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PRODUCTION OF CITY SCALE-MODELS USING LASER ENGRAVING AND 3D PRINTING TECHNIQUES

Abstract: *In the last decade, increased availability of 3d printers and laser cutters has led to development of specialized market for producing models as souvenirs and personalized gifts. One type of such models are city scale-models. The topic of this research deals with the examination of various laser engraving and laser cutting techniques, as well as the application of 3d printing in the production of specialized city scale-models. The aim of the research is to find the most efficient way of realising this project while fulfilling the following criteria: production time, quality of the final result (need for additional processing) and total production costs. Results of this research are successfully fabricated city scale-models and a tabular overview containing data on the basis of which the best approach can be determined, in relation to given predispositions.*

Key words: *Fabrication, city scale-model, digital city model, laser engraving, laser cutting, 3d printing*

1. INTRODUCTION

Architectural models, commonly known as maquettes, have a long history serving as a multifaceted instrument, wielded by architects to visualize, refine and articulate their visions and concepts over the ages. Originally conceived to portray singular structures or fragments thereof, during the period from 17^{th} to 19^{th} century, utility of the maquettes expanded with the ambition to represent entire urban landscapes [1]. Crafting these, as well as maquettes in general, demands special attention to selecting suitable materials, fabrication methods, as well as an appropriate scale, which, among other things, depends on the number of details to be displayed on the model.

Crafting models at scale represents a sophisticated discipline, encompassing the art of constructing tangible replicas of objects while meticulously preserving their proportions and relative dimensions. The scale at which the model will be made depends on the type of the model, as well as its purpose. Among diverse categories of models delineated by the spaces they portray, city models stand as exemplars [2]. These scaled models serve a myriad of purposes, ranging from architectural planning to educational exhibits and beyond. A notable facet of city models lies in their incarnation as three-dimensional urban maps, dotting the landscapes of myriad national parks, entertainment venues, transport hubs and civic precincts [3].

The proliferation of industrial CNC machinery, encompassing laser cutters, milling devices, and 3D printers, alongside the evolutionary strides in computer graphics, has revolutionized the creation of physical models, elevating both precision and intricacy to unprecedented heights. Technological strides have not only broadened the horizons of urban model crafting beyond architectural realms, but have also birthed a distinct market catering to their commercial production needs.

2. FIELD OF RESEARCH

The flourishing market for the production and retail of various, frequently personalized models/maquettes owes its growth to the expanding accessibility of industrial machinery, notably lasers and 3D printers, extending beyond traditional industrial and engineering spheres. Particularly noteworthy within this market are city models. The concept of owning a customized miniature city has spurred the establishment of a specialized market catering to the creation of such maquettes, even for commercial applications.

The subject of this research revolves around discovering an effective method of producing city scale-models conducive to commercial purposes. The study encompasses testing various fabrication approaches, such as laser engraving and 3D printing, to provide an overview of more suitable methods based on the requirements of quality, cost, and time needed for creating such models.

2.1 State of the art

By analyzing the current state of the art, two distinct types of city scale-models have been identified: models produced via 3D printing and models crafted using laser engraving and cutting techniques. The process of manufacturing a city scale-model with 3D printing entails [4]:

- Generation of digital model using several different layers of data obtained by optical radar or satellite images.
- Manual refinement of the fine details of the digital model.
- Additional processing of the physical model after printing is completed.

City scale-models created using laser engraving and cutting techniques typically also consist of multiple layers. However, in this case, layers are manufactured separately using the appropriate laser technique (engraving and/or cutting) followed by a process of assembling all layers to obtain the final physical model. The base layer typically consists of engraved outlines representing buildings, on top of which comes the layer of cut roads. In cases where a water surface exists on the chosen territory, an additional layer, representing such surfaces, is often placed underneath. Challenges with this method include the absence of terrain relief, significant material loss during road layer fabrication, and the time required for assembling all layers.

Both production approaches rely on the presence of either a digital city model for 3D printing or vector data for laser engraving and cutting. The majority of urban area data is typically sourced from specialized *Geographic Information System* (GIS) files, with *OpenStreetMap* (OSM) being one such example. However, the difficulty lies in the methods used to interpret these data geometrically. An automated method for city generation involves utilizing *CADMAPPER*, a website that facilitates the creation of a DXF file containing data specific to the chosen urban area. The issue with this type of model generation is the lack of a comprehensive database for all areas. Typically, only larger and more well-known global territories are covered. Furthermore, generating data for an area exceeding 1km^2, through this source, may incur fees.

2.2 Problem

Analysis of the current state in the field of large-scale city model production has highlighted certain problems and limitations regarding the fabrication process. The primary issue revolves around generating a digital city model. Using conventional modeling techniques in this case wouldn't be practical given the extent of the territory needing to be modeled. Accordingly, finding such a process would ensure coverage of all urban territories, not just globally recognized cities, as is currently the state in the field.

Problems encountered in the process of creating a physical model using 3D printing revolve around the duration of the printing itself, as well as the need for additional post-print processing. Based on this, the question about finding appropriate settings to ensure time efficiency in the printing process without compromising the final quality of the fabricated model arose.

Problems with the application of laser engraving and cutting techniques, as seen in current manufacturing approaches, manifest in the lack of three-dimensionality of fabricated models, as well as unnecessary loss of large amounts of material. Another issue with the application of laser techniques is time, namely, the time spent on engraving and cutting certain parts that contain complex geometric bases, as well as the time required for subsequent assembly of all necessary layers. By considering these issues, the question of the efficiency of using raster engraving technology as a solution to existing problems arose. The application of raster engraving in this case would be based on the use of a depth map of the selected urban area. Generating a depth map implies the existence of a digital model of that area, which again leads to the aforementioned problem.

2.3 Research aim

The aim of this research is to find an efficient method for manufacturing models of large urban areas using laser engraving and 3D printing techniques, ensuring that the resulting product meets the following criteria:

- time required for model preparation
- time required for model fabrication
- quality of the final product
- expenses of model production.

Time required for model preparation refers to the efficiency in collecting data on the selected urban area and interpreting this data into a digital model that would be fabricated. Time required for model fabrication relates to optimizing the time needed for 3D printing and laser processing, aiming to produce a model that requires minimal, ideally no post-processing. Quality criteria applies to the final result of the fabricated model in terms of the need for post-processing. In the case of laser engraving technique, this would relate to the intensity of burnt parts of the model, while in the case of 3D printing technique, it would concern the smoothness level of the obtained surfaces and the occurrence of artifacts. Expenses of model production pertains to the market costs of necessary materials, as well as the costs associated with the use of laser and 3D printer.

The initial hypotheses are:

- It is possible to generate an adequate digital model of the city using available data and tools.
- The time requirement for model production will be better met with the implementation of laser engraving techniques.
- The quality criterion for the model will be better achieved through the use of 3D printing.
- Based on market material prices and machine labor time, it is expected that the laser fabrication approach will be more cost-effective regarding the cost criterion of fabrication.

3. METHODS

The research methodology can be delineated into two primary phases. The initial phase of the study focused on generating the digital model, while the subsequent phase involved the fabrication of the physical model, utilizing laser engraving and 3D printing technologies. The chosen geographical area for this research encompasses a segment of the city of Novi Sad, Serbia, and a portion of the municipality of Petrovaradin, inclusive of a section of the Danube River. The total surface area of the selected territory is approximately 10 square kilometers. Considering the dimensions of the selected area, it was determined that the final physical model should measure 20x20cm, corresponding to a scale of 1:15000.

3.1 Digital model

Three methods for generating the digital model were tested. As the emphasis of this research lies on the utilization of various fabrication techniques, only the chosen approach for generating the 3D model will be further elaborated, including the rationale behind the choice of this specific method.

The chosen methodology relied on the application of visual programming, utilizing the *Grasshopper* add-on in the *Rhinoceros* software. This approach involved retrieving OSM and HGT data from the *OpenStreetMap* and *NASA EarthData* websites, respectively, and using the Elk plugin for *Grasshopper* to visualize the collected data. The *Elk* plugin provides the option to read HGT files through which the relief of the selected area was generated, Figure 1.

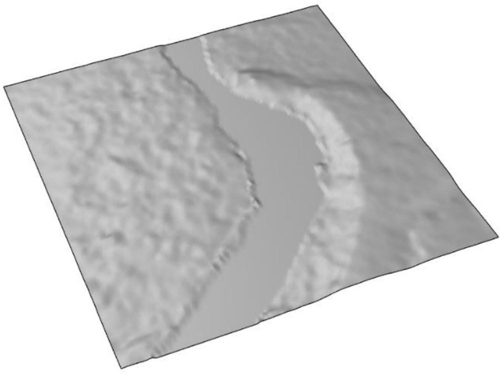

Figure 1 Terrain relief obtained based on HGT data

OSM data was initially represented via lines, which needed to be further processed to generate appropriate geometry (such as buildings, roads, etc.). Since these lines were generated in a planar form, the first step to obtaining the appropriate geometry was projecting the lines onto the terrain surface. In the case of building construction, the projection was performed onto the lowest point of the terrain below them, followed by extrusion to create solids. For roads, thickness was first added to the projected lines, after which this geometry was subtracted from the terrain geometry. The final step involved integrating buildings and terrain with plotted roads into a single model, Figure 2.

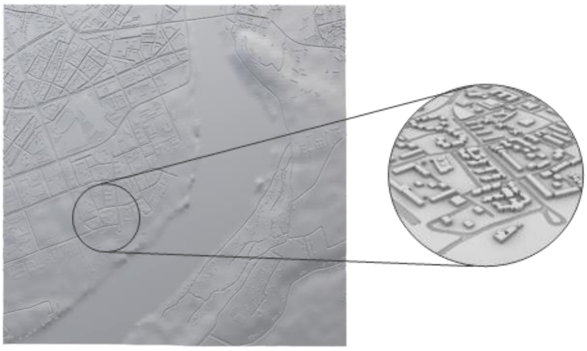

Figure 2 Digital model with enlarged detail

This method of fabrication provides favorable outcomes concerning both the quality of the model grid and the level of detail achievable from the available data. Utilizing the *Grasshopper* add-on allows for the creation of code that automates the entire process, while also enabling quick modifications of the model.

3.2 Laser Engraving

Testing various fabrication approaches using laser engraving was conducted on a smaller model, sized 10x10cm, corresponding to a scale of 1:30000 in the given scenario. These experiments primarily focused on raster engraving, which necessitates having an image for engraving purposes. Consequently, a depth map was derived from the digital model. This testing phase involved testing four different methods of laser engraving. Plywood was selected as the preferred material, although MDF is also available as an alternative. One of the key reasons for choosing plywood over MDF is its ability to generate fewer burn marks during the laser engraving process. Additionally, plywood requires less laser power to achieve the desired engraving depth when compared to MDF. These factors make plywood a more favorable choice for achieving high-quality results in laser engraving applications.

In the first test, the depth map of the final digital relief model was utilized, Figure 3 Left. This map was raster engraved a total of three times. In each pass, the laser focus height parameter was reduced by 1mm. This step is crucial because a certain amount of material is subtracted in each engraving layer, necessitating the adjustment of the laser focus to achieve adequate and precise results. The engraving process lasted 21 minutes. Final results are shown in Figure 3 Right.

Figure 3 Left – Digital model depth map; Right – Physical model after engraving

While this approach resulted in a physical model with terrain relief, it did not meet the desired level of detail in representing the buildings. While the outlines of buildings on the left bank are visible, they are entirely obscured on the right bank. Moreover, the delineation of the river's boundary is not sufficiently clear.

The second tested approach also involved raster engraving of the depth map, but this time a model without relief, i.e., a flat terrain model, was used. The flat terrain model was obtained by applying the previously described modeling method, where roads and buildings remained on a flat plane and were not projected onto the terrain, Figure 4 Left. The depth map of such a model was engraved in 4 passes, however, even after 4 passes, the roads and streets were not noticeable. As in the previous case, in each pass, the laser focus parameter was reduced by 1mm. The engraving process lasted 28 minutes. Final results are shown in Figure 4 Right.

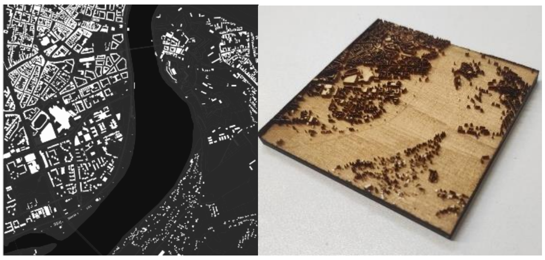

Figure 4 Left – Digital model depth map; Right – Physical model after engraving

The next approach involved a combination of vector and raster engraving. The idea was to first engrave the layer of buildings using raster engraving, Figure 5 Left, followed by vector engraving to outline the roads and river course, Figure 5 Right.

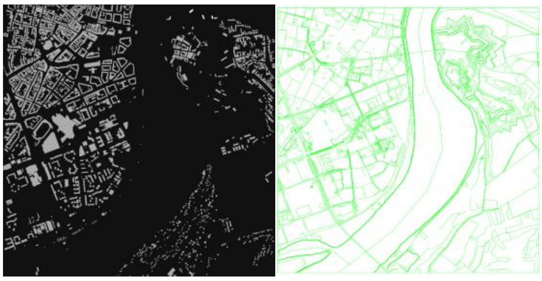

Figure 5 Left – Depth map used for raster engraving; Right – Vector layer used for vector engraving

This approach proved to be unsuccessful both in terms of visual results, Figure 6, and production time. The total engraving time was 31 minutes.

Figure 6 Results of the third laser fabrication approach

The new idea was to separate all details into individual layers, with each layer being raster engraved in a single pass. Accordingly, in the fourth approach, the depth map with flat terrain was divided into three maps - one showing buildings, and the other two showing streets and the river, Figure 7. In the case of raster engraving, the laser will have the highest intensity on the darkest parts of the image. Based on this fact, the idea was for the layer containing the buildings to be placed on a dark background, theoretically resulting in the appropriate height of the buildings in one pass, while the layers of streets and river would be placed on a light background to avoid the risk of damaging the edges of the already engraved buildings.

Figure 7 Left – Buildings layer; Middle – Streets layer; Right – River layer

Each layer was engraved in a single pass. First, the buildings were engraved, followed by the streets, and finally the river. The engraving process lasted 21 minutes. This method provided the opportunity to shorten the production time by merging the layers of streets and river into one. The visual results in both cases, whether using three layers or merging the layers of roads and river, were identical, Figure 8, while the engraving time was reduced by 7 minutes.

Figure 8 Results of the fourth laser fabrication approach

Since this approach provided a satisfactory level of detail, did not require additional refinement of the resulting physical model, and yielded the best results in terms of fabrication time, it was adopted as the most efficient. It was then applied in the process of creating the final model sized 20x20cm. The engraving time per layer at this dimension was 12 minutes, resulting in a total fabrication time of 24 minutes.

3.3 3D Printing

Testing the 3D printing technique was conducted on a sample sized 5x5cm, based on a digital model sized 20x20cm. In the 3D printing process, PLA filament[1] was used. PLA is biodegradable and more environmentally friendly. PLA tends to have less shrinking during printing, resulting in more consistent and reliable prints and is generally easier to print with due to its lower printing temperature and reduced tendency to clog the printer nozzle.

Testing the application of 3D printing in this research primarily involved testing the parameters that need to be adjusted before printing, such as print speed, infill pattern, and layer thickness. In this part of the research, variations of the model obtained by the mentioned

[1] https://www.3drepublika.com/proizvodi/pla-3d-republika/

modeling method were used. These variations included different ways of representing roads - model featuring embossed roads and model featuring debossed roads, and one variation of a model without relief, Figure 9.

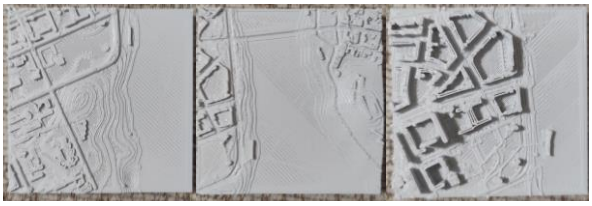

Figure 9 Left – Embossed roads; Middle – Debossed roads; Right – No relief

The layer thickness parameter was set to 0.2mm, and the printer movement speed was set to 50mm/s. The model without relief yielded the poorest visual results. Models with relief visually provided better results, as expected, since such models offer a more detailed representation of the actual terrain. There were no gaps or traces of nozzle movement in the models with relief, indicating a high-quality digital model and settings. The model with embossed somewhat lost its three-dimensional effect because the heights of the buildings and roads were approximately equal, while the model with debossed roads provided the best results in terms of proportions. As a result, the subsequent test aimed to assess the achievable surface smoothness level of the model with debossed roads, prompting the adjustment of the layer thickness parameter to 0.06mm. The printing results are shown in Figure 10.

Figure 10 Printing results with the 0.06mm layer thickness

Although this testing produced the best results in terms of the quality of the final model, printing the final model with such settings would've taken 2 days and 4 hours. For this reason, the decision was made to print the final model using the settings used in the first test, with a layer thickness of 0.2mm. With these settings, the printing time for the final model of the city, sized 20x20cm, was 20 hours and 20 minutes, Figure 11.

Figure 11 Final model with the 0.2mm layer thickness

6. RESULTS

The utilization of visual programming through the *Grasshopper* plugin in *Rhinoceros* software has emerged as an effective means for generating the necessary digital model. Its benefits include the capacity for swift and simple adjustments to the model (such as representing streets, roads, and buildings), as well as the creation of relief. Additionally, it streamlines the time and costs involved in generating the required elements, leveraging readily available data. In testing laser engraving methods, four approaches were experimented with: three using raster engraving and one combining raster and vector engraving. Results indicated that the most effective method involved raster engraving of various city layers, proving superior in both production time and final result quality.

Tabular overview of tested approaches and fabrication time is provided in Table 1. Each test was conducted on a sample size 10x10cm.

Table 1

Tabular summary of the results – Laser engraving

Model	Data type - approach	Time
With relief	Raster – 1 layer, 3 passes	21 min
No relief	Raster – 1 layer, 4 passes	28 min
No relief	Raster + vector – 1 pass each	31 min
No relief	Raster – 3 layers, 1 pass	21 min
No relief	Raster – 2 layers, 1 pass	14 min

Testing related to 3D printing revealed potential issues with digital models and identified printing settings that would satisfy both the criteria of production time and quality in terms of detail level. The most effective approach in terms of laser engraving and 3D printing was applied to produce physical models sized 20x20cm, at a scale of 1:15000, Figures 12 and 13.

Figure 12 Final model at 1:15000 scale – Laser engraved

Figure 13 Final model at 1:15000 scale - 3D printed

The tabular overview of fabrication time, material consumption, and total costs for the finally chosen approaches and models is provided in Table 2.

Table 2

Tabular summary of the results – Final models

Model	Technique	Time	Material	Expenses
No relief	Laser engraving	24 min	20x20cm plywood	~ 10 e
With relief	3D printing - final settings	20h 20m	150g PLA filament	~ 30 e
	3D printing - fine settings	2 days 4h	158g PLA filament	~ 80 e

7. CONCLUSION AND FUTURE RESEARCH

Within the market of producing large urban segments as models, opportunities for their efficient fabrication have emerged. Fabrication of such models involves generating a digital model and crafting a physical model using CNC machines such as lasers and 3D printers. This research tested multiple approaches to such fabrication, employing various modeling techniques to obtain the digital model and utilizing laser engraving and 3D printing technologies to create the physical model. Based on defined criteria covering model preparation time, model fabrication time, final model quality, and production costs, the result of this research is the fabrication of a model representing a larger urban area of the territory of the city of Novi Sad, at a scale of 1:15000.

Regarding the criterion of model preparation time, the most efficient method for obtaining the digital model of the city was found to be the use of visual programming with the *Grasshopper* plugin in *Rhinoceros* software. The advantages of this approach are reflected not only in the time required to generate the digital model but also in the level of detail that this method can provide, thereby satisfying the criterion of digital model quality.

Regarding the criterion of model fabrication time, the initial hypothesis that the time criterion would be better satisfied with the use of laser engraving techniques proved to be correct. However, even in the case of 3D printing, it was shown that it is possible to optimize the fabrication time by using appropriate parameters, ensuring that the quality of the final model is not compromised.

Concerning the quality criterion, it was demonstrated that using 3D printing techniques can achieve a higher level of detail, including terrain relief. Testing parameters such as layer thickness and printing speed led to the conclusion that the quality achievable with the finest settings is not as crucial as the printing time, which directly impacts the cost of fabrication.

Although it was confirmed that the laser fabrication approach is more cost-effective in terms of fabrication costs, suitable adjustments were also found for 3D printing, minimizing the fabrication costs using this technique.

Future research would focus on further commercializing this process and would involve investigating the local market's interest in such a product. This would require developing a cost-effective method for mass production of these models. One of the planned approaches is to create molds, particularly for models made using 3D printing techniques, while fabrication using laser engraving would involve optimizing production to reduce laser working time, making the process more cost-effective. Optimization of production to reduce laser working time would primarily involve manipulating the intensity of colors in the depth map to find the optimal grayscale values for each layer, allowing the same results to be achieved using only one map. With such optimization, production time would be halved, directly reducing production costs and increasing profitability in mass production.

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