEXT		2	1
PARAM	6c89b558-5af8-4d53-a065-85cff1284717	Id Concio7	TEXT		2	1
PARAM	926e2c5a-6863-47e6-a977-6290b4a2c8d0	Fine concio1	TEXT		2	1
PARAM	46cfec5b-e1dc-43d8-8db6-cf025baec418	Fine concio2	TEXT		2	1
PARAM	070aa05c-6adc-4f08-be72-14288866b68c	Anomalia4	TEXT		2	1
PARAM	4a76a15c-832b-433b-b542-fd4a64fac29d	Id Concio3	TEXT		2	1
PARAM	2f153661-b252-44a3-8964-17a8093f25fe	Anomalia3	TEXT		2	1
PARAM	80593a62-86ca-49e3-8024-80f8a4863852	Inizio concio3	TEXT		2	1
PARAM	d16fe662-10ba-4616-9f31-44f113729ef4	Id Concio5	TEXT		2	1
PARAM	107c3c6e-2061-4d50-ba2e-c53fb55a69a3	Anomalia1	TEXT		2	1
PARAM	12b22c71-0eea-43e1-8976-aff54b53edab	Pressione (kPa)5	TEXT		2	1
PARAM	6f830f76-b9dd-4883-a5a5-420454c89b20	Inizio concio2	TEXT		2	1
PARAM	c2b7c078-c557-457e-8086-0ae0be13efe6	Inizio concio6	TEXT		2	1
PARAM	33066e7b-ebcc-4347-a8ba-35fda481dfc4	Pressione (kPa)2	TEXT		2	1
```

Figure 19: *Parameters defined in the "as-built data" spreadsheet (**left**) and transformed in the shared parameter *.txt format **(right)**.*

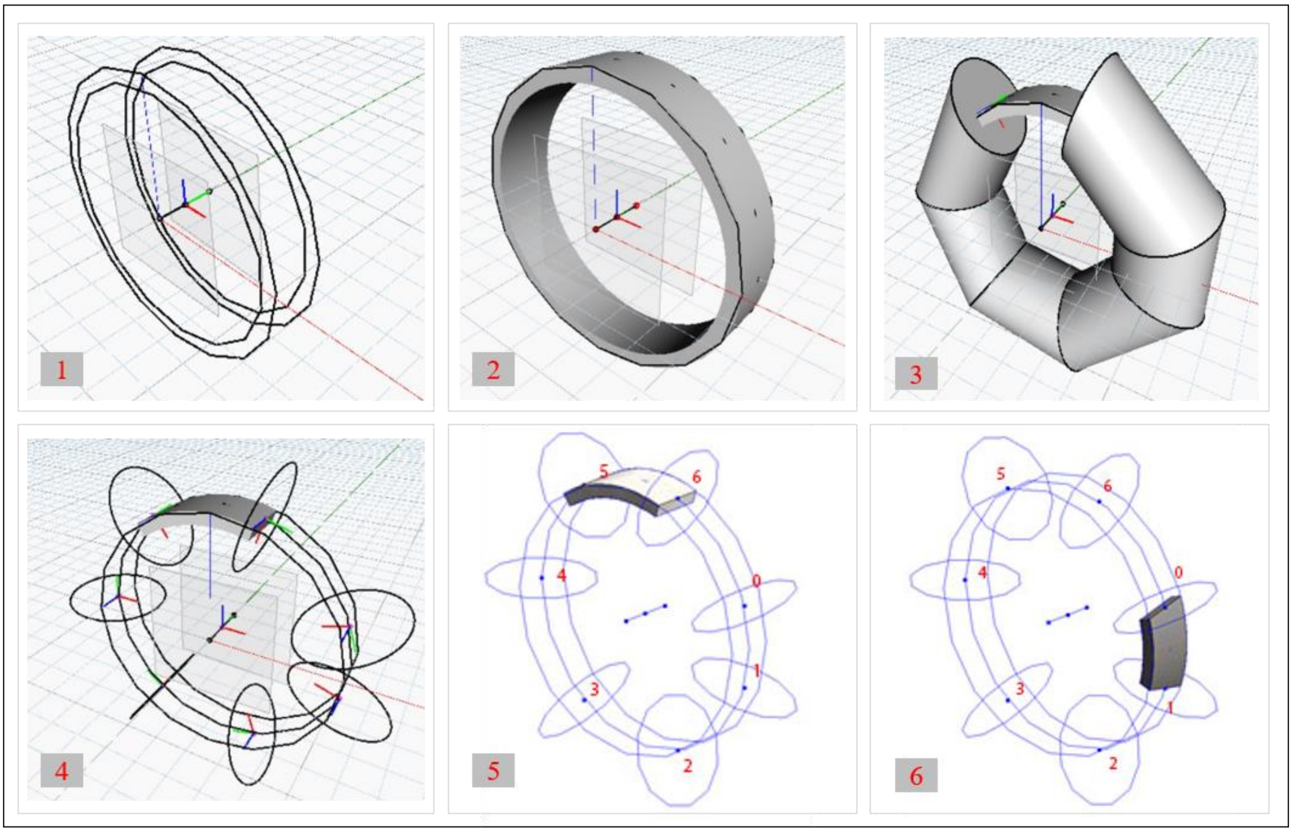


Figure 20: *Steps of the algorithmic segment components generation.*

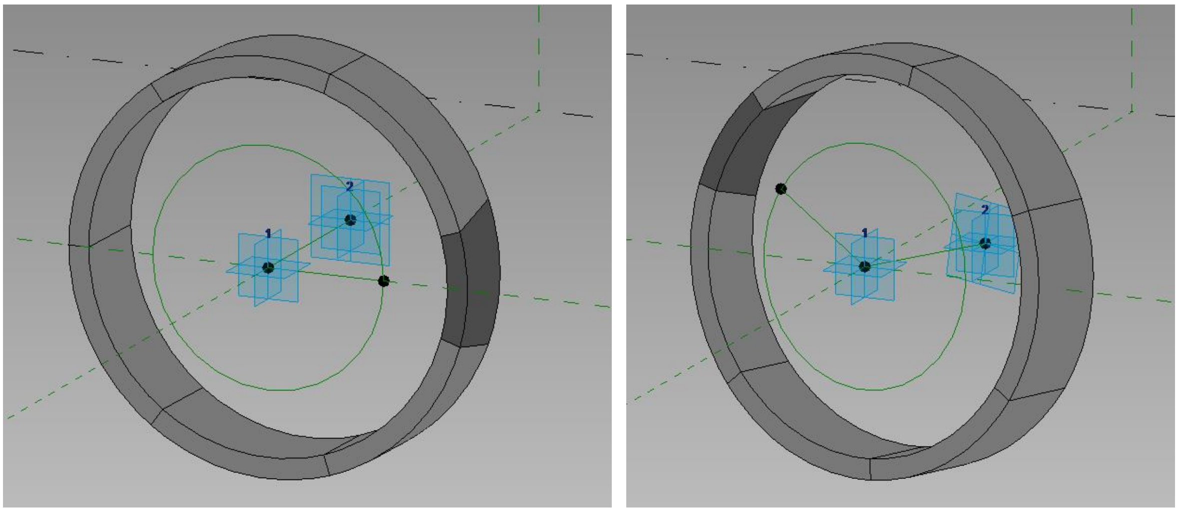


Figure 21: *Final ring component adoptive family comprising seven-segment sub-components.*

3.2.3 Section 3 –Automated as-built modelling

Following the preliminary study and setup of the input data, once the BIM components for the tunnel lining rings and segments are generated according to the design specification, is possible to enter the last phase of the system. Here, the last algorithm comes into play for the automated tunnel as-built model generation by going through the following operations:

1. *Data and components' input*: The algorithm automatically loads the BIM ring component (family) and the data comprised in the as-built database (spreadsheet), starting from a blank project file.
2. *The positioning of the ring component (iterated)*: For each record of the as-built database (line of the spreadsheet), corresponding to a ring with the related segments, the algorithm reads the spatial coordinates the first positioning point (x,y,x) and then determines the coordinates of a second point (x',y',z') required for the rotation and alignment of the ring based on the as-built information (Figure 22 and Figure 23). Both the positioning point is consistent with the tunnel as-built alignment and stand in the centre of the side faces of the ring component.
3. *As-built data attachment for the positioned ring and segments* (iterated): Once a ring is positioned and correctly oriented, the algorithm reads the remaining non-geometrical information from the as-built database and attach them both to the whole ring family and the specific segments.

The algorithm execution is straightforward, and the operation distinction above reported is formal. The operation 2 and 3 are iterated for each record of the as-built data spreadsheet. This spreadsheet corresponds to the placement and information enrichment of each ring installed by the TBM, finally generating the complete as-built model of the tunnel lining (Figure 24). Therefore, being the number of records directly related to the number of instances of ring families that have to be placed and processed, this could affect the algorithm performances. Nonetheless, even though the algorithm didn't go under a formal optimisation phase, various tests resulted in execution times of the order of seconds to model tunnel's sections of about 500 meters, hence comprising hundreds of rings.

Moreover, at this stage of development, the algorithm doesn't distinguish between the placement of ring components or model data population. As such, a change or correction in the as-built information that could be detected later requires to generate a brand new as-built model rather than just modifying the data present in the current one.

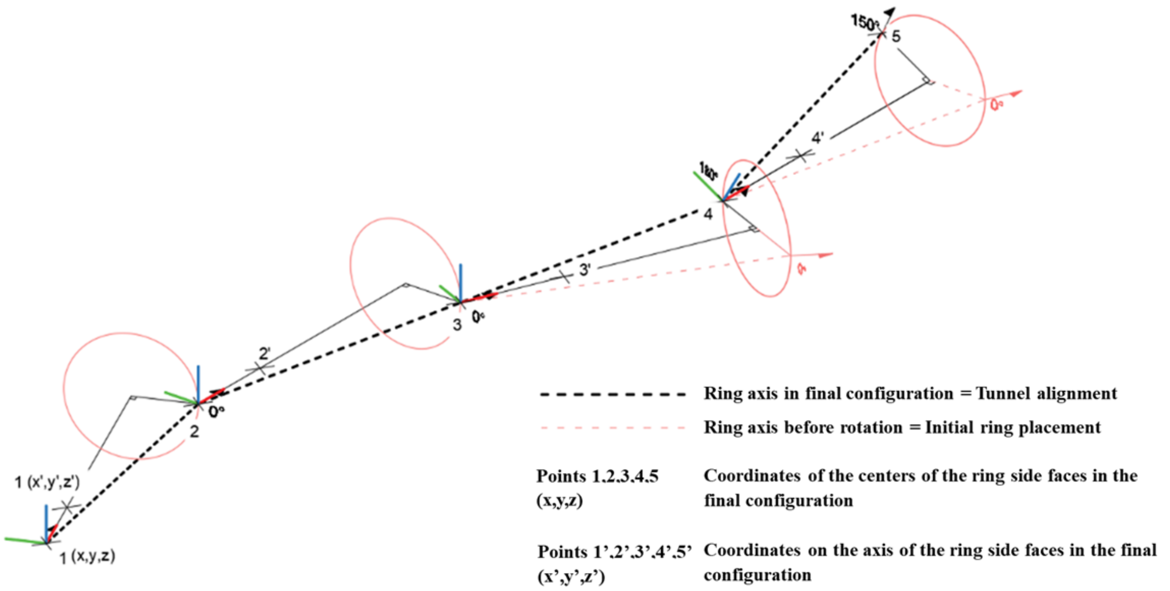


Figure 22: *Geometrical scheme of the solution of the positioning and rotation process for five consecutive ring components.*

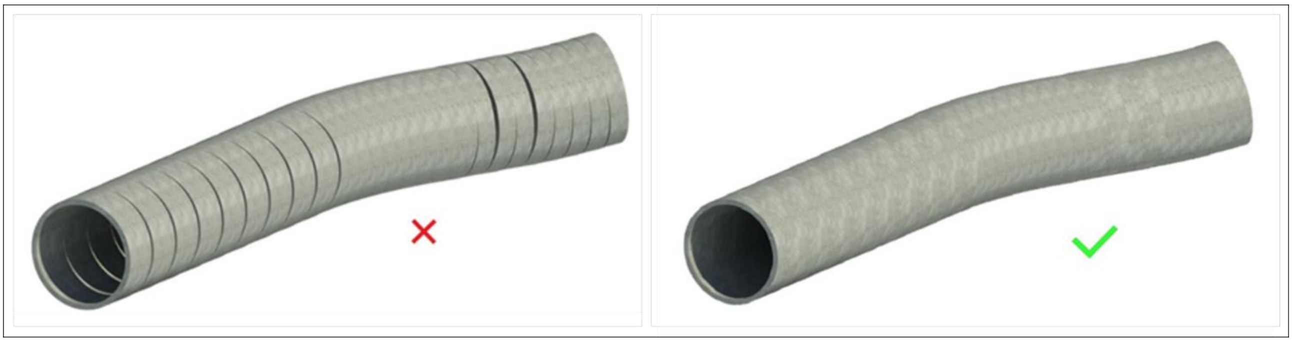


Figure 23: *Ring components positioning phases: just placed in the correct location along the tunnel alignment (**left**); placed and rotated correctly in function of the ring geometry (**right**).*

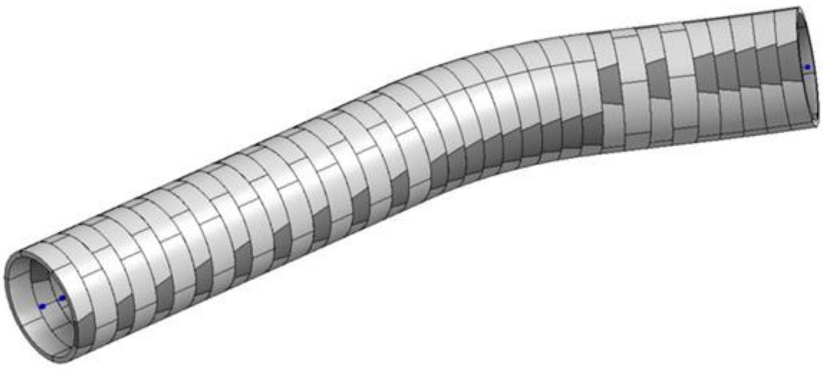


Figure 24: *As-built test model for a tunnel section with rings correctly positioned and oriented.*

4 Conclusion

This research addresses an approach to modelling of complex curved geometries and massive datasets linked to linear infrastructures, such as roads, railways, and tunnels. As mentioned in the reviewed literature, the state of the art solutions in this respect often fail in providing an integrated solution to cover both design and as-built stages. Existing solutions also fail to collect and apply a vast amount of data that could be captured by the Tunnel Boring Machine (TBM) during the construction phase. Being motivated by these critical gaps in theory as well as practice, this study developed a framework and working prototype for the integration of BIM and computational design into an intuitive approach for the generation of as-built models of mechanised tunnelling projects, leveraging the real-time data collected by the TBM.

The main advantages of this method over traditional approaches include the on-demand creation of as-built BIM model based on boring and erection of tunnelling project data. It also includes standardisation and parameterisation of prefabricated concrete tunnel linings, leading to a reduction in the time, error and redundancy in modelling processes. Furthermore, the data-driven model, which relies only on data collected from the TBM facilitates on-demand, parameterised, BIM generation, keeping the data footprint small for new projects and accommodating standardisation of existing projects. The proposed approach was evaluated by implementing the described model and testing its output against expectations. The effectiveness of the proposed approach was demonstrated through comparisons with conventional modelling and fulfilment of interoperability for both BIM platforms and TBM typologies.

4.1 Significance of the research

The work presented here makes a significant contribution to research and practice of BIM, computational design and automation of infrastructure design. In particular, it develops a novel system for translating data obtained from TBM operation into as-built BIM models which fulfils several significant gaps identified in the literature relating to interoperability and novelty. The application of procedural modelling techniques in large scale infrastructure projects is not currently widely used. This research provides practitioners with a novel approach to address the challenges they encounter in this critical area of their routine activities. Although several researchers have reported the potentials of procedurally generating BIM models, the credibility of results may be questionable without the parametric data to ensure model concurrence across BIM platforms. The developed on-demand data to the model system enables the researchers to demonstrate concurrence via the described parametric model. This research addresses these issues and validates them using a simulated dataset.

The implications of this work extend beyond the construction industry in terms of interoperability, reliability and efficiency for other research considering automated as-built or as-is modelling solutions, or the broader application of on-demand reconstruction from parametric data. The solution has further implications as a demonstration of reducibility of seemingly erratic spatial data. At the present stage, this research was predominantly reliant on off the shelf Autodesk products. Yet, the authors believe that further exploitations of the findings using openBIM approaches and vender neutral technologies, such as IFC can help better integration of the advanced solutions in this research. In this regard, BuildingSMART International is currently developing projects to implement the open IFC standard applied to linear infrastructures, e.g. railways, tunnels, roads, aqueducts. In these projects, one dimension is prevailing above others, e.g. specifical length over width. This demonstrates the relevant contribution that the IFC semantic enrichment could provide stakeholders in construction sector working on linear infrastructure such as construction companies, software houses, clients, facility management companies and so forth also meeting their modelling requirements.

For this reason, the improvement of the ontological version of the IFC schema is largely promoted in the sector also since the ifcOWL Ontology is available. The presented research work can support a robust knowledge-based mapping and modelling of tunnelling domain to provide the sector with a data framework that in future will support modelling, simulation and monitoring tools. Based on the presented research, authors, on the one hand, are now working on ontology-based modelling of the mechanised tunnelling domain. The research presented in this paper provided the authors with a preliminary data schema for mapping the geometrical representation of mechanised tunnelling in terms of IFC semantic enrichment (class hierarchy, relations, properties). This study has proven the feasibility of the effective implementation of the computational design methodology for the as-built generation. Yet, the authors are working to implement the presented algorithms with an extensive dataset together with the integration of the system with on-site real-time monitoring tools.

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References

[1] C. Rhodes, Construction industry: statistics and policy, House of Commons Library, 2019. http://researchbriefings.files.parliament.uk/documents/SN01432/SN01432.pdf (Last Accessed on September 2020).

[2] R. Crotty, The impact of building information modelling: transforming construction, Routledge, London, 2013, ISBN: 1136860568.

[3] B. Kumar, A practical guide to adopting BIM in construction projects, Whittles Publishing, Dunbeath, UK, 2015, ISBN: 1849951462.

[4] S. Abrishami, J. Goulding, F.P. Rahimian, A. Ganah, Integration of BIM and generative design to exploit AEC conceptual design innovation, Information Technology in Construction. 19 (2014) 350–359. https://www.itcon.org/paper/2014/21 (Last Accessed on September 2020).

[5] R. Fruchter, S. Herzog, N. Hallermann, G. Morgenthal, Drone site data for better decisions in AEC global teamwork, in: 16th International Conference on Computing in Civil and Building Engineering, Osaka, 2016. http://www.see.eng.osaka-u.ac.jp/seeit/icccbe2016/Proceedings/Full_Papers/187-141.pdf (Last Accessed on September 2020).

[6] J.S. Goulding, F. Pour Rahimian, Industry preparedness: Advanced learning paradigms for exploitation, in: Construction Innovation and Process Improvement, 2012: pp. 409–433. https://doi.org/10.1002/9781118280294.ch18.

[7] J.S. Goulding, F. Pour Rahimian, Offsite production and manufacturing for innovative construction: People, Process and Technology, Routledge, 2019, ISBN: 1351376888.

[8] J.S. Goulding, F. Pour Rahimian, M. Arif, M.D. Sharp, New offsite production and business models in construction: priorities for the future research agenda, Architectural Engineering and Design Management. 11 (2015) pp. 163–184. https://doi.org/10.1080/17452007.2014.891501.

[9] F. Pour Rahimian, R. Ibrahim, M.N. Baharudin, Using IT/ICT as a new medium toward implementation of interactive architectural communication cultures, in: Proceedings - International Symposium on Information Technology 2008, ITSim, 2008. https://doi.org/10.1109/ITSIM.2008.4631984.

[10] F. Pour Rahimian, R. Ibrahim, R.W.B.O.K. Rahmat, M.T.B. Abdullah, M.S.B.H. Jaafar, Mediating cognitive transformation with VR 3D sketching during conceptual architectural design process, Archnet-IJAR. 5 (2011) pp. 99–113. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84859901332&partnerID=40&md5=c4302d365a3fbcd604828293299f447b (Last Accessed on September 2020).

[11] European Construction Sector Observatory, Building Information Modelling in the EU construction sector, 2019.

https://ec.europa.eu/docsroom/documents/34518/attachments/1/translations/en/renditions/native (Last Accessed on September 2020).

[12] J. Egan, Rethinking construction, Department of Environment, Transport and the Region, London, 1998, ISBN: 011752994X.

[13] S.M. Latham, Constructing the team: Joint review of procurement and contractual arrangements in the United Kingdom construction industry, HMSO, London, 1994, ISBN: 011752994X.

[14] C. Newman, D. Edwards, I. Martek, J. Lai, W.D. Thwala, I. Rillie, Industry 4.0 deployment in the construction industry: a bibliometric literature review and UK-based case study, Smart and Sustainable Built Environment. (2020). https://doi.org/10.1108/SASBE-02-2020-0016.

[15] F. Pour Rahimian, V. Chavdarova, S. Oliver, F. Chamo, L. Potseluyko Amobi, OpenBIM-Tango integrated virtual showroom for offsite manufactured production of self-build housing, Automation in Construction. 102 (2019) pp. 1–16. https://doi.org/10.1016/j.autcon.2019.02.009.

[16] P. Pilechiha, M. Mahdavinejad, F. Pour Rahimian, P. Carnemolla, S. Seyedzadeh, Multi-objective optimisation framework for designing office windows: quality of view, daylight and energy efficiency, Applied Energy. 261 (2020) pp. 114356. https://doi.org/https://doi.org/10.1016/j.apenergy.2019.114356.

[17] S. Seyedzadeh, F.P. Rahimian, S. Oliver, I. Glesk, B. Kumar, Data driven model improved by multi-objective optimisation for prediction of building energy loads, Automation in Construction 116 (2020) pp. 103188. doi: https://doi.org/10.1016/j.autcon.2020.103188

[18] S. Seyedzadeh, F. Pour Rahimian, P. Rastogi, I. Glesk, Tuning machine learning models for prediction of building energy loads, Sustainable Cities and Society. 47 (2019) pp. 101484. https://doi.org/https://doi.org/10.1016/j.scs.2019.101484.

[19] S. Seyedzadeh, F.P. Rahimian, S. Oliver, S. Rodriguezb, I. Glesk, Machine learning modelling for predicting non-domestic buildings energy performance: a model to support deep energy retrofit decision-making, Applied Energy. https://doi.org/https://doi.org/10.1016/j.apenergy.2020.115908

[20] F. Elghaish, S. Abrishami, M.R. Hosseini, Integrated project delivery with blockchain: An automated financial system, Automation in Construction. 114 (2020) pp. 103182. https://doi.org/https://doi.org/10.1016/j.autcon.2020.103182.

[21] F. Moshtaghian, M. Golabchi, E. Noorzai, A framework to dynamic identification of project risks, Smart and Sustainable Built Environment. (2020). https://doi.org/10.1108/SASBE-09-2019-0123.

[22] F. Pour Rahimian, S. Seyedzadeh, S. Oliver, S. Rodriguez, N. Dawood, On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning, Automation in Construction. 110 (2020) pp. 103012. https://doi.org/10.1016/j.autcon.2019.103012.

[23] F. Elghaish, S. Abrishami, Developing a framework to revolutionise the 4D BIM process: IPD-based solution, Construction Innovation. 20 (2020) 401–420. https://doi.org/10.1108/CI-11-2019-0127.

[24] S. Oliver, Communication and trust: rethinking the way construction industry professionals and software vendors utilise computer communication mediums, Visualisation in Engineering. 7 (2019) pp. 1. https://doi.org/10.1186/s40327-019-0068-y.

[25] M. Poljanšek, Building Information Modelling (BIM) standardisation, JRC Technical Reports. (2017) pp. 1–18. https://doi.org/10.2760/36471.

[26] B. Buckley, K. Logan, The Business Value of BIM for Infrastructure 2017, 2017. https://www2.deloitte.com/content/dam/Deloitte/us/Documents/finance/us-fas-bim-infrastructure.pdf (Last Accessed on September 2020).

[27] B. Abdal Noor, S. Yi, Review of BIM literature in construction industry and transportation: meta-analysis, Construction Innovation. 18 (2018) pp. 433–452. https://doi.org/10.1108/CI-05-2017-0040.

[28] J.C.P. Cheng, Q. Lu, Y. Deng, Analytical review and evaluation of civil information modeling, Automation in Construction. 67 (2016) pp. 31–47. https://doi.org/10.1016/j.autcon.2016.02.006.

[29] A. Costin, A. Adibfar, H. Hu, S.S. Chen, Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations, Automation in Construction. 94 (2018) pp. 257–281. https://doi.org/10.1016/j.autcon.2018.07.001.

[30] A. Bradley, H. Li, R. Lark, S. Dunn, BIM for infrastructure: An overall review and constructor perspective, Automation in Construction. 71 (2016) pp. 139–152. https://doi.org/10.1016/j.autcon.2016.08.019.

[31] F.G.B. Blanco, H. Chen, The Implementation of Building Information Modelling in the United Kingdom by the Transport Industry, Procedia - Social and Behavioral Sciences. 138 (2014) pp. 510–520. https://doi.org/10.1016/j.sbspro.2014.07.232.

[32] NBS, 10th Annual BIM Report, (2020) pp. 1–39 https://www.thenbs.com/knowledge/national-bim-report-2020 (Last Accessed on September, 2020).

[33] M. Minagawa, S. Kusayanagi, Study on BIM utilisation for design improvement of infrastructure project, Procedia Engineering. 125 (2015) pp. 431–437. https://doi.org/10.1016/j.proeng.2015.11.113.

[34] A. Gerbov, V. Singh, M. Herva, Challenges in applying design research studies to assess benefits of BIM in infrastructure projects: Reflections from Finnish case studies, Engineering, Construction and Architectural Management. 25 (2018) pp. 2–20. https://doi.org/10.1108/ECAM-12-2016-0260.

[35] J. Daller, M. Žibert, C. Exinger, M. Lah, Implementation of BIM in the tunnel design – Engineering consultant's aspect, Geomechanik Und Tunnelbau. 9 (2016) pp. 674–683. https://doi.org/10.1002/geot.201600054.

[36] R. Sorge, D. Buttafoco, J. Debenedetti, A. Menozzi, G. Cimino, F. Maltese, B. Tiberi, Bim implementation – Brenner base tunnel project, Tunnels and Underground Cities: Engineering and Innovation Meet Archaeology, Architecture and Art- Proceedings of the WTC 2019 ITA-AITES World Tunnel Congress. (2019) pp. 3122–3131. https://doi.org/10.1201/9780429424441-331.

[37] M. Amerio, Doha Metro Project: 3TI lesson learned, Transportation Research Procedia. 45 (2020) 866–873. https://doi.org/10.1016/j.trpro.2020.02.082.

[38] M. Pasetto, A. Giordano, P. Borin, G. Giacomello, Integrated railway design using Infrastructure-Building Information Modeling. The case study of the port of Venice, Transportation Research Procedia. 45 (2020) pp. 850–857.

https://doi.org/10.1016/j.trpro.2020.02.084.

[39] I. Caetano, L. Santos, A. Leitão, Computational design in architecture: Defining parametric, generative, and algorithmic design, Frontiers of Architectural Research. (2020). https://doi.org/10.1016/j.foar.2019.12.008.

[40] V. Getuli, P. Capone, Computational workspaces management : a workflow to integrate workspaces dynamic planning with 4D BIM, Proceedings of 35th International Symposium on Automation and Robotics in Construction (ISARC 2018, Berlin, Germany), (2018) pp. 1117-1124 https://doi.org/10.22260/ISARC2018/0155.

[41] V. Getuli, S.M. Ventura, P. Capone, A.L.C. Ciribini, BIM-based Code Checking for Construction Health and Safety, Procedia Engineering. 196 (2017) pp. 454–461. https://doi.org/10.1016/j.proeng.2017.07.224.

[42] A. Darko, A.P.C. Chan, M.A. Adabre, D.J. Edwards, M.R. Hosseini, E.E. Ameyaw, Artificial intelligence in the AEC industry: Scientometric analysis and visualisation of research activities, Automation in Construction. 112 (2020) pp. 103081. https://doi.org/10.1016/j.autcon.2020.103081.

[43] V. Getuli, P. Capone, A. Bruttini, S. Isaac, BIM-based immersive Virtual Reality for construction workspace planning : A safety-oriented approach, Automation in Construction. 114 (2020) pp. 103160. https://doi.org/10.1016/j.autcon.2020.103160.

[44] W. Natephra, N. Yabuki, T. Fukuda, Optimising the evaluation of building envelope design for thermal performance using a BIM-based overall thermal transfer value calculation, Building and Environment. 136 (2018) pp. 128–145. https://doi.org/10.1016/j.buildenv.2018.03.032.

[45] S. Taleb, A. Yeretzian, R.A. Jabr, H. Hajj, Optimisation of building form to reduce incident solar radiation, Journal of Building Engineering. 28 (2020) pp. 101025. https://doi.org/10.1016/j.jobe.2019.101025.

[46] I.G. Dino, A.E. Sari, O.K. Iseri, S. Akin, E. Kalfaoglu, B. Erdogan, S. Kalkan, A.A. Alatan, Image-based construction of building energy models using computer vision, Automation in Construction. 116 (2020) pp. 103231. https://doi.org/10.1016/j.autcon.2020.103231.

[47] R. Doe, Facilitating integration of computational design processes in the design and production of prefabricated homes, Architectural Science Review. 61 (2018) pp. 246–254. https://doi.org/10.1080/00038628.2018.1466686.

[48] A.Q. Gbadamosi, A.M. Mahamadu, L.O. Oyedele, O.O. Akinade, P. Manu, L. Mahdjoubi, C. Aigbavboa, Offsite construction: Developing a BIM-Based optimiser for assembly, Journal of Cleaner Production. 215 (2019) pp. 1180–1190. https://doi.org/10.1016/j.jclepro.2019.01.113.

[49] G. Ning, L. Junnan, D. Yansong, Q. Zhifeng, J. Qingshan, G. Weihua, D. Geert, BIM-based PV system optimisation and deployment, Energy and Buildings. 150 (2017) pp. 13–22. https://doi.org/10.1016/j.enbuild.2017.05.082.

[50] A.K. Ali, O.J. Lee, H. Song, Robot-based facade spatial assembly optimisation, Journal of Building Engineering. 33 (2021) pp. 101556. https://doi.org/10.1016/j.jobe.2020.101556.

[51] A. Hollberg, G. Genova, G. Habert, Evaluation of BIM-based LCA results for building design, Automation in Construction. 109 (2020) pp. 102972. https://doi.org/10.1016/j.autcon.2019.102972.

[52] S. Eleftheriadis, P. Duffour, D. Mumovic, BIM-embedded life cycle carbon assessment of RC buildings using optimised structural design alternatives, Energy and Buildings. 173 (2018) pp. 587–600. https://doi.org/10.1016/j.enbuild.2018.05.042.

[53] S. Eleftheriadis, P. Duffour, P. Greening, J. James, B. Stephenson, D. Mumovic, Investigating relationships between cost and CO2 emissions in reinforced concrete structures using a BIM-based design optimisation approach, Energy and Buildings. 166 (2018) pp. 330–346. https://doi.org/10.1016/j.enbuild.2018.01.059.

[54] M. Mangal, J.C.P. Cheng, Automated optimisation of steel reinforcement in RC building frames using building information modeling and hybrid genetic algorithm, Automation in Construction. 90 (2018) pp. 39–57. https://doi.org/10.1016/j.autcon.2018.01.013.

[55] C. Koch, A. Vonthron, M. König, A tunnel information modelling framework to support management, simulations and visualisations in mechanised tunnelling projects, Automation in Construction. 83 (2017) pp. 78–90. https://doi.org/10.1016/j.autcon.2017.07.006.

[56] J. Ninić, C. Koch, J. Stascheit, An integrated platform for design and numerical analysis of shield tunnelling processes on different levels of detail, Advances in Engineering Software. 112 (2017) pp. 165–179. https://doi.org/10.1016/j.advengsoft.2017.05.012.

[57] J. Ninić, C. Koch, A. Vonthron, W. Tizani, M. König, Integrated parametric multilevel information and numerical modelling of mechanised tunnelling projects, Advanced Engineering Informatics. 43 (2020). https://doi.org/10.1016/j.aei.2019.101011.

[58] J. Ninić, H.G. Bui, C. Koch, G. Meschke, Computationally Efficient Simulation in Urban Mechanized Tunneling Based on Multilevel BIM Models, Journal of Computing in Civil Engineering. 33 (2019) pp. 1–17. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000822.

[59] J. Stascheit, J. Ninić, G. Meschke, F. Hegemann, U. Maidl, Building Information Modelling in mechanised shield tunnelling - A practitioner's outlook to the near future, Geomechanik Und Tunnelbau. 11 (2018) pp. 34–49. https://doi.org/10.1002/geot.201700060.

[60] G.H. Erharter, T. Marcher, MSAC: Towards data driven system behavior classification for TBM tunneling, Tunnelling and Underground Space Technology. 103 (2020) pp. 103466. https://doi.org/10.1016/j.tust.2020.103466.

[61] Y. Zhou, Y. Wang, L. Ding, P.E.D. Love, Utilising IFC for shield segment assembly in underground tunneling, Automation in Construction. 93 (2018) pp. 178–191. https://doi.org/10.1016/j.autcon.2018.05.016.

[62] L. Chen, P. Shi, Q. Tang, W. Liu, Q. Wu, Development and application of a specification-compliant highway tunnel facility management system based on BIM, Tunnelling and Underground Space Technology. 97 (2020) pp. 103262. https://doi.org/10.1016/j.tust.2019.103262.

[63] C. Boje, A. Guerriero, S. Kubicki, Y. Rezgui, Towards a semantic Construction Digital Twin: Directions for future research, Automation in Construction. 114 (2020) pp. 103179. https://doi.org/10.1016/j.autcon.2020.103179.

[64] Y. Tchana, G. Ducellier, S. Remy, Designing a unique Digital Twin for linear infrastructures lifecycle management, Procedia CIRP. 84 (2019) pp.545–549. https://doi.org/10.1016/j.procir.2019.04.176.

[65] V. Pətrəucean, I. Armeni, M. Nahangi, J. Yeung, I. Brilakis, C. Haas, State of research in automatic as-built modelling, Advanced Engineering Informatics. 29 (2015) pp. 162–171. https://doi.org/10.1016/j.aei.2015.01.001.

[66] T. Czerniawski, F. Leite, Automated digital modeling of existing buildings: A review of visual object recognition methods, Automation in Construction. 113 (2020) pp. 103131. https://doi.org/10.1016/j.autcon.2020.103131.

[67] L. Barazzetti, Parametric as-built model generation of complex shapes from point clouds, Advanced Engineering Informatics. 30 (2016) pp. 298–311. https://doi.org/10.1016/j.aei.2016.03.005.

[68] I. Brilakis, M. Lourakis, R. Sacks, S. Savarese, S. Christodoulou, J. Teizer, A. Makhmalbaf, Toward automated generation of parametric BIMs based on hybrid video and laser scanning data, Advanced Engineering Informatics. 24 (2010) pp. 456–465. https://doi.org/10.1016/j.aei.2010.06.006.

[69] L. Sanhudo, N.M.M. Ramos, J.P. Martins, R.M.S.F. Almeida, E. Barreira, M.L. Simões, V. Cardoso, A framework for in-situ geometric data acquisition using laser scanning for BIM modelling, Journal of Building Engineering. 28 (2020). https://doi.org/10.1016/j.jobe.2019.101073.

[70] X. Xiong, A. Adan, B. Akinci, D. Huber, Automatic creation of semantically rich 3D building models from laser scanner data, Automation in Construction. 31 (2013) pp. 325–337. https://doi.org/10.1016/j.autcon.2012.10.006.

[71] G. Zhang, P.A. Vela, I. Brilakis, Automatic generation of as-built geometric civil infrastructure models from point cloud data, Computing in Civil and Building Engineering - Proceedings of the 2014 International Conference on Computing in Civil and Building Engineering. (2014) pp.406–413. https://doi.org/10.1061/9780784413616.051.

[72] N. Hidaka, T. Michikawa, A. Motamedi, N. Yabuki, T. Fukuda, Polygonization of point clouds of repetitive components in civil infrastructure based on geometric similarities, Automation in Construction. 86 (2018) pp. 99–117. https://doi.org/10.1016/j.autcon.2017.10.014.

[73] L. Yang, J.C.P. Cheng, Q. Wang, Semi-automated generation of parametric BIM for steel structures based on terrestrial laser scanning data, Automation in Construction. 112 (2020) pp. 103037. https://doi.org/10.1016/j.autcon.2019.103037.

[74] H. Fathi, F. Dai, M. Lourakis, Automated as-built 3D reconstruction of civil infrastructure using computer vision: Achievements, opportunities, and challenges, Advanced Engineering Informatics. 29 (2015) pp.149–161. https://doi.org/10.1016/j.aei.2015.01.012.

[75] B.F. Spencer, V. Hoskere, Y. Narazaki, Advances in Computer Vision-Based Civil Infrastructure Inspection and Monitoring, Engineering. 5 (2019) pp. 199–222. https://doi.org/10.1016/j.eng.2018.11.030.

[76] C. Kim, C. Kim, H. Son, Automated construction progress measurement using a 4D building information model and 3D data, Automation in Construction. 31 (2013) pp. 75–82. https://doi.org/10.1016/j.autcon.2012.11.041.

[77] Z. Pučko, N. Šuman, D. Rebolj, Automated continuous construction progress monitoring using multiple workplace real time 3D scans, Advanced Engineering Informatics. 38 (2018) pp. 27–40. https://doi.org/10.1016/j.aei.2018.06.001.

[78] H. Son, F. Bosché, C. Kim, As-built data acquisition and its use in production monitoring and automated layout of civil infrastructure: A survey, Advanced Engineering Informatics. 29 (2015) pp. 172–183. https://doi.org/10.1016/j.aei.2015.01.009.

[79] X. Xie, X. Lu, Development of a 3D modeling algorithm for tunnel deformation monitoring

based on terrestrial laser scanning, Underground Space (China). 2 (2017) pp. 16–29. https://doi.org/10.1016/j.undsp.2017.02.001.

[80] Y.J. Cheng, W.G. Qiu, D.Y. Duan, Automatic creation of as-is building information model from single-track railway tunnel point clouds, Automation in Construction. 106 (2019). https://doi.org/10.1016/j.autcon.2019.102911.

[81] M. Arastounia, Automated as-built model generation of subway tunnels from mobile Lidar data, Sensors (Switzerland). 16 (2016). https://doi.org/10.3390/s16091486.

[82] L. Attard, C.J. Debono, G. Valentino, M. Di Castro, Tunnel inspection using photogrammetric techniques and image processing: A review, ISPRS Journal of Photogrammetry and Remote Sensing. 144 (2018) pp. 180–188. https://doi.org/10.1016/j.isprsjprs.2018.07.010.

[83] Y. Xue, S. Zhang, M. Zhou, H. Zhu, Novel SfM-DLT method for metro tunnel 3D reconstruction and Visualisation, Underground Space (China). (2020) pp. 1–8. https://doi.org/10.1016/j.undsp.2020.01.002.

[84] E. Menendez, J.G. Victores, R. Montero, S. Martínez, C. Balaguer, Tunnel structural inspection and assessment using an autonomous robotic system, Automation in Construction. 87 (2018) pp. 117–126. https://doi.org/10.1016/j.autcon.2017.12.001.

[85] H. Cui, X. Ren, Q. Mao, Q. Hu, W. Wang, Shield subway tunnel deformation detection based on mobile laser scanning, Automation in Construction. 106 (2019) pp. 102889. https://doi.org/10.1016/j.autcon.2019.102889.

[86] A. Sánchez-Rodríguez, B. Riveiro, M. Soilán, L.M. González-deSantos, Automated detection and decomposition of railway tunnels from Mobile Laser Scanning Datasets, Automation in Construction. 96 (2018) pp. 171–179. https://doi.org/10.1016/j.autcon.2018.09.014.

[87] W. Wittke, Stability analisys and design for mechanized tunneling,WBI PRINT 6, VGEVerlag Gluckauf GmbH, Essen (2006), ISBN 978 3 7739 1306 7.