BIM-based parametric modeling of roads and infrastructure objects

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Abstract

The paper presents results of a joint research project PR3MIK between the University of Maribor Faculty of Civil Engineering and the company Lineal d.o.o. In 2014, the partners established an industry research group within the Lineal d.o.o. In the paper an internationally awarded research work of the group is presented (winner of the CITA Smart Collaboration Challenge 2014, (Irish Building Magazine, 2015)).
The research group has focused on BIM research for roads and infrastructure objects, mainly design of roads, development of smart parametric building blocks for 3D road design (roadway, intersections, road re-design) and the development of algorithms for the detection of road elements from the 3D point clouds acquired by laser scanning. This article contributes to the field of advanced BIM methods for design of roads and infrastructure objects.

Keywords: BIM, parametric modeling, 3D road design, 3D point cloud, feature extraction

1 Introduction

Design of infrastructure facilities in the field of roads, railways, bridges and tunnels, which is based on 3D-model, is one of the essential pre-conditions for the project progress in accordance with the building information modeling approach (Eastman, Teicholz, Sacks, & Liston, 2011). Following this approach the infrastructure projects are a step closer to the working methods, which are already intensively used in the building construction. The entire construction industry (buildings, infrastructure and industrial) must strive to operate according to the principles of BIM. This ideally means that all participants, in all phases of the construction project, consistently apply a common digital data model, in order to avoid duplication of work and communication problems due to different data interfaces.

Depending on BIM strategy being developed in more and more countries (BIM Industry Working Group, 2011), it is realistically to expect that by 2016 in many construction disciplines the level of the 3D-managed environment using BIM software tools, eg. BIM-server (Beetz, van Berlo, de Laat, & van den Helm, 2010)) will be reached.

In the implementation of BIM approach, there are two main concepts: the file-based and server-based approach. Using the file-based approach stakeholders in an infrastructure construction project exchange (sub) models such as the files formatted in LandXML and / or IFC. On the other hand use of the server-based approach means exchange of (sub) models via central BIM-server. Figure 1 shows a successful experiment in which we used server-based BIM-approach to exchange roundabout information in IFC format.

The driving force in the process of transition from traditional 2D design to the efficient 3D-model-oriented design is the capability of detecting conflicts in the planning stage and, consequently, at least in theory, to control or even reduce the time of construction. Because of the multiplication effects on the cost such a project can also be cheaper.

The fastest and most expensive way to set up a managed 3D environment is the use of existing proprietary (commercial) software. Integration processes using such software result in the so-called proprietary BIM. Such BIM-approach enables all those involved in the construction project relatively easy data exchange between different programs within the same licensed group of programs. A tipical characteristics of the BIM approach where only proprietary (commercial) software is in place is the monopolization of the end-user market. As a consequence a proprietary BIM becomes depedent on the software manufacturer.

With a growing understanding of BIM among construction engineers it is also obvious that the use of a particular program does not guarantee BIM yet, but is only a tool in the process to implement it. In addition to the good professional solutions stakeholders in a construction project should also be motivated to use open and sustainable solutions that contribute to the interoperable BIM. Independent organization where concepts such as openness, sustainability, interoperability and integrated approach to the lifecycle of the construction objects (buildings, infrastructure) are actually realized, is buildingSMART (buildingSMART International, 2014). The buildingSMART organization develops open standards and specifications for the BIM approach (buildingSMART, 2014). BuildingSMART's data model, known under the name Industry Foundation Classes (IFC) represents a growing and rich data schema applicable to more and more construction industry domains that simplifies the exchange of data between different proprietary software. IFC is the primary data model for digital models of buildings. IFC with its version IFC4 (IFC 2x4) is an official ISO standard (ISO 16739:2013, 2013).

2 Overview of Open BIM for infrastructure objects

The latest buildingSMART's IFC4 does not yet include data schemas for infrastructure works industry domain (i.e. infrastructure objects, like roads, railways and tunnels). Historically, the only relevant industry standard to start with was the LandXML (LandXML.org, 2014), which over the last 15 years had many contributions (Rebolj, Tibaut, Čuš-Babič, Magdič, & Podbreznik, 2008) and has evolved into the mature LandXML 2.0 schema for infrastructure design including section template formats supplementing design of cross sections, as-built data collection, hydrology data and point cloud and LIDAR format for large surfaces.

With the support of the buildingSMART organization a new buildingSMART IFC for Infrastructure (buildingSMART - IFC for Infrastructure, 2015) project started recently with the goal to standardise interoperability in the field of planning and realization of infrastructure objects. The initiative originates from the OpenINFRA initiative (OpenINFRA-Initiative, 2015), which adopts LandXML and uses it to extend the IFC with IFC Alignment (Amann, Singer, & Borrmann, 2015) as a basis for further development for roads and bridges (IFC-Road, IFC-Bridge). One result of this development is also an open-source viewer (OpenINFRA Viewer) for 3D preview of infrastructure objects physically represented as LandXML files. The OpenINFRA Viewer helped us in our research as a neutral validator for LandXML files.

Despite the fact that software for infrastructure objects design is not yet sufficiently adapted to open BIM standards as opposed to building constructions, it is already possible to use existing open source solutions for early applications with the freedom to rely on open standards (i.e. LandXML). This is a real promise for the Open BIM for infrastructure (Amann & Borrmann, 2015).

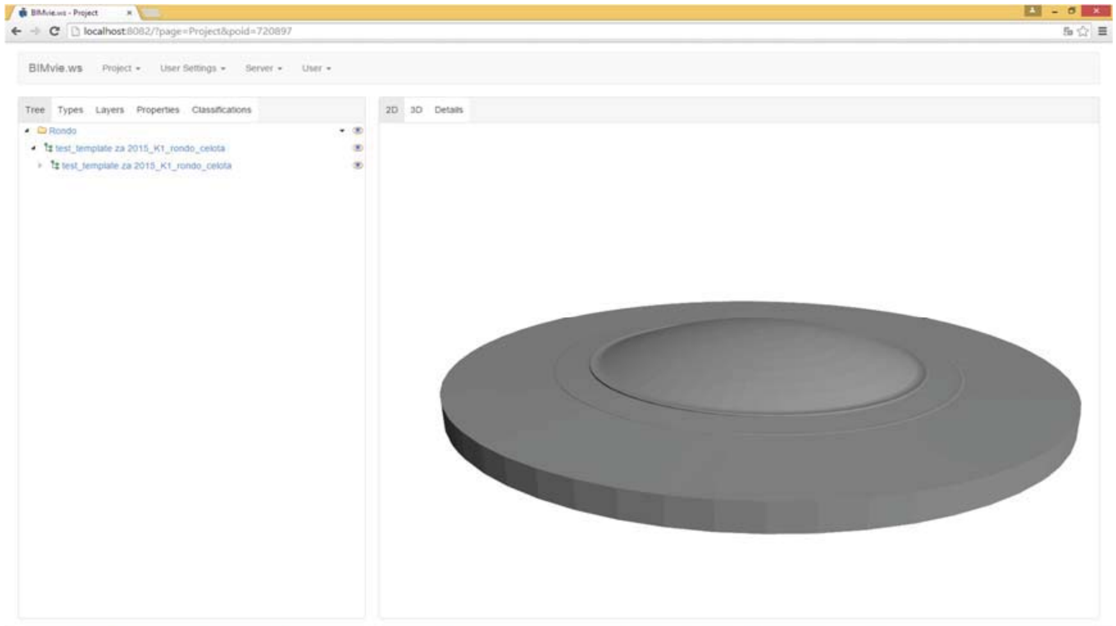

Figure 1. Server-based BIM approach: IFC-model for a roundabout using the open BIM-server (bimserver.org)

3 Research project PR3MIK

An industry research group PR3MIK (PR3MIK, 2014) is a development initiative between industry (Lineal, 2014) from Maribor and the Faculty of Civil Engineering at the University of Maribor (UMFG, 2014). The reserach group is funded thru the European Social Fund (Investing in your future) and the Ministry of Economic Development and Technology in Slovenia. The research group is registered with the national Agency for Research and Development (ARRS) and involves researchers from a variety of interdisciplinary fields: construction including IT in construction, surveying (laser scanning and infrastructure) and software engineering. The research group focuses on development of parametric assemblies for roads and rails. The development is largely based on the concepts of BIM and current standards such as buildingSMART IFC for infrastructure and LandXML.

The research group follows the research plan:

1. BIM research for roads and infrastructure
    a. Review of " state-of -the-art " concepts, technologies and best practices
    b. Research of potentials of nD models for road design
2. BIM market research for design of road and infrastructure
    a. Market analysis for target regions
    b. Overview of referential projects in targeted areas
    c. Identification and analysis of potential partners
3. Development of parametric assemblies for 3D-design of roads
    a. Development of parametric assemblies describing road cross sections (roadways, intersections, planum, drainage, reconstruction, etc.) that dynamically adapt to the terrain.
4. Development of algorithms for feature extraction from 3D point cloud data obtained from LiDAR device
5. Integration of project results into business processes

3.1 Development of smart parametrical assemblies for 3D-design of roads

Parametrical assembly is a software widget that describes a cross-section profile, which is a plane curve that creates three-dimensional road corridor when applied along the horizontal and vertical curves in a roadway alignment. Parametric assembly can be considered as a "smart widget", because not only its internal behaviour can be pre-determined thru its parameters but it also communicates dynamically with terrain elevations along the alignment. The smart behaviour is maintained also during model updates. For our research a parametrical assembly for roundabout was developed (Figure 2). The assembly contains all horizontal (central island, curb, drainage, apron) and vertical (sub-base, base, binder, surface) cross-section elements from the central island to the truck apron. The remaining horizontal part of the roundabout (travel lane, curb, sidewalk, curb, berm) is modelled with another assembly. The assembly for roundabout was applied on a circular alignment curve and the result (Figure 3) is a generated corridor defined by a discrete number of cross-sections.

In our project we developed over 15 different parametric assemblies.

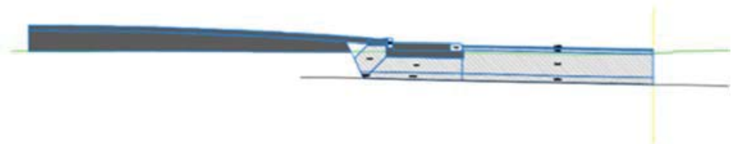

Figure 2. Cross-section view of the parametrical assembly for roundabout

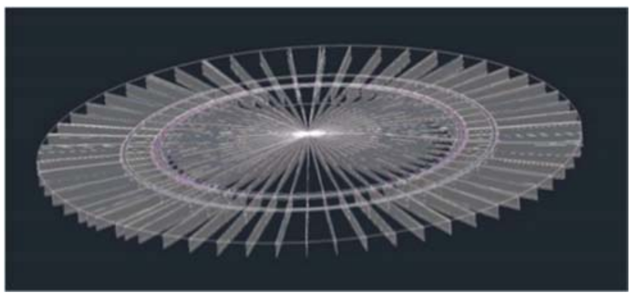

Figure 3. Application of the parametrical assembly for roundabout: discrete cross-sections

3.2 Application of new parametrical assemblies for a new road segment to an existing roundabout

As part of our research the developed parametric assemblies were also validated on real use cases. Our use case included a roundabout where a new outgoing/incoming road segment was planed. The new road segment is a connection to an existing parking place.

The roundabout "Pariške komune" was originally designed with traditional 2D-approach; therefore the first step was to re-model it with our new approach using the two new assemblies, one for roundabouts and another for roadway with sidewalk. Figure 4 shows the roundabout model placed in the digital city model.

Next step was to apply another subassembly for the new road segment. The new road segment was modelled with the two new assemblies:

- Right side of the road was modelled with the assembly that creates following horizontal elements: travel lane, curb, sidewalk, curb, and berm. (Figure 5)
- Left side of the road was modelled with the assembly that creates following horizontal elements: travel lane, curb, and sidewalk. (Figure 6)

Both new assemblies included following vertical layers: sub-base, base, humus, pavement and crown.

Figure 4. 3D-model of the roundabout placed in the 3D-city model

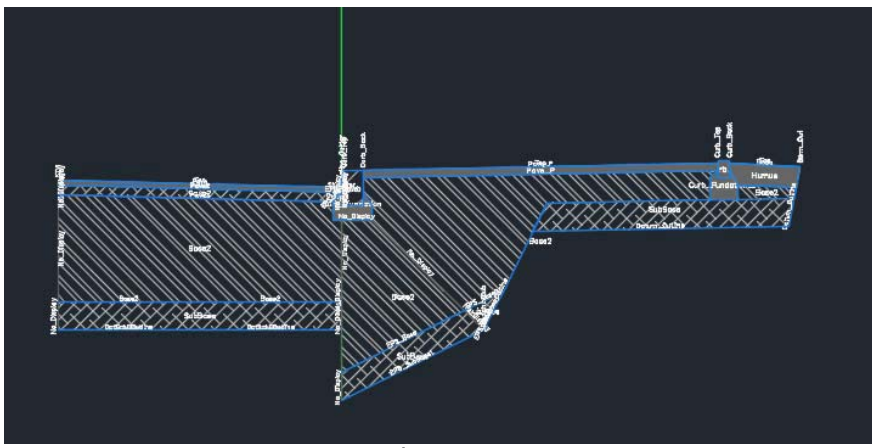

Figure 5. subassembly for roadway-curb-sidewalk

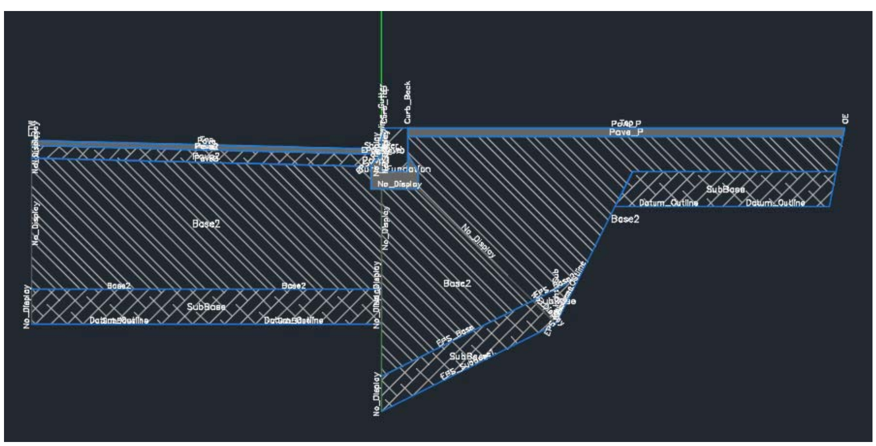

Figure 6. subassembly for roadway-curb-sidewalk-curb-berm

The new corridor for the road segment was then used for generation of longitudinal solid objects inside of the Autodesk AutoCAD Civil 3D 2015 software. The software was also used for creation of mass elements with explicit information about geometry and quantities for individual layers of the road segment. The final model is by definition a proprietary BIM-model, which was exported to Autodesk Infraworks for visualization (Figure 7). The software was also used for review of cross-sections (Figure 8), which proves the concept of development and application of parametric assemblies. The model was also used for preparation of BIM 4D-model, which was used for simulation against the construction schedule.

Figure 7. Final BIM model of the roundabout with a new road segment

Figure 8. Cross-section cut of the new road segment

3.3 Reconstruction of roundabout from 3D point cloud

The development of remote sensing for data acquisition about objects on the earth's surface (vegetation, buildings and infrastructure, even people and animals) enables very fast and accurate capture of data with very high resolution. Because of price and accessibility the most important technology in practice is the LiDAR (Light Detection and Ranging). Most commonly the LiDAR sensor is attached to a platform that moves over area of interest and performs laser scans. The LiDAR system consists of a laser scanner, a global positioning system and the inertial measurement unit (IMU). Result of scanning is a vast amount of unstructured (topologically unconnected), geometric data - 3D points associated with scalar values. Therefore, the research focus is transferred from the actual data capture to their maintenance and processing. The amount of data acquired with the LiDAR technology quickly outgrows several terabytes (i.e. some square km of terrain) thereby overcoming the computational capabilities of the most computer systems. The volume of LiDAR data is a major obstacle in the implementation of effective procedures for their processing and use.

Figure 9 shows a vehicle with mounted LiDAR device used for collection of data about the earth's surface. Such a LiDAR system is able to capture data with a density of over 8000 points / m2 and with accuracy under one centimetre for both vertical and horizontal positions.

Figure 9. A car with mounted LiDAR device (courtesy of Mensuras d.o.o.)

The mobile LiDAR system was used for the acquisition of 3D point cloud for the given use case related to the roundabout Pariške komune. The captured points including the roundabout and its surrounding (road links, buildings, infrastructure, trees) were stored in the standard LiDAR exchange format (LAS). The format is capable to store any three-dimensional data (x,y,z), which then form a 3D point cloud. The 3D point cloud was merged to the digital city model (Figure 10).

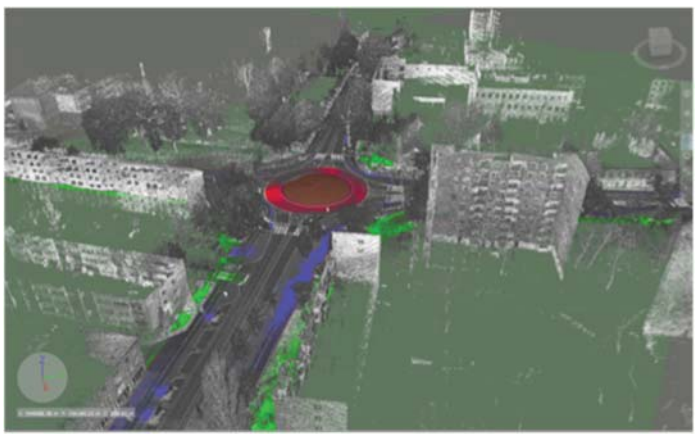

Figure 10. 3D point cloud merged with the digital city model

In order to analyze the captured 3D point cloud we have developed a library for reading and visualization of data from the LiDAR LAS format. The purpose of the development was the need for the analysis and interpretation of the unstructured 3D points. For data visualization the OpenGL technology was used. Since the data in the LAS file is unstructured and without topological connections, it is sufficient to use a point as a graphical primitive for visualization. Figure 11 shows the visualization of the LiDAR data for the roundabout containing few millions of 3D points.

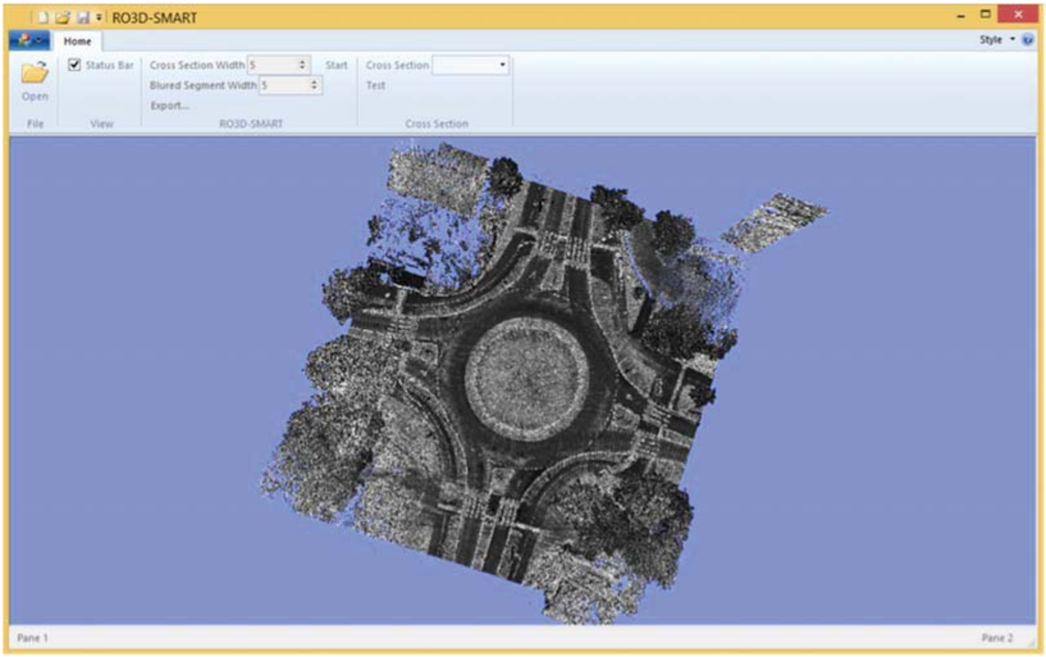

Figure 11. Visualization of the 3D point cloud for the roundabout Pariške komune

In order to use the point cloud as a meaningful source of data, which can also be used for roundabout re-design (i.e. new road segment) with our parametrical assemblies, we have decided to develop a new algorithm for extraction of characteristic boundary lines (breaklines) for the roundabout. Because of the roundabout' circular design the point cloud was sectioned (cut) into segments (cross-sections) that passes through the centerpoint of the roundabout. The Figure 12 shows such a segment where central island and curbs are visible. The width of the segment is equivalent to diameter of the roundabout. Depending on the purpose and type of road, other sectioning approaches are reasonable as well. For a typical road with longitudinal alignment, the most common sectioning approach for its corresponding point cloud would be to create segments perpendicular to the road alignment (cross-sections).

This was followed by analysis of the points from the cross-section, where we tried to identify characteristic points inside cross-section elements. An example of the cross-section on Figure 12 comprises more than 200,000 points. As first all redundant points were removed from the cross-section (duplicated and collinear points). With removal of redundant points the total number of cross-section points decreased almost by half, which greatly reduced algorithms' workload. The remaining set of points was searched for so called dominant points. The points represent edges (turn points) of the characteristic cross-section elements. The dominant points were then exported to a LandXML file. The LandXML format is well supported by existing road design software. We used Autodesk AutoCAD Civil 3D to import the file and then apply our parametrical assemblies on top of it. Figure 13 shows the LandXML file with characteristic points extracted from point cloud. These points specify the minimal set of points, which sufficiently determine a cross-section layout of the roundabout.

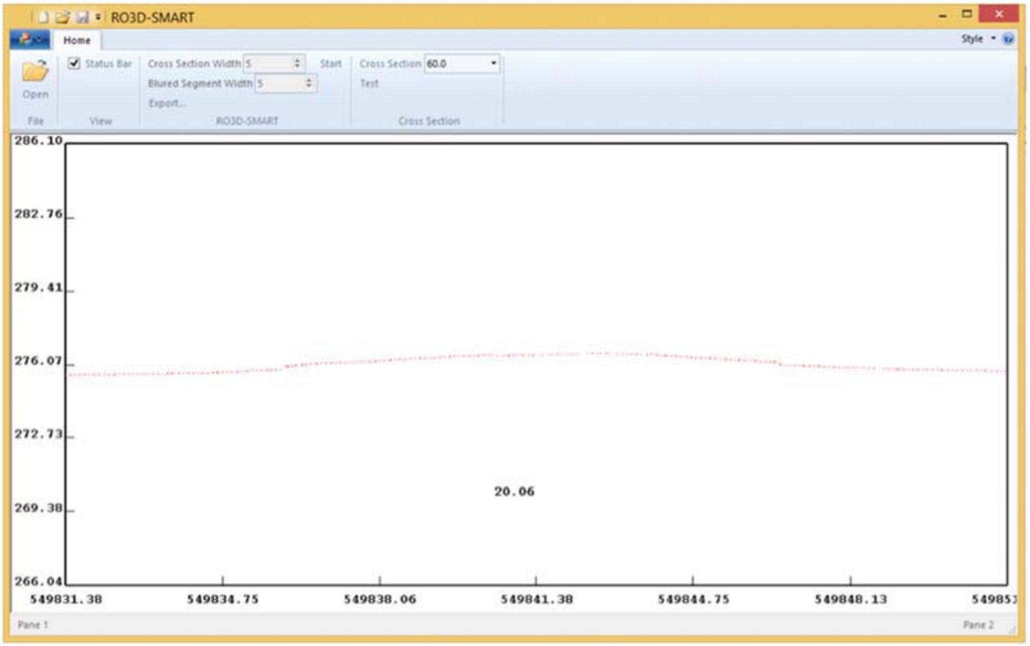

Figure 12. Cross-section view of a roundabout cross-section breakline

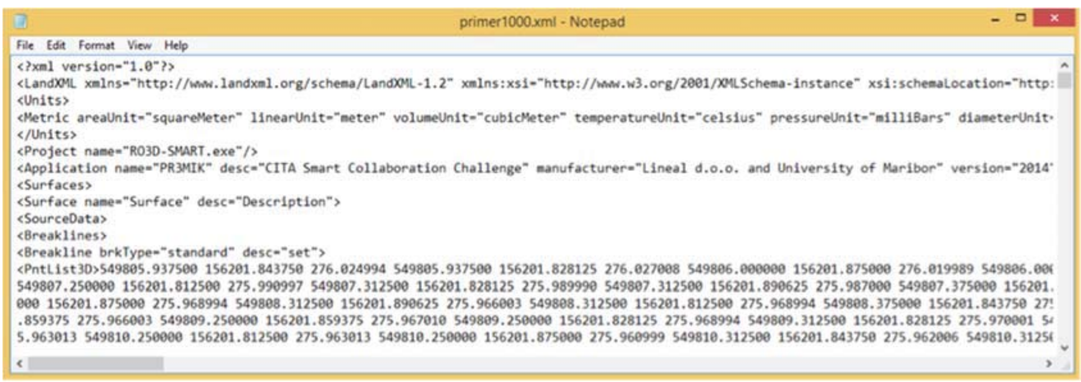

Figure 13. LandXML file with characteristic cross-section points from the 3D point cloud

4 Conclusions

In the paper the research project PR3MIK and its awarded research results were presented. The project undertook the challenge of introducing BIM approach in the field of civil engineering: development of smart parametrical assemblies for 3D-design of roads and re-design and re-construction of roads using data obtained from a cloud of 3D points (LIDAR). In the paper a BIM process using the two results from design of the roundabout to its re-design with a new road segment with the quantified volumes and cost data.

The research is on-going and includes development of further parametrical assemblies for 3D-design of roads and improvement of the algorithm for assessment of the 3D point clouds towards detection of road features with prior and without prior semantic knowledge about road.

5 Acknowledgements

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