



Utilizing IFC for shield segment assembly in underground tunneling

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ABSTRACT

The shield method is a common approach used for subway tunnel excavation. A critical function of the shield method is the segment assembly process. It is, therefore, imperative to have access to information to be able to manage and control the performance of segment assembly during the construction process. However, an issue that hinders the capacity to undertake these tasks during construction is the inability of existing Building Information Modeling (BIM)-related software used to design tunnels to support information exchanges during a project's execution. The Industry Foundation Class (IFC) has evolved as an open and neutral data format to support information exchanges, but they are yet to be able to accommodate the segment assembly process. Considering the absence of such a data format, this research contributes to the extant literature through extending the IFC standard by treating the segment assembly shield used in construction as an 'object'. It also proposes a new typesetting (i.e. positioning of segments) algorithm that can be used to automatically determine constraints. Moreover, the algorithm can define the design information that is required to enact data exchanges during construction. The newly developed IFC extensions are validated by demonstrating the successful transfer from a tunnel's parametric design models to the segment assembly system.

1. Introduction

Building Information Modeling (BIM) is being widely used throughout the construction industry, though the level of its implementation varies significantly. Several countries such as the United Kingdom (UK) and Singapore have mandated the use of BIM on public sector projects over a specified value [1,2]. Fundamentally, the use of BIM enables the creation of a single database (i.e. 'building information model and hereinafter model'), which is built from objects that are created from embedded discipline specific information. As a result, this enables the automatic generation and updating of views and documentation [3–6]. However, to effectively enable the exchange of information contained within a model and ensure its interoperability with other software applications, requires a structured, neutral non-proprietary and open standard to be adopted [7,8]. The Industry Foundation Class (IFC) acts as this standard, and provides a broad description for building components from semantic and geometric perspectives [9]. The IFC specification is developed and maintained by *BuildingSmart* International as a 'data standard', which has been accepted as ISO-15926. The specification of the IFC standard includes a:

- html documentation (including all definitions, schemas, libraries);

- URL for the IFC EXPRESS long form schema; and
- URL for the ifcXML XSD schema.

While the IFC standards for vertical assets (e.g., buildings) have been evolving and maturing over a number of decades, those of a horizontal nature (e.g., roads and tunnels) have not advanced at a similar rate of development [10,11]. This has been recognized by *BuildingSmart* and they are committed to enhancing its standards to enable standardized infrastructure life-cycle asset data management by initiating "*openInfra*" [12]. This initiative aims to develop common principles for achieving process integration during the design, construction and maintenance phases of infrastructure assets. The 'IFC Alignment' project, which aims to provide a baseline to enable IFCs to be used for bridges and roads, provides two (2D)-and-three-dimensional (3D) alignment information for spatial location of infrastructure. However, IFC-extensions for tunneling related works remain limited.

The construction of subway infrastructure involves a variety of methodologies and techniques, with a popular approach being shield tunneling [4–6,13]. During construction, the tunnel lining acts as permanent support structure that prevents its collapse from soil deformation and water infiltration [14]. As one of the main structural components, a segment is a critical element of a tunneling project, requiring

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its accurate placement. The quality of the segment assembly is closely related to its geometric parameters, and the deviation between its design and actual axis [15].

The use of IFC-extensions for tunneling pose a number of challenges. First and foremost, the generation of a model for a tunnel's design stage is dependent on the use of several pieces of software. But, shield tunnel elements have not been accommodated in existing BIM-related software. The corollary being the inability to support information exchanges that are needed to effectively manage the construction process. Secondly, several constraints need to be considered during the segment assembly process, such as the deviation control between the two adjacent segments. However, these constraints arise from the need for dynamic control that is embedded in assembly process, which is difficult to express in a design model. The assembly process of the segments should be considered when constructing IFC - extensions for tunneling construction.

With developments in IFC, the propensity to enable such exchanges to materialize has become a feasible option that has been widely considered within the infrastructure domain [16–20]. Previous research has tended to focus on the components of tunnels and extending their entity elements [21–26]. However, there has been an absence of studies that has focused on determining the logical relationships between different elements from the perspectives of design and construction constraints during the shield tunnel segment assembly process. For example, entities such as tunnel and segment have been defined and a model's hierarchy provided [16]. Descriptions of the attribute information and assembly constraints of these entities have not been forthcoming but are needed for the segment assembly process. In filling this void, the research presented in this paper contributes to the extant literature by extending the IFC standard and treating the segment assembly in shield construction as an 'object'. As a result, a new typesetting algorithm to determine its constraints and defines the design information that is required to enact data exchanges during construction is proposed and validated.

2. Literature review

2.1. Shield tunnel segment assembly

The segment assembly method forms an integral part of the shield tunneling process. As noted in Fig. 1 segments are directly assembled into a ring that forms the lining of a tunnel [4–6]. To ensure the quality of a tunnel's lining, the assembly process must be strictly controlled [27,28]. That is, the positioning of the segment assembly points need to be determined accurately and rapidly during the tunneling construction process.

Moreover, any displacement during the segments assembly should be strictly controlled to ensure adherence to construction codes and standards. Typically, two types of system are used to guide the tunneling process:

1. Gyroscope, for example, Japan's GYRO and TMG-32 systems [29]. This system is connected to the 'attitude management software' that is used to manage of the shield machine, but as its precision is $> 0.5^\circ$, the reliability of the system needs to be improved.
2. Laser measurement automatic guidance technology, which is mainly used in the UK ZED system, Germany VMT company SLS-T (TBM Guidance System) and ROBOTEC systems [30]. Such systems can automatically select the segment according to their measurement and design deviation curve. Staff can modify parameters of the software according to the status of the site. However, when selecting segments, its common practice to set a factor parameter at either [0, 1] based on the workers experience.

A key to segment assembly typesetting is its positioning algorithm [31]. In China, however, there has been a paucity of research that has

examined the typesetting and correction process; the selection of segments is typically undertaken based on a workers' experience. As a result of this knowledge gap, several studies have been undertaken. For example, Wang et al. [32] obtained the relationship between the wedge volume, length of the segment, fitting error, and the minimum radius of the curve, providing a reference for the selection of the segment design parameters. Conversely, Gong et al. [33] calculated the 3D coordinates and derived a formula of a ring's flat and vertical curves using the least squares method. Taking into account the sequence of construction and the parameters associated with the assembly process, Xie and Xiaozhi [34] used coordinate system transformation theory to propose a typesetting algorithm.

2.2. Shield tunnel extension model based on IFC

A product model for shield tunnel construction was initially proposed by Yabuki [20], which defined several entities, attributes and relationship entities such as *IfcSegment*, *IfcSegmentType*, *IfcRelAggregates*. Building on this early work, Hegemann et al. [35] incorporated a Tunnel Boring Machine (TBM) for the purpose of describing the shield's geometry and the semantics, as well as process information. Similarly, Borrmann and Jubierre [16] introduced a novel approach for the design of multi-scale product models that provided inherent coherence between the semantic and geometric entities.

Alternatively, Stascheit et al. [36] classified holistic IFC product models into three areas: (1) ground data model (GDM); (2) tunnel model (TM), and (3) TBM model. In developing a model, Amann et al. [37] specifically pointed out that the alignment curve is a crucial part of the design. This led to the introduction of an '*IfcReferenceCurveAlignment2D*' element that referenced the horizontal and vertical alignment curve, which can be integrated in a refined version of an existing shield tunnel product model. Lee and Kim [23] developed a methodology to produce an extended schema using an IFC-Based data schema to accommodate design information based on the New Austrian Tunneling Method.

Several studies that have focused on extending various components of a tunnel using an IFC have tended treat each one as an independent part (e.g. [23,36]). As a result, essential design information is unable to be represented. For example, wedges, the segment number and assembly points have not been previously considered. The constraints associated with the segment assembly have also not been considered, even though they are integral to the construct process. Prior to a ring's assembly, its needs to be fitted and arranged according to the constraint conditions, such as the deviation and stitch control, to ensure it fits the design axis of the tunnel. To aid the assembly process, an IFC-extension for tunneling should incorporate an algorithm, as the foundation of the typesetting process. Yet, the absence of assembly algorithms renders it difficult to validate the design with the actual construction that has occurred.

3. Basic information analysis of subway shield segment assembly

A complete tunnel consists of a large number of rings that have been arranged in a uniform width whereby a set of short fold lines fit the design axis. The deviation between actual propulsion and design axis is unavoidable. Thus, deviation control becomes a crucial part of assembly process. In fact, the deviation control is achieved through the choice of a reasonable segment and typesetting algorithm, which can assist with amending the shields alignment during its operation.

3.1. Segment assembly

The universal segment is a pre-cast concrete lining ring with a specific amount of wedge. The shield tunnel construction process involves fitting a design curve for assembling a segment. Through the rotation and the combination of the ring, the deviation of the design

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