Optimization design method for noise barrier tunnel junction on merging lanes using quad junctions

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ABSTRACT
Noise barrier tunnels (NBTs) are road facilities installed to reduce road traffic noise. Although building information modeling (BIM) has been widely used in civil engineering, alignment problems must first be addressed for BIM to be applied in transportation infrastructure; this is because unlike buildings, roads are linear. The array of tunnel frames based on the centerlines of individual roads cause the discontinuity of components at junctions of two NBTs. This leads to structural instabilities and poor airtightness, which in turn cause vulnerabilities such as noise and water leakage. To address these issues, this study proposes an optimization design method for NBT junctions using quad meshes. We created a Y-branch topology of NBTs using quad meshes, performed data arrangement using mesh segmentation and mesh reorder, and used the results to optimize the design via performance analysis. During mesh segmentation and mesh reorder, an interface in which the user directly enters curves to improve the efficiency of the algorithm was also developed. In addition, a case study of a main road with eight lanes that merged with a sub road with one lane was conducted, data arrangement was performed successfully, and a BIM-compliant model that used various geometric data was generated through optimization.

1. Introduction

1.1. Research background and purpose

Because of urbanization, cities are now congested with people and traffic. Although high-rise apartment complexes and three-dimensional roads improve the access of people to city centers, the subsequent road traffic noise negatively affects the physical, mental, and social functions of individuals (WHO 2018). Seoul, a megacity, faces serious road traffic noise because apartments account for 42.2% of the residential environment (KOSIS 2018). As of 2013, more than 20% of people living in Seoul are exposed to the road traffic noise of 65 dB(A). This is a serious issue, considering that only 12.2% are exposed to such noise in European countries (Korea Ministry of Environment 2013).

There are three main causes of road traffic noise: engines, airflow, and tire-road friction (Korea Ministry of Environment 2004). In South Korea, noise barriers are the most common noise reduction facility used with high-rise buildings, and as of 2017, a total of 1,700 km of noise barriers are found on roads (Korea Ministry of Environment 2017). Noise barriers are divided into two types: noise barrier walls (NBWs) and noise barrier tunnels (NBTs). NBTs, the subject of this study, are more effective in blocking noise than NBWs by completely enclosing noise sources (Korea Ministry of Environment 2003). NBTs consist of reinforced concrete foundation, steel frames, and aluminum panels. Three foundations are installed in the middle and on both sides of the road. Frames are arranged along the road at regular intervals. Panels are installed between the frames and play the most important role in blocking noise. Additional functions, such as transparency and solar power generation, have been recently added to panels.

Researchers in the field of transportation infrastructure are starting to adopt building information modeling (BIM), which has been widely used in the field of architecture. BIM includes “all the information and properties about that building such as design plans, product information, schedule sequencing, and operations” (Costin et al. 2018) of conventional three-dimensional (3D) computer-aided design (CAD) building models.

In the case of NBTs, the following benefits are expected by using BIM. First, road scan data and 3D models increase the precision of the design, thereby reducing the design errors caused by 3D road alignment. Second, performance in multiple aspects, such as illuminance, fluid dynamics, and energy harvesting, can be simultaneously considered, in addition to its main functions of noise blocking and structure, by performing simulation using 3D models. This improves the safety of drivers and adds additional functionality to NBTs.
BIM is not suitable for representing linear infrastructures, such as roads, bridges, and tunnels, because it was developed based on the rectangular coordinate system considering the structural systems of buildings. The alignment model is devised to overcome this problem and is reflected in Industry Foundation Classes (IFC) 5, the standard data schema of BIM (Aman et al. 2014).

NBTs that follow a single road centerline enable alignment-based design automation by using the shield tunnel method. However, additional consideration is needed for the intersection of two roads, unlike shield tunnels. The array of tunnel frames based on the centerlines of individual roads causes the discontinuity of components at the junction of two NBTs. This is structurally unstable and leads to poor airtightness, resulting in noise and water leakage. Figure 1 shows the typical solution used to address this problem in an existing NBT junction. Although an NBT is installed on the main road, only an NBW is installed on the sub road instead of an NBT, causing discontinuity between the two structures.

To deal with the Y-branch of the NBT junction, the use of polygon meshes for topological modeling is required. Vertices, edges, and faces, which constitute polygon meshes, provide basic geometric data that can be used for the creation or arrangement of architectural components. Triangle or quad meshes are the most common solution for freeform buildings. Among the polygon meshes, quad meshes are suitable for representing portal framed structures and panels of NBT and can be easily used for performance analysis. This study aims to propose an optimization design for NBT junctions using quad meshes, saving resources required for NBT construction while maintaining the performance of the NBT.

1.2. Research scope and method

NBT junctions are installed on merging lanes or diverging lanes. Merging and diverging lanes have the same Y-branch from a topological perspective, but different driving directions.

The study was performed in a digital environment where integrated performance analysis is conducted, and non-uniform rational basis spline (NURBS) and meshes are supported. Mesh editing and performance analysis can be conducted using a plug-in method, and the data generated by individual plug-ins can be transferred and edited through a visual programming language or scripting. We focused on extracting and utilizing geometric data that enable the analysis of various performances from quad meshes, rather than the precision of the analysis of individual performances.

The remainder of this paper is structured as follows. First, the literature on architectural modeling using polygon meshes is reviewed in Section 2. The usability of quad meshes in designing the NBT junction is determined by examining mesh segmentation for the semantic utilization of polygon meshes and the existing shield tunnel modeling approach. Based on the characteristics of quad meshes and the mesh segmentation technique, a method to extract the geometric data required for performance analysis from quad meshes and conduct optimization design via performance analysis was proposed in Section 3. The proposed method was applied to actual NBTs to test its feasibility in various scenarios in Section 4. Finally, Section 5 discusses the significance of the results obtained, and Section 6 concludes the paper.

2. Theoretical background

2.1. Polygon meshes and architectural freeform modeling

A polygon mesh is a collection of vertices, edges, and faces, representing complex objects in computer graphics. It uses a combination of simple polygon cells with triangles and quadrangles being the most common. Polygon meshes can be represented using various methods: face-vertex meshes (FV mesh) are the most common mesh representation using a set of faces and vertices. Mesh faces consist of the indices of the mesh vertices combined in the counterclockwise direction. The mesh vertices with two or more identical coordinates generated by the contact of mesh faces can be welded into a single mesh vertex. In other words, one mesh vertex is shared by one or more
mesh faces, and the geometry is represented even when it moves because face connectivity is maintained.

The most significant benefit of meshes in representing an object is that they do not have topological constraints. It is difficult, however, to control meshes because they have no intrinsic parameterization like NURBS. To overcome this limitation, mesh vertices are rearranged so that they can be used as parameters. Maya, Autodesk’s computer animation and modeling software, rearranges mesh vertices or provides the “reorder vertices” command that matches the mesh vertex order from one mesh to another (Autodesk 2017).

In architectural design modeling, polygon meshes are used for generating non-linear geometry. Smooth meshes can be obtained by performing recursive subdivision for the mesh faces of coarse meshes. Catmull-Clark subdivision (Catmull and Clark 1978) and Loop subdivision (Loop 1987) are the representative algorithms. The vertices, edges, and faces of meshes correspond to the nodes, beams, and panels of a structure, respectively. They can be used for the analysis of various performances, such as in structural and environmental simulation.

Quad meshes have many advantages in designing freeform architecture compared to triangle meshes. From the perspective of a design tool, quad meshes are easier to manipulate and more intuitive for the designer than triangle meshes. Most geometries have two dominant local directions in which quad meshes can be arranged. The use of triangle mesh, on the other hand, requires the arbitrary selection of the third edge direction (Bommes et al. 2012). Secondly, from the perspective of performance analysis, quad meshes are more suitable than triangle meshes for finite element simulation. Quad meshes produce fewer errors than triangle meshes because the number of components is smaller, and the faces are arranged along the curve direction (Shepherd and Johnson 2008). Thirdly, quad meshes are more efficient than triangle meshes in resource utilization. Triangle meshes generally have heavier loads than quad meshes because they require more parts. This is because six edges meet at a typical vertex of a triangle mesh, whereas four edges meet at a typical vertex of a quad mesh. Moreover, triangle meshes involve significant material waste as they are produced by cutting manufactured rectangular panels (Pottmann et al. 2007).

In the construction or implementation of a building with freeform geometry, the planarity of surface components is an important constraint. For a certain face to become planar, all vertices must be on the same plane. It is not necessary to consider this condition for triangle meshes because all faces are planar. On the other hand, quad meshes are produced from a single curved surface in a limited manner, or it requires the planarization process of the mesh faces by optimizing the positions of mesh vertices. In the design of single- and multi-layer freeform structures, studies to secure the planarity of quad meshes have been actively conducted since the 2000s (Pottmann et al. 2007). Most BIM authoring tools utilize constructive solid geometry (CSG) to represent the complex relationships of building systems and are also introducing NURBS for the representation of curved surfaces (Isikdag, Zlatanova, and Underwood 2013). However, most of them do not use meshes, except for model viewing in digital displays (Miller and Stasiuk 2017).

2.2. Mesh segmentation

The main drawback of polygon meshes is their lack of a structural or hierarchical description (Benhabiles 2011). Mesh segmentation enables high-level reproduction by dividing the area of polygon meshes from a geometric or semantic perspective (Rodrigues, Morgado, and Gomes 2018). The main criteria of mesh segmentation include the planarity, geodesic distances, normal directions, and dihedral angles of mesh elements. Various methodologies are being developed for mesh segmentation including region growing, watershed-based, Reeb graphs, model-based, skeleton-based, and clustering (Benhabiles 2011). In this study, we focus on clustering.

Clustering, which belongs to unsupervised learning, classifies data without labels into sets based on the similarity of their attributes (Jain, Murty, and Flynn 1999). It is divided into the following: hard clustering, where one data item is assigned to exactly one cluster; and soft clustering, one data item is assigned to multiple clusters. Studies that use the clustering technique for mesh segmentation have been recently conducted. The K-means algorithm as hard clustering and Fuzzy C-means as soft clustering were applied to mesh segmentation, and the results were compared with direct segmentation by humans (Khattab et al. 2016). It was found that soft clustering exhibited better accuracy and consistency than hard clustering in terms of mesh segmentation.

Meanwhile, approaches have also been made using human visual perception. A tool that allows non-experts to perform mesh segmentation by directly sketching on meshes was developed. An interactive tool for mesh segmentation, Paint Mesh Cutting, was developed by combining sketch and the Gaussian mixture model (GMM), a soft clustering technique (Fan, Lic, and Liu 2011). GMM is a method of grouping clusters of data that are highly likely to belong to each distribution, assuming that the probability distribution of the entire data is made up of a combination of several Gaussian distributions.

In architecture, the utilization of mesh segmentation has been adopted for reverse engineering and
façade or shell structure of freeform architecture. In reverse engineering, the triangle meshes generated by applying Delaunay triangulation to the point cloud obtained through 3D scan are mainly studied (Agathos et al. 2007). In freeform architecture, mesh segmentation is used to determine the design direction for optimization based on geometry. 3D panels were grouped using GMM based on the geometry attributes of the panels with freeform façades (Miller 2018).

2.3. **Tunnel modeling approach**

Because there is no specialized program for NBTs, we refer to shield tunnel design tools such as Midas GTS NX and Autodesk Civil 3D to understand the latest methods and limitations of tunnel modeling. Both programs place the cross-section of the tunnel along the road centerline. For the modeling of intersections, such as the tunnel cross-passage, each cross-section is placed along each road centerline. Practical approaches to creating parametric models by linking Civil 3D through Revit Dynamo and API have also been attempted (Chamfray, Houlston, and McGregor 2018). Midas GTS NX enables both design and performance analysis by supporting automated mesh generation (Midas UK 2014). The intersection of two tunnels could be represented with high accuracy using triangle mesh; however, it was not converted into integrated quad meshes.

2.4. **A necessity for NBT design method using quad meshes**

We propose a method for implementing the Y-branch of the NBT junction in quad meshes, which are suitable for topological modeling and useful for performance analysis. Although the arrangement of cross-sections along individual road centerlines reflects the order of data, quad meshes additionally require extracting the aligned geometric data for performance analysis and optimization.

3. **Methods**

3.1. **Conceptualizing the methodology**

Quad meshes are developed to their final geometry through optimization by performance analysis. Performance analysis requires different geometric data, depending on the method. Mesh vertices and mesh faces that constitute quad meshes provide basic geometric data that can be converted into points, curves, surfaces, and meshes.

Mesh primitives, such as planes, spheres, boxes, and cones, provided by a mesh editing tool, have a data sequence when they are first created. For the quad meshes that represent the Y-branch of the NBT junction, however, the list orders of mesh vertices and mesh faces are modified during the editing process, leading to an irregular arrangement of the indices of mesh elements not visually understood by the designer. For the geometric data extracted from quad meshes to be utilized in the performance analysis and optimization processes intended by the designer, they need to be reordered from the perspective of a grid system.

The following conditions must be met so that quad meshes can be used for optimization by performance analysis: condition (1) quad meshes must be divided into two, based on the roads; condition (2) the points, curves, and surfaces extracted from individual quad meshes must be reordered to facilitate the creation of panels and the transversal and longitudinal structures; and condition (3) the algorithm that meets condition (1) and condition (2) must operate in merging lanes with various conditions in a stable manner.

To meet condition (1), mesh segmentation with clustering, one of the unsupervised learning methods, can be used. Quad meshes can be divided into two by clustering based on the roads because adjacent mesh faces share similar geometric data. To meet condition (2), reordered geometric data are extracted from each quad mesh using the mesh reorder technique. The designer can now deal with quad meshes from the perspective of a grid system based on the new indices; hence, the second condition has been satisfied. To meet condition (3), the designer can improve the efficiency of the algorithm by directly entering curves. The input and modification of curves provide the designer with an intuitive and simple interface for controlling the algorithm.

The proposed method consists of the following steps (Figures 2 and 3): step (1) Form generation, step (2) Panel clustering by roads, step (3) Reordered geometry extraction, and step (4) Component mapping and optimization.

3.2. **Form generation**

The Y-branch of the NBT junction is modeled using welded quad meshes. A narrow sub tunnel is connected to the wide main tunnel (Figure 4(a)). The panel size and spacing of the structure are adjusted by subdividing the quad meshes using the Catmull-Clark algorithm. The mesh edges of the quad meshes correspond to the structure, and the mesh faces correspond to panels. As shape optimization is performed in step (3), the topological match is prioritized over geometrical accuracy with the target design for quad meshes in this step (Figure 4(b)).

A valence of mesh vertices refers to the number of incident edges (Bommes et al. 2012). Quad meshes have two mesh vertices with valence 5 at the point
where the main tunnel and sub tunnel meet (Figure 4(c)). The mesh edges connected to these mesh points can be used as boundaries for dividing the quad meshes into walls and roofs (Figure 4(d)). Lastly, the mesh edges are divided into transversal and longitudinal structures, based on the road centerlines. The number of longitudinal structures is the same for the walls of both tunnels. On the other hand, the number
of longitudinal structures for the roofs of the two tunnels can be respectively controlled because the longitudinal structures of the roof of the sub tunnel are connected to some of the transversal structures of the main tunnel (Figure 4(e)).

3.3. Panel clustering by roads
Quad meshes can be classified via clustering because adjacent elements have similar geometric data. In this study, mesh segmentation was performed using GMM, a soft clustering technique (Figure 5(c)). GMM requires training input, weights, and the number of clusters as input values. The number of clusters is two, which is the number of roads.

All training inputs increase their impact on the clustering results as their weight increases. It is difficult, however, for the designer to set a balance between multiple weights whenever different alternatives are dealt with. To solve the problem, the designer is allowed to affect the clustering results by entering arbitrary curves that pass through the center of each road instead of adjusting the weights (Figure 5(a)). In other words, the geometric relationships between the area centroid of the mesh face and the arbitrary curves close to it were utilized as training inputs. The designer can control the training inputs by moving the arbitrary curves until the clustering results are satisfactory (Figure 5(d)).

A total of five training inputs and weights were set in this study as follows (Figure 5(b)): input (1) The area of mesh face [weight: 2]; input (2) The x, y, and z values of the vector from the area centroid of mesh face to the closest point on the curve [weight: 1]; and input (3) The parameter on the curve domain of the point on the curve closest to the area centroid of the mesh face [weight: 1].

3.4. Reordered geometry extraction
It is necessary to order transversal structures along the road centerline. In addition, the sub components of a structure need to be ordered from left to right (or in the opposite direction). Therefore, the designer can utilize the necessary geometric data by modifying the list order of the mesh elements.
The transversal and longitudinal structure centerlines of the NBT are obtained by joining mesh edges connected in the specific directions of the quad meshes. The four mesh vertices that constitute a mesh face are arranged in a counterclockwise direction. This connection also determines the order of mesh edges in a list. Since the relative position of the first point of a mesh vertex is different, the structure centerline in a specific direction cannot be selected at once.

The mesh vertices of a mesh face are reordered based on the road direction. As the roads have different curvatures, the designer needs to enter multiple arbitrary curves into the road center so that the mesh vertices of a mesh face can be controlled by the curve closest to the area centroid of the mesh face. XY planes are created on the area centroids of the mesh faces and arranged in the road direction. Polar coordinates are applied to each XY plane to reorder the four mesh vertices of the corresponding mesh face (Figure 6(a)).

As the mesh vertices are reordered, the mesh edges are also automatically reordered. The mesh edges corresponding to the transversal structure curves are extracted as specific indices, and they are joined as polylines. The list order of the transversal structure curve is modified based on the curve domain of the road centerline (Figure 6(b)).

The control points and segments extracted from the transversal structure curves are used to create structural joints, longitudinal structure centerlines, and panel surfaces. The list order of all objects follows that of the transversal structures already sorted. For a mesh, the index of a mesh vertex is the list index of the point. Thus, the indices of the mesh faces are reordered by referring to the indices of the panel surfaces (Figure 6(c)). The methods shown in Figure 6 are targeted for the main tunnel, and the same principles are also applied to the sub tunnel.

### 3.5. Component mapping and optimization

The reordered geometric data such as points, curves, surfaces, and meshes are utilized for the arrangement of the architectural component library. For all geometric data, the list orders are classified by position. Therefore, they can be selected by the designer, and it is possible to create additional structures that cannot be expressed with meshes. In addition, the geometric data can be combined with an optimization algorithm to enable optimization design by performance analysis. Optimization includes shape optimization and allocation optimization. For shape optimization, performance simulation is performed through the transformation of NBT. The shape of quad meshes is changed by moving mesh vertices. Mesh vertices in a specific area of quad meshes can be selected. This is more efficient and more specific than selecting points manually or selecting mesh vertices using mesh topology.

![Figure 6. Process of reordered geometry extraction (Main tunnel).](image-url)
4. Case study

4.1. Overview of roads and NBTs

The proposed method was applied to the design of the NBT junction, located in Incheon, South Korea. The sub road (single lane with 8 m width) merged with the main road heading north (eight lanes with 40 m width). The NBT must meet the following constraints: constrain (1) Obstacles present immediately before the merge point must be removed to improve the mutual visibility of the main and sub roads; constraint (2) Both sides of the NBT must have a height of facility limit of 4.5 m, and the central part must be higher than 6.5 m, considering the heights of vehicles; and constraint (3) The spacing between the transversal structures of the NBT is set to 5 m.

4.2. Modeling NBTs

For this case study, Rhino 3D was used as the main CAD software. Rhino 3D supports not only NURBS but also advanced mesh editing functions. A series of algorithms were developed using Grasshopper, which is the visual programing language of Rhino 3D.

The Y-branch was created using quad meshes (Figure 7(a)), which were subdivided to model the geometry of the NBT with 5 m spacing between its transversal structures (Figure 7b). One curve for each tunnel was entered for mesh segmentation, and the curves were adjusted until 100% accurate mesh segmentation was achieved (Figure 7c). Two curves were entered for each tunnel for mesh reorder (Figure 7d). Once the mesh reorder was performed based on the quad meshes of the main road, reordered geometric data required for performance analysis could be obtained, including structure components for each direction (16 transversal structures and 25 longitudinal structures), panels, and meshes (Figure 8).

4.3. Optimization

Three optimizations were performed, namely panel planarization, structural optimization, and panel allocation optimization. The purpose of these optimizations was to reduce resource requirements. The optimization process shows various ways in which the geometric data with reordered indices are used for performance analysis. The quad meshes were transformed only in panel planarization, and they were utilized for the optimization performed later. Structural optimization and panel allocation optimization were performed by varying the allocation of architectural components without changing the shape of quad meshes.

4.3.1. Panel planarity optimization

In a digital model, soundproof panel components with a specific thickness can be morphed according to the curvatures of mesh faces. However, in reality, planar soundproof panels can be installed after being deformed within the range that their material properties allow. The purpose of this optimization is to modify quad meshes to have as many planes as possible or mesh faces close to planes to improve the constructability of soundproof panels.

Shape optimization to secure panel planarity was performed using kangaroo physics (Piker 2013), which is the real-time physics engine of Grasshopper. The planarity of a flat panel is zero,

![Figure 7. Quad mesh editing process.](image-url)
and it increases as the curvature of the panel increases. The Kangaroo engine reduces the panel planarity by allocating virtual properties to the mesh vertices and mesh edges. Because the points constituting a mesh face are shared with neighboring mesh faces, higher planarization force has a larger impact on panels, which were previously planes, thereby reducing the average planarity value.

To prevent the overall deformation of meshes before optimization, only the meshes at the point where the curvatures of the mesh faces were severe, i.e., the junction of the two tunnels, were extracted and optimized. Out of 512 mesh faces, only 108 were utilized for optimization. Planarization was performed at different planarization forces from 1.5 to 3.0. The number of panels and the maximum displacement of mesh vertices according to the planarity range were measured (Table 1). Mesh faces with planarity below 0.01 allowed by the properties of the material were regarded as planes.

As shown in Figure 9 and Table 1, as the planarization force increased, the number of surfaces close to planes with \( p = 0 \) also increased, but the height of the junction of the two tunnels showed a tendency to be lower because the overall distortion of the quad meshes became more severe than before. Considering this, the results for planarization force = 2.5 were selected as an optimal design.

### Table 1. Results of panel planarity optimization.

|                            | Before planarization | After Planarization |
|---------------------------|----------------------|---------------------|
| Planarization force       | 0                    | 1.5                 | 2.0 | 2.5 | 3.0 |
| Total                     | 108                  | 108                 | 108 | 108 | 108 |
| Non-planar panels (EA) \( \| p > 0.01 \) | 71                   | 71                  | 60  | 37  | 19  |
| Planar panels (EA) \( 0 < p \leq 0.01 \) | 37                   | 37                  | 48  | 71  | 89  |
|                          \( x = 0 \) | 0                    | 0                   | 0   | 0   | 0   |
| Maximum displacement of mesh vertex (m) | \( 0 \) | 2.24                 | 2.66 | 3.00 | 3.53 |

\( p \) planarity
4.3.2. Structural optimization

Structures were optimized using the same cross-sections depending on the belonging tunnel and their directions. Optimal structures were selected among the existing cross-sections of European standard wide flange beams (HEA) made from steel 235. Under the same conditions, optimization was performed to minimize the quantity of materials and maintain the displacement of each component below 10 cm.

The central columns on the centerline of the main road, which cannot be expressed with quad meshes, were created using the reordered points. Karamba3D (Preisinger and Heimrath 2014), an add-on of Grasshopper, was used for structural analysis, and Galapagos, a basic component of Grasshopper, was used for optimization using the genetic algorithm. Supports were designated by selecting both ends of the transversal structures. Only gravity (1 kg/N) was considered when setting the load. The specific purpose of structural optimization was to minimize the quantity of materials while maintaining the maximum displacement of each component at 10 cm or less.

![Figure 9](image-url) Panel planarity optimization of each planarization force.

![Figure 10](image-url) Results of structural optimization.

Table 2. Results of structural optimization.

| Maximum displacement (cm) | Mass of structure (kg) | Main tunnel | Sub tunnel |
|---------------------------|------------------------|-------------|------------|
| Before Optimization      | 9.98                   | HEA300     | HEA120     |
| After Optimization       | 9.98                   | HEA300     | HEA120     |

| T^1 | L^2 | C^3 | T   | C   |
|-----|-----|-----|-----|-----|
| HEA100: 96*100*5.0*8.0 |
| HEA200: 190*200*6.5*10.0 |
| HEA300: 290*300*8.5*14.0 |
| HEA120: 114*120*5.0*8.0 |
4.3.3. Panel allocation optimization

Opaque soundproof panels made of cement or aluminum limit access to daylight and the visibility of occupants living in nearby buildings. They also block the view of motorists or form permanent shadows on roads, thereby causing the road surface to freeze in winter and increasing the chances of accidents. One solution is combining transparent soundproof panels made of plastic or glass with opaque panels. Because transparent soundproof panels are more expensive than opaque panels, they must be allocated to meet the required performance in minimum quantity. The purpose of panel allocation optimization is to create the optimal design for preventing the road surface from freezing considering daylight hours in winter. Other environmental factors involved in freezing, such as humidity, temperature, and solar radiation, were not considered in this study.

To analyze daylight hours, Ladybug for Grasshopper, an environmental analysis tool based on the EnergyPlus engine, was used. Inchon 471,120, provided by EnergyPlus, was used as climate data. The measurement of daylight hours was performed every hour from 09:00 to 18:00 hours on the winter solstice (21 December 2019). The size of the grid on the road where daylight hours were measured was 2 m by 2 m.

The transparency of transparent soundproof panels was set to 100%. For the allocation of the soundproof panels, the longitudinal direction was selected to consider the visual comfort of motorists. The columns of the opaque and transparent panels were allocated in the longitudinal direction using a random algorithm. The specific purpose of panel allocation optimization was to allow all the parts of the roads to be exposed to sunlight for more than four hours a day using minimal transparent soundproof panels. The random seed of the random algorithm and the ratio of transparent soundproof panels to opaque panels were optimized using a genetic algorithm. However, only the transparent soundproof panels were used to secure the vision of motorists on the wall where the two roads start to meet.

The optimization resulted in two patterns, which had 264 transparent soundproof panels out of 512 (Figure 11). For both patterns, daylight hours ranged from four to nine hours. For the average daylight hours, Pattern A with 7.22 h had longer hours than Pattern B slightly with 7.10 h. Pattern B, however, was selected as the optimal design because it exhibited more uniform panel allocation across the NBT roofs than Pattern A, thereby providing homogeneous internal illumination.

Figure 12 shows the BIM-compliant model that reflected the three optimization results. The structures

Figure 11. Results of panel allocation optimization.

Figure 12. Completed BIM-compliant model.
and panel components were mapped to the quad meshes deformed by panel planarization.

5. Discussion

This study proposed a basic approach for the digital design of NBTs. It reflects the changes in the role of the designer in the digital design era.

First, we addressed the limitation of the algorithm via intervention from the designer. By allowing the designer to directly enter and adjust the curves, we could successfully extract geometric data for elements from the given quad meshes. In general, rule-based algorithms may lose accuracy depending on the various conditions of the design target. Algorithms may not perfectly respond to the curvatures of roads and the cross-sectional geometry of tunnels. BIM does not have sufficient data to derive perfect results at all times through machine learning (Correa 2015). To enable the cyclic and non-linear processes of digital design, the format of data should be prepared for the next step. This is as it is difficult to obtain the desired results in the analysis phase if even only one element is not properly classified. Moreover, an algorithm that works perfectly for an arbitrary alternative may inevitably need longer analysis time as it requires more data and precise search. To overcome these problems, the algorithms need to be combined with intuition of designers. The communication between numerous geometric data and the designer makes it possible to derive the desired results within a short period of time.

Second, modeling and performance analysis using quad meshes enable the CAD-CAE integration process. They also enable the multidisciplinary utilization of human resources inputted to the design process, as well as material resources inputted to the construction of NBT. The range of performance analysis could be extended using various geometric data that could be extracted from quad meshes. Meshes were used for panel planarity optimization; curves and points for structural optimization; and surfaces for panel allocation optimization. The three-step optimization reduces component manufacturing cost while maintaining the performance of the design. This CAD-CAE integration process shows the potential to reverse the 80/20 modeling/analysis ratio that has been performed in the existing industries (Bazilevs et al. 2010). Minimizing analysis-suitable geometry modeling, which has dominated the existing design process, makes it possible to allocate human resources to more creative work. It is expected that multidisciplinary teams, including designers, engineers, and builders, will approach the optimal alternative through design modifications based on the performance analysis results.

6. Conclusion

In this study, a method to create the Y-branch topology of an NBT junction using quad meshes was proposed. Data arrangement using mesh segmentation and mesh reorder, and optimization design through performance analysis were performed. Using a case study where a main road with eight lanes merged with a sub road with one lane, geometric data arrangement was performed successfully, and a BIM-compliant model was generated through optimization that used various geometric data. Our results can be applied to design software dedicated to other linear road facilities, as well as NBTs, and contribute to solving design problems from the freeform architectural design that uses quad meshes.

This study has the following limitations. First, the method needs to be extended to analyze roads with three-dimensional curvatures. Additionally, the offset of quad meshes must be considered, and the subsequent shape optimization must be analyzed to express more specific components for each part. For future works, we recommend employing subdivision modeling such as T-spline or Rhino Sub-D to model NBTs with a curved surface.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was funded by the Infrastructure and Transportation Technology Promotion Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government [Grant No. 20CTAP-C151928-02].

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