Multi-scale geometry in civil engineering models: Consistency preservation through procedural representations

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Abstract

For the planning of large infrastructure projects, such as tunnelled inner-city carriageways, completely different scales have to be considered – ranging from the scale of several kilometres for the general routing of the carriageway down to centimetre scale for the detailed planning of track nodes. However, today's planning software hardly supports multi-scale approaches. The paper presents a new methodology for creating and storing multi-scale geometric models for infrastructure projects which explicitly defines dependencies between the individual levels-of-detail (LoD). These explicit dependencies allow for automated consistency checks and even automated consistency preservation. The methodology relies on parametric modelling technologies, including the use of dimensional and geometric constraints for defining flexible 2D sketches, as well as the procedural definition of complex 3D models through the sequential use of geometric operations such as extrusion, transformation and Boolean operations. Applying the methodology presented in this paper ensures that modification on coarse LoDs are automatically propagated to all finer LoDs, thus providing means for an automated preservation of consistency and, at the same time, significantly reducing the effort required for re-elaboration.

Keywords: Procedural Modelling, Construction History, Infrastructure, Level-of-Detail

1 Introduction

For the planning of large infrastructure projects, such as tunnelled inner-city carriageways, widely differing scales have to be considered – ranging from the kilometre scale for the general routing of the carriageway down to the centimetre scale for the detailed planning of individual track nodes. Despite the multi-scale characteristics inherent to the planning of carriageways, today's carriageway planning software does not support multi-scale geometric modelling. The research unit "3DTracks" funded by the German Research Foundation (DFG) is tackling this issue by developing a methodological basis for introducing multi-scale geometry into civil engineering models.

The paper presents a new methodology for creating and storing multi-scale geometric models for infrastructure projects which explicitly defines dependencies between the individual levels-of-detail. These explicit dependencies allow for automated consistency checks and even automated consistency preservation. The methodology relies on parametric modelling technologies (Shah & Mäntylä 1995), including the use of dimensional and geometric constraints for defining flexible 2D sketches, as well as the procedural definition of complex 3D models through the sequential use of geometric operations such as extrusion, transformation and Boolean operations.

Parametric modeling techniques facilitate a step-wise development of infrastructure models evolving from a coarse level of detail to the finer ones, which precisely reflects the well-established best practice in infrastructure planning. Conventionally, fundamental modifications on a coarse level in a late planning phase, such as the modification of the principal tunnel axis, are forcing the planners for a complete re-elaboration of all related models and plans, e.g. the detailed tunnel geometry. Applying the methodology presented in this paper ensures that modifications on a coarse LoD are automatically propagated to all finer LoDs, thus providing means for an automated preservation of consistency and, at the same time, significantly reducing the effort required for re-elaboration.

2 Related work

The concept of multiple geometric representations on different scales is well known from both cartographic applications as well as 3D city modeling. For example CityGML, an open standard for the storage of 3D city models based on GML, provides 5 different Levels of Detail (Kolbe 2008). The LoD concept in these application areas relies on the independent storage of individual geometric models on each level of detail. As the dependency between the individual levels is not explicitly represented, inconsistency may arise easily. Nevertheless, for geographic applications the concept of independent LoD representations is well suited since GIS applications are relying on rather static data sets, which are rarely subject to modifications.

For the highly dynamic planning stage of large infrastructure projects, a more robust approach is required. To realize this, we propose the definition of explicit dependencies between the different levels of detail during the creation of the multi-scale model. The creation is intended to be performed top-down, i.e. from coarser levels to the finer one, thus reflecting the typical planning procedure. This top-down approach for defining and managing multi-scale geometry is contrasting with the well-known methods used in cartographic applications, which implement a bottom-up approach usually known as generalization. This is can be explained by the fact that in cartography, maps are created by subsequently abstracting real-world objects, whereas in civil engineering the workflow starts at an abstract level, becoming more and more concrete as planning evolves.

3 Methodology

The proposed methodology for the creation and management of multi-scale geometric models relies on an explicit definition of dependencies between the individual levels-of-detail. These explicitly available dependencies allow for an automatized preservation of the consistency of the multi-scale model.

The definition of the dependencies is realized by applying technologies provided by parametric CAD systems (Shah & Mäntylä 1995). The core concept is not to store the final outcome of the construction process, i.e. an explicit geometric model, but instead the history of the individual construction operations. Such models, which are referred to as *procedural models* or *construction history models*, combine the use of dimensional and geometric constraints for defining flexible 2D sketches, with the concept of a procedural definition of complex 3D models through the subsequent use of geometric operations such as extrusion, rotation and Boolean operations (Mun et al. 2003, Stiteler 2004, Pratt et al. 2005, Koch & Firmenich 2010). Parametric modelling concepts have recently been applied to model infrastructure facilities, such as bridges and roadways (Ji et al. 2010, Ji et al. 2011, Obergriesser et al. 2011).

Using these techniques allows for a step-wise development of the infrastructure model evolving from a coarse level of detail to the finer ones. This precisely reflects the well-established best practice in infrastructure planning. In the proposed concept, the LoDs can be flexibly defined by the planning team according to the requirements of the infrastructure project under consideration. During the modelling process, the switches between one LoD and another are explicitly triggered by the designing engineer who in this way decides which geometric elements belong to which LoD. As an example, Figure 1 illustrates the five different levels of detail defined for the design of a tunnelled subway track (see also Section 6).

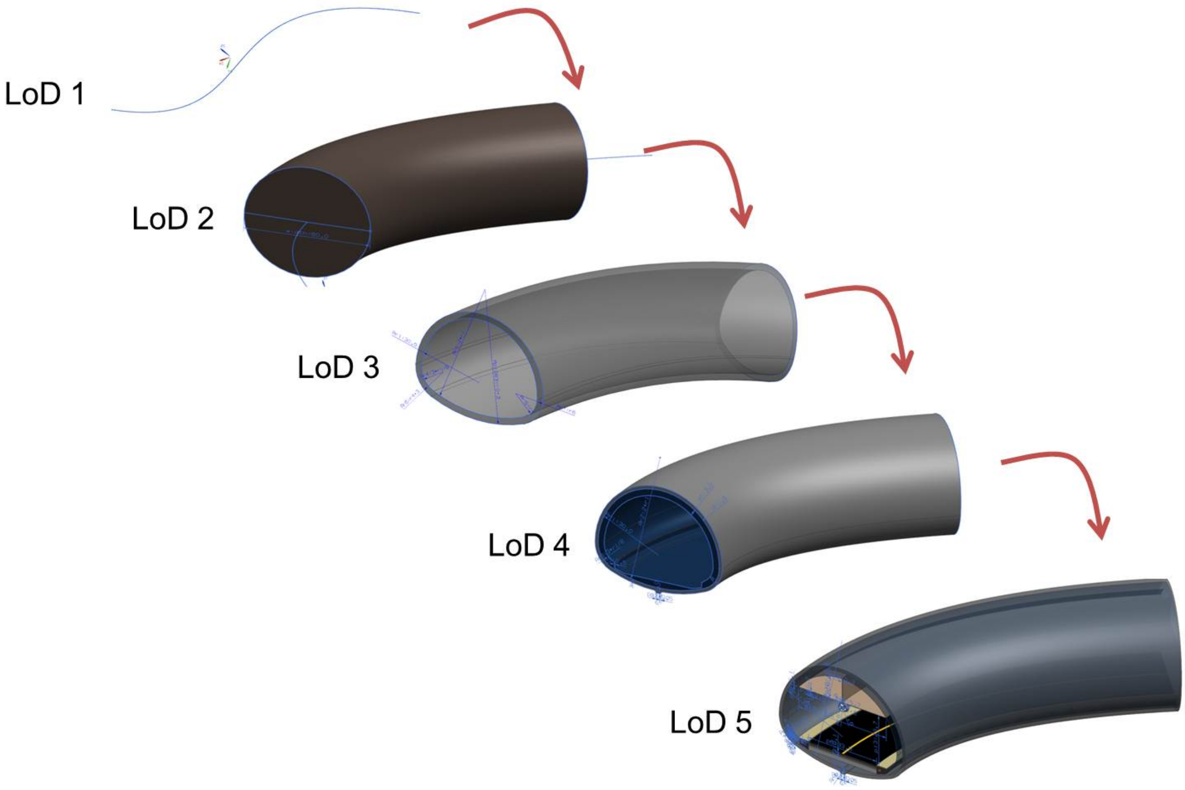
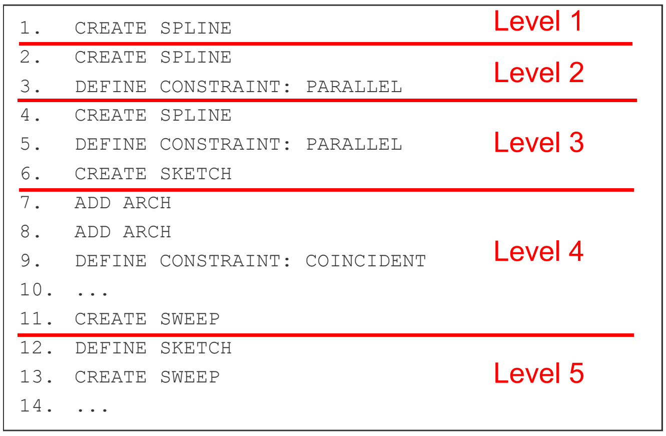


Figure 1. Illustration of the five different levels-of-detail defined for railway tunnel design. The concept of procedural modelling allows for the explicit definition of dependencies between geometric elements on different levels-of-detail.

Applying procedural technologies for multi-scale modelling provides the possibility for a stringent definition of dependencies between individual geometric elements on different levels of detail. Thus the levels-of-detail of the model are not isolated from each other, but inter-related by means of the construction history. Accordingly, the resulting multi-scale model is inherently consistent and preserves a high degree of flexibility. Modifications of elements of a coarse LoD, such as the principal axis of the tunnel are automatically propagated to all dependent objects on the finer LoDs.

However, there are limits to the degree of modifications on coarse levels which can be propagated to finer ones. These limits are mainly driven by operations in the construction history which only produce results if certain conditions are fulfilled by their operands. A typical example is the Boolean intersect operation which only generates a valid volume object if the operands do overlap. If their position is determined by earlier operations, the Boolean operation might fail, resulting in a non-evaluable procedural model.



```
CREATE SPLINE
CREATE SPLINE
DEFINE CONSTRAINT: PARALLEL
CREATE SPLINE
DEFINE CONSTRAINT: PARALLEL
CREATE SKETCH
ADD ARCH
ADD ARCH
DEFINE CONSTRAINT: COINCIDENT
...
CREATE SWEEP
DEFINE SKETCH
CREATE SWEEP
...
```

Figure 2. Illustration of a construction history captured by a procedural model. The switches between the individual LoDs are explicitly triggered by the user.

4 Parametric Modelling

The proposed methodology for creating inherently consistent multi-scale models relies on the use of parametric modelling technologies (Shah & Mäntyla 1995) for defining dependencies between the geometric elements of the different LoDs. The concepts underlying parametric modelling have been developed in the 1990's and subsequently implemented in mature commercial CAD systems, including Autodesk Inventor, Dassault CATIA and Siemens NX. Today, these systems are used mainly in the mechanical engineering domain, but there is an increasing adoption also in the AEC industry (Lee et al. 2006, Ji et al. 2011, Obergriesser et al. 2011).

The majority of the available parametric CAD systems implement a twofold approach, comprising the definition of 2D sketches including dimensional and geometric constraints on the one hand and the subsequent procedural definition of 3D volumes through the sequential use of geometric operations such as extrusion, transformation and Boolean operations on the other hand (Bettig & Shah, 2001). The realization of the proposed multi-scale approach makes use of both principles for defining dependencies between geometric elements.

For the composition of a parametric sketch, the user can apply geometric constraints to pairs of geometric elements (points, lines, arcs), thus specifying their relative position. Figure 3 depicts some of the geometric constraints available in major parametric CAD systems. Additionally, dimensional constraints can be used to restrict the size or the position of a geometric element. For defining dimensions, parameters can be used and their values can be interrelated to each other by means of arithmetic expressions. These two types of constraints allow the generation of complex 2D designs capturing geometric rules and providing a high degree of flexibility. This is typically achieved by the integration of a geometric constraint solver which computes a feasible solution to the given set of constraints (Anderl & Mendgen 1998). The user is informed if the sketch is over-constrained (no solution is available) or under-constrained (there are too many solutions). If it is well-constrained the valid solution is immediately displayed (Figure 4).

The second important concept provided by parametric CAD systems is the explicitly available construction history. The system records each single construction operation and displays the resulting list as part of the user interface. All operations are parameterized – e.g. the height of an extrusion is an explicitly available parameter. The maintenance of the construction history stands in strong contrast to conventional systems which only store the result of the construction operations, usually be means of an explicit boundary representation. The procedural approach provides the user of the system the possibility to easily modify an existing model by going back in the construction history, adapting the corresponding parameter or replacing a construction operation.

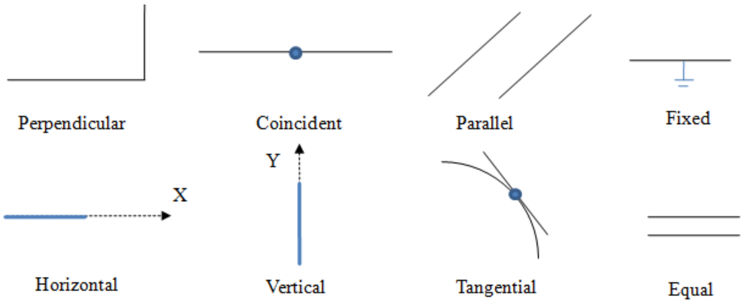


Figure 3. Geometric constraints typical provided by parametric CAD systems

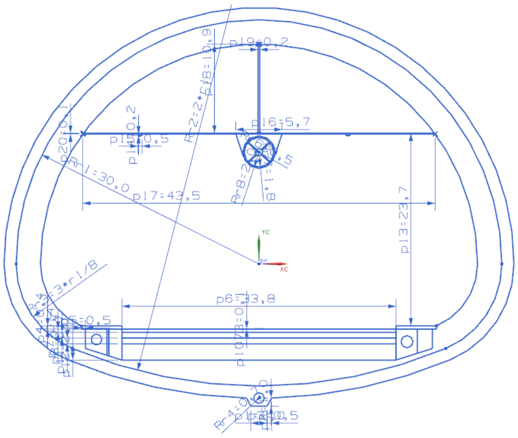


Figure 4. A complex parametric sketch defining the cross-section of a tunnel.

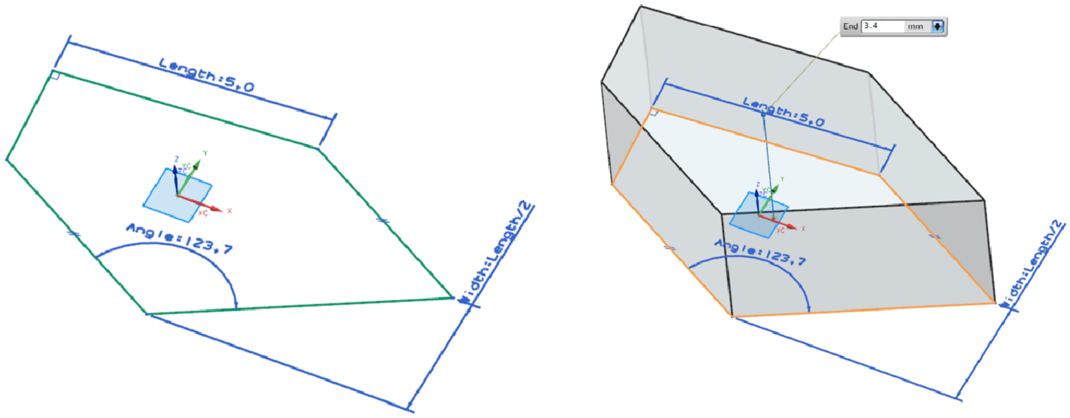


Figure 5. A sketch definition and the subsequent application of an extrusion operation

The construction operations provided by parametric 3D CAD systems include operations which create volume objects from parametric sketches (e.g. sweeping, extrusion etc.). On the resulting volume objects subsequent 3D operations may be applied, such as union, intersection, chamfering etc. The combination of these different aspects of parametric design allow for a highly flexible creation of complex 3D models.

For the implementation of the methodology presented in Section 3 we make use of both aspects, parametric sketches and the construction history, to define dependencies between the geometric elements of different levels of detail. In order to preserve the flexibility of the multi-scale model we do not maintain the resulting explicit geometry of the representations on the different LoDs but instead store the underlying sketches and construction operations. The resulting geometry description is denoted as procedural representation.

5 A neutral format for procedural multi-scale models

Within the AEC industry, the data exchange between different stakeholders is of crucial importance. The use of neutral, open data formats has proven to be the most suitable approach to realize this data exchange. A neutral data model which provides the possibility to share a procedural description of multi-scale models is able to transmit the dependencies between the different LoDs and allows to maintain the flexibility and the inherent consistency of the model. Since such a data model does currently not exist, it has been developed in the course of the 3DTracks research project.

The developed data model consists of two main parts. The first part provides the possibility to describe parametric sketches which may include geometric elements as well as the applied dimensional and geometrical constraints. This part has been published in (Ji et al. 2011). The second part allows for storing the construction history of the geometric model. By contrast to the rather generic approach taken by Part 55 of the STEP standardization framework (ISO 2005), the available construction operations are explicitly represented by the data model.

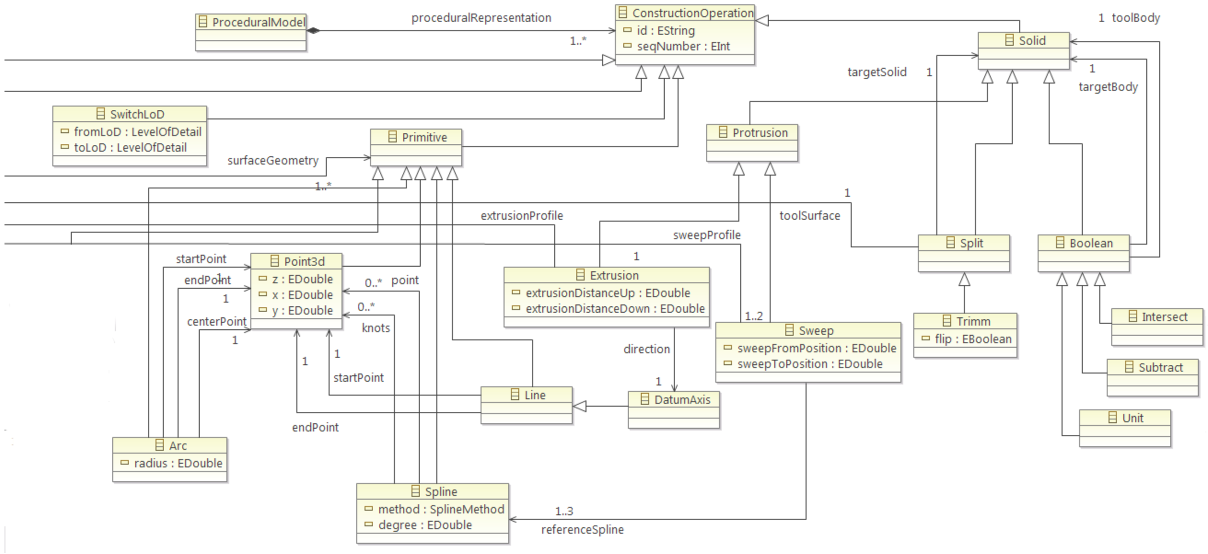


Figure 6. A sketch definition and the subsequent application of an extrusion operation

Figure 6 shows a section of the developed data model. The *Procedural Model* consists of an ordered list of *Construction Operations*. For *Construction Operation* there are a number of subclasses defined, among others *Primitive*, *Sketch,* and *Solid. Primitive* objects are *Points, Lines, Splines* and *Arcs*, for example. A *Sketch* objects comprises primitive objects as well as dimensional and geometric constraints. *Solid* is the superclass of all operations which generate or modify a solid, such as the different protrusions, the Boolean operations, or specific split operations. *Protrusion* is subclassed by *Extrusion* and *Sweep.* Both operations take a sketch as the first argument, while *Extrusion* uses a simple direction as second one, *Sweep* uses a spline as the extrusion path. In both case, the third argument is the protrusion distance. A particular subclass of *ConstructionOperation* is *SwitchLoD*: Objects of this type mark the beginning of the next level-of-detail in the operation list.

By means of these classes the most important parts of a procedural model can be captured. However, in this early stage of our research we excluded more specific construction operations such as chamfering, for example. In future, we will extend the data model to include the full set of construction operations necessary to model infrastructure projects.

6 Case Study

As a case study the methodology has been applied to create a multi-scale model of a section of a tunnelled subway track. The result is depicted in Figure 1. On the first level, the track axis is modelled by means of a simple curve. For the Level 2 representation, a cylindrical hull geometry is created by sweeping a 2D cross-section (a parametric sketch) along the path created on LoD 1. The representation is further refined on Level 3, where the sketch is extended by the inner contour line which is defined in a constant distance to the outer contour line defined on Level 2. The subsequent sweep operation then returns a rough representation of the tunnel's concrete shell. On Level 4 more details are added by refining the contour lines of the concrete shell, this time in dependency on the geometric elements comprising the LoD 3 representation. On the finest level, LoD 5, all necessary components of the tunnel, including the track bed and the ventilation elements are added.

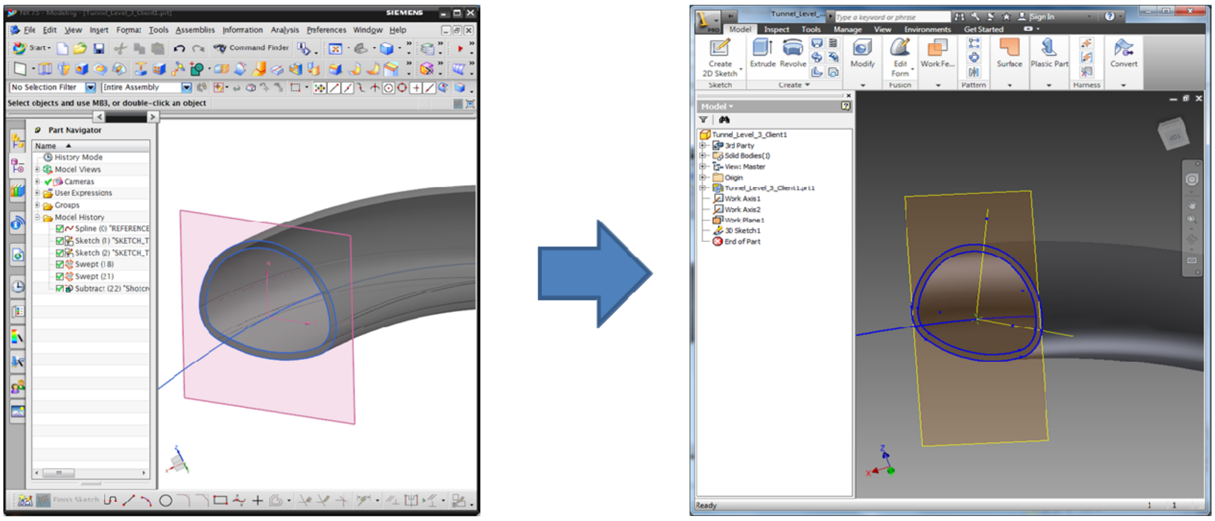


Figure 7: The realized exchange of a procedural model between Siemens NX and Autodesk Inventor

The capability of the data model introduced in Section 5 to correctly transmit a procedural model has been tested by realizing the data exchange between two parametric design systems, namely Siemens NX and Autodesk Inventor (Figure 7). To this end, the data model has been implemented as XML Schema and the actual data has been transmitted by a corresponding instance file. Despite significant differences in the way these two systems implement parametric modelling, we successfully managed to rebuild the procedural model in the receiving application, preserving all dependencies defined in the original system.

7 Conclusions and future research

The paper has introduced a new methodology which allows for creating multi-scale models whose individual level-of-details are inherently consistent with each other. The core concept is the definition of dependencies between geometry objects on different LoDs by making use of procedural geometry representations. The implementation of the concept is based on the application of parametric modelling techniques. The methodology is general and applicable to a wide range of infrastructure project types. A first case study conducted for the multi-scale modeling of a tunneled subway track proves the general feasibility of the approach. In future, we will extend our investigations to more comprehensive infrastructure models. Further, we aim at integrating the proposed multi-scale approach with semantic product modeling. To this end, LoD concepts have to be introduced in semantic models and methods for a flexible definition of links between individual geometric and semantic entities have to be developed.

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