

MULTICOLOUR 3D-PRINTED GEOVISUALISATION

MASTER'S THESIS

submitted in partial fulfilment of the requirements for the degree
of

Master of Science (MSc)

**PARIS-LODRON UNIVERSITY SALZBURG
(PLUS)**

Faculty of Digital and Analytical Sciences

Department of Geoinformatics

and

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With the support of Erasmus+ programme of the European Union. This Master's Thesis has been developed in the framework of the Erasmus Mundus Joint Master Degree (EMJMD) "Copernicus Master in Digital Earth", jointly coordinated by Paris-Lodron University Salzburg, Department of Geoinformatics, Austria together with University of South Brittany, Computer Science Department, France and Palacký University Olomouc, Department of Geoinformatics, Czech Republic.

ANNOTATION

In the dynamic intersection of Geoinformatics and 3D printing, the exploration of multicolour 3D geovisualisations emerges as a crucial area of research. This diploma thesis aimed to investigate and evaluate the potential for creating multicolour 3D geovisualisations using Fused Filament Fabrication type 3D printers and associated tools. To achieve this aim, the objectives included the preparation of ten models of varying complexity to test the capabilities of the available multicolour printing equipment in the 3D Laboratory of the Department of Geoinformatics at Palacký University Olomouc, the development and optimisation of printing parameters for achieving high-quality prints, and the creation of a comprehensive multicolour 3D printing booklet for knowledge dissemination within the department. Additionally, the study aimed to assess the environmental impact of multicolour 3D printing, particularly focusing on waste material. The data used to create the models in this research was acquired from the Copernicus Land Monitoring Service, OpenStreetMap, ARCDATA PRAHA and other sources. The data was processed using ArcGIS Pro and QGIS and then 3D modelling was carried out in primarily in SketchUp. Other tools such as 3D Builder and Autodesk Netfabb were used for editing the models to make them ready for printing. The models were configured and sliced in PrusaSlicer, Canvas and Bambu Studio to create the G-code for printing. The models were printed using the Prusa i3 MK3S, Palette 3 Pro, Bambu P1S, Bambu AMS and Prusa XL. Post-processing steps were carried out to refine the final products. User testing was conducted to gain valuable feedback and assess the quality of the models. The results of which were critically reviewed and implemented where possible. Adobe InDesign and other Creative Cloud tools were used to design the booklet documenting the key steps in the research. The final output of the diploma thesis included 14 multicolour 3D geovisualisations and a corresponding booklet documenting the key insights gained throughout the research. Based on the equipment tested, the Prusa XL was the most efficient at producing the models, however, the cost of the printer may be prohibitive. The use of a multi-material add-on to a single extruder printer provides a good balance between price and functionality, with a significant increase in waste and print time. However, this option offers the best value and is more likely to be adopted by a wider audience.

KEYWORDS

Multicolour 3D Printing, 3D Modelling, Fused Filament Fabrication, 3D Maps, Terrain Models, City Models

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This thesis has been composed by *Jevaughn Henry* the Erasmus Mundus Joint Master's Degree Program in Copernicus Master in Digital Earth for the academic years 2022/2023 and 2023/2024 at the Department of Geoinformatics, Faculty of Digital and Analytical Sciences, Paris Lodron University Salzburg, and Department of Geoinformatics, Faculty of Science, Palacký University Olomouc.

Hereby, I declare that this piece of work is entirely my own, the references cited have been acknowledged and the thesis has not been previously submitted to the fulfilment of the higher degree.

20 May 2024, Olomouc

A handwritten signature in black ink, appearing to be 'J. Henry', written in a cursive style.

Jevaughn Henry

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ASSIGNMENT OF DIPLOMA THESIS

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Theses guidelines

The thesis aim is to explore, examine and evaluate possibilities of multi-colour 3D geovisualisations using FFF-type 3D printers and compatible tools available in the 3D laboratory of the Department of Geoinformatics. The student will examine multiple approaches of combining multiple filament colours and present them on 10 case studies including terrain models, thematic maps, urban models etc. Special focus should be given to designing complex models of more than two colours distributed both vertically and horizontally. COPERNICUS data should be used for at least one of the models.

The student will attach all created datasets and thesis outputs in digital form. The student will also create a website about the thesis following the rules available on the department's website and a poster about the diploma thesis in A2 format. The student will submit the entire text (text, attachments, poster, outputs, input and output data) in digital form.

Extent of work report: **max. 50 pages**
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- [2] Horowitz, Seth & Schultz, Peter. (2014). Printing Space: Using 3D Printing of Digital Terrain Models in Geosciences Education and Research. Journal of Geoscience Education. 62. 10.5408/13-031.1. 152-169.
- [3] Wang, Zizhao & Shen, Hongyao & Wu, Senyang & Jianzhong, Fu. (2020). Colourful fused filament fabrication method based on transitioning waste infilling technology with a colour surface model. Rapid Prototyping Journal. ahead-of-print. 10.1108/RPJ-04-2020-0072.
- [4] Zwirowicz-Rutkowska, Agnieszka & Mościcka, Albina & Araszkievicz, Andrzej & Wabiński, Jakub & Kiliszek, Damian. (2023). Tactile maps of historical gardens: method of content selection. Heritage Science. 11. 45. 10.1186/s40494-023-00886-8.
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CONTENT

LIST OF ABBREVIATIONS.....	9
INTRODUCTION.....	10
1 OBJECTIVES.....	11
2 STATE OF ART.....	12
2.1 History of 3D Printing.....	12
2.2 3D Printing Methods.....	13
2.2.1 Fused Filament Fabrication.....	14
2.2.2 Advantages and Disadvantages of FFF.....	15
2.3 FFF Multicolour 3D Printing Methods.....	16
2.3.1 Pause and Swap.....	16
2.3.2 Dual Extruder.....	17
2.3.3 Single Extruder with Multi-Material Add-on.....	18
2.3.4 Tool Changer.....	19
2.4 Geospatial 3D Printing.....	19
3 METHODOLOGY.....	23
4 DESIGN OF 3D MODELS.....	28
4.1 Data Collection.....	28
4.2 Data Processing and Model Creation.....	32
4.2.1 Modelling using GIS Software.....	32
4.2.2 Modelling using SketchUp.....	35
4.2.3 Paper Maps to 3D-Printable Maps.....	36
4.2.4 Test Models.....	37
5 MULTICOLOUR 3D PRINTING.....	39
5.1 Model and Printer Configuration.....	39
5.2 Printing the Models.....	46
5.2.1 Safety Measures.....	48
5.2.2 Post-processing Steps.....	49
5.2.3 Printing Challenges.....	49
6 USER TESTING.....	50
7 BOOKLET CREATION.....	53
8 RESULTS.....	55
8.1 Multicolour Models.....	55
8.2 Multicolour 3D Printing Booklet.....	57
8.3 Waste Management.....	57
8.4 Results of User Testing.....	58
9 DISCUSSION.....	60
10 CONCLUSION.....	62
REFERENCES AND INFORMATION SOURCES	
ATTACHMENTS	

LIST OF ABBREVIATIONS

Abbreviation	Meaning
3D	Three-dimensional
3MF	3D Manufacturing Format
CAD	Computer-aided Design
DEM	Digital Elevation Model
DSM	Digital Surface Model
DXF	Drawing Exchange Format
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
KGI	Department of Geoinformatics at Palacký University Olomouc
MSRP	Manufacturer's Suggested Retail Price
PLA	Polylactic Acid
STL	Stereolithography
SVG	Scalable Vector Graphics
VOC	Volatile Organic Compound

INTRODUCTION

In an era of technological advancement and carrying a “computer” in your pocket, 3D printing still awes the general onlooker. The 3D printing landscape has continued to evolve since its introduction in the 1980s and more recent popularisation in the 2010s. Innovation has been at the core of 3D printing, evidenced by its roots in the prototyping industry. The technology, however, has not been limited to a single industry but has had cross-cutting uses in healthcare, automotive, manufacturing and many more. One of the notable areas where the technology has been applied is the representation of geospatial information, a field that has traditionally been confined to paper and digital maps. Researchers over the years have applied 3D printing technologies to a variety of geospatial-related fields such as cartography, geomorphology, education, urban planning and archaeology (Brus & Barviř, 2015; Horowitz & Schultz, 2014; Santamaría-Peña et al., 2023; Wabiński & Kuzma, 2017; Zwirowicz-Rutkowska et al., 2023). However, the utilisation of 3D printing in the geospatial industry remains relatively low.

One of the many innovations in 3D printing has been printing models with multiple colours. This advancement has trickled down to consumer-grade 3D printers that are more accessible to the public. Using Fused Filament Fabrication, the most popular of the 3D printing technologies, multicolour printing is achievable at a relatively low cost of entry. Virtual 3D models benefit from being interactive and easily customisable. Whereas physical 3D printed models are static, and, in the past, the majority have been restricted to a single colour or a few colours distributed vertically. Physical 3D models have been proven to aid in making geospatial data more accessible, understandable and engaging (Heidkamp & Slomba, 2017). Therefore, having colour distributed horizontally and vertically is an important factor in achieving greater utilisation of 3D models as colour is an important graphic variable in geovisualisation. Multicolour 3D printing using low-cost FFF technology enhances the potential geospatial applications of 3D printing.

The application of multicolour FFF printing to create complex geovisualisations is an understudied area as in most cases, equipment availability is a challenge. The Department of Geoinformatics at Palacký University Olomouc is unique in that it has a 3D Lab with existing and new equipment that can take full advantage of multicolour FFF printing. This research is exploratory and seeks to test the potential of the cutting-edge technology and equipment available in the lab. Furthermore, the diploma thesis was designed to blend Geoinformatics, Cartography and Additive Manufacturing to examine and evaluate the possibilities inherent in multicolour 3D printing.

Beyond the technical aspects, this thesis explores the opportunity for making more maps inclusive and accessible. Users have traditionally interacted with maps on paper and a screen; hence map design needs to be adjusted for tactile usage. By engaging with end-users directly, the study aims to ensure that the final models exceed the needs and expectations of its diverse user base. The exploration of the possibilities to create multicolour 3D-printed geovisualisations will facilitate knowledge dissemination within the department and serve as a guide for 3D printing enthusiasts.

1 OBJECTIVES

The overarching aim of the diploma thesis is to explore, examine and evaluate the possibilities of multicolour 3D geovisualisations, primarily focused on Fused Filament Fabrication (FFF)-type 3D printers and compatible tools available in the 3D Laboratory of the Department of Geoinformatics (KGI) at Palacký University Olomouc (UPOL). The study will examine various approaches to combining filament colours in complex models of more than two colours distributed horizontally and vertically. To achieve the aim, the specific sub-goals of the study are:

- To prepare 10 models (with varying complexity) to test the available multicolour printing equipment.
- To develop and optimise printing parameters and processes for achieving high-quality FFF multicolour prints.
- To create a multicolour 3D printing booklet for use in the department showcasing the printing results and lessons learnt.
- To assess the environmental impact of multicolour 3D printing (focused on waste material).

By creating impactful multicolour 3D geovisualisations, the results of the work will have two beneficial categories. Firstly, the models created will have the potential to be applied in areas such as education (to teach complex topics), urban planning, and use in the visually impaired community. Secondly, the methods tested and utilised can be reproduced by other researchers or the public to create models for personal or public use.

2 STATE OF ART

This chapter reviews the foundational background of 3D printing to understand its origins and development. The second section looks at the methods of 3D printing with a particular focus on fused filament fabrication, which is the primary technology to be applied in this study. Furthermore, relevant research is evaluated concerning the application of 3D printing in geovisualisation, with special attention to multicolour printing. The end goal of this review is to assess how and to what extent multicolour 3D printing has been used in the geospatial industry and academic research to aid in its future development.

2.1 History of 3D Printing

3D printing is an additive manufacturing technique that has its origin in rapid prototyping. According to the ISO standard, ISO/ASTM 52900:2021, additive manufacturing (AM) is a technology that creates physical objects by the successive addition or deposition of material (International Organization for Standardization, 2021). In that regard, 3D printing uses three-dimensional digital models to build physical objects by the deposition of layers of a material (Bozkurt & Karayel, 2021; Manoj Prabhakar et al., 2021; Ngo et al., 2018). Since its invention, 3D printing has been utilised in industries such as manufacturing, aviation, medicine and the automotive industry (Prince, 2014). Some of the main benefits of this technology include flexible design and customisation, manufacturing of complex structures, minimisation of waste and fast on-demand production (Ngo et al., 2018). These benefits and the gradual increase in access to the technology since its invention have contributed to the popularity of 3D printing in the past years.

The history of 3D printing dates back several decades. In 1945, Murray Leinster described the general concept of 3D printing in his short story, “Things Pass By” (Turney, 2021). Moving ahead to 1983, Charles Hull printed the first 3D-printed part (shown in Figure 1a below) and in 1984 he filed a patent for an ‘Apparatus for Production of Three-Dimensional Objects by Stereolithography’. Hull also created the stereolithography (STL) file format, digital slicing and infill methods that remain in use in modern 3D printing. In 1986, Hull co-founded the company, 3D Systems Corporation, and in 1987 the company released the first commercial 3D printer (shown in Figure 1b), the SLA-1 Stereolithography printer (3D Systems, 2017). The printer made it possible to fabricate complex parts in a fraction of the time compared to traditional methods. Even though other researchers and companies had patents describing 3D printing methods, Hull was the inventor of the first commercial 3D printer and was credited with inventing 3D printing (Prince, 2014).



Figure 1 a) First 3D-printed part by Charles Hull. b) First commercial 3D printer, SLA-1.
Source: 3D Systems (2017)

2.2 3D Printing Methods

There are several different methods and materials used in 3D printing. Some of these 3D printing methods include stereolithography (SLA), fused filament fabrication (FFF) or fused deposition modelling (FDM), laminated object manufacturing (LOM), polyjet, selective laser sintering (SLS), selective laser melting (SLM) and electron beam selective melting (EBSM) (Manoj Prabhakar et al., 2021; Prince, 2014). These methods fall under the seven main categories of additive manufacturing, as shown in Figure 2, from the ISO standard, ISO/ASTM 52900:2021. Figure 3 shows a visualisation of how these categories are differentiated by the material used and how the layers are processed. Hence, the desired use case and properties of the model must be considered when selecting the correct printing method. The materials that can be used in 3D printing vary from polymers, ceramics, metals, and composites. Polymers constitute the largest proportion of material that is used at present and historically, it was the first material group to be used for 3D printing. The most frequently used polymers include polylactic acid (PLA), resin, polycarbonates (PC), acrylonitrile butadiene styrene (ABS) and polyamides (Bozkurt & Karayel, 2021).

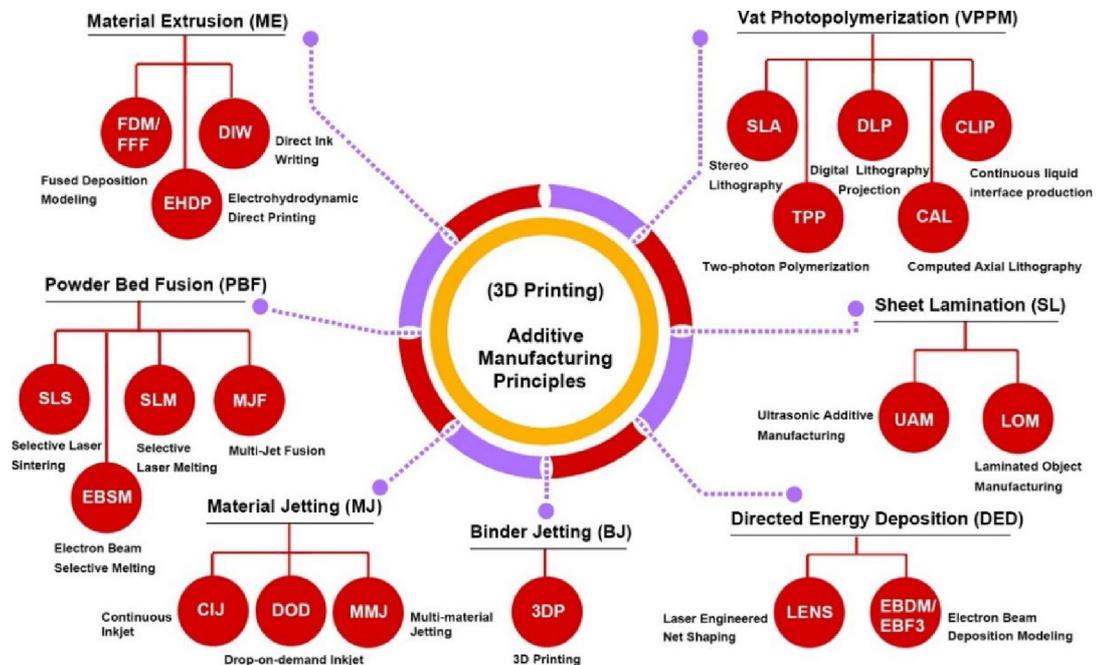


Figure 2 Breakdown of 3D printing methods by ISO categories. Source: Yuan et al. (2021)

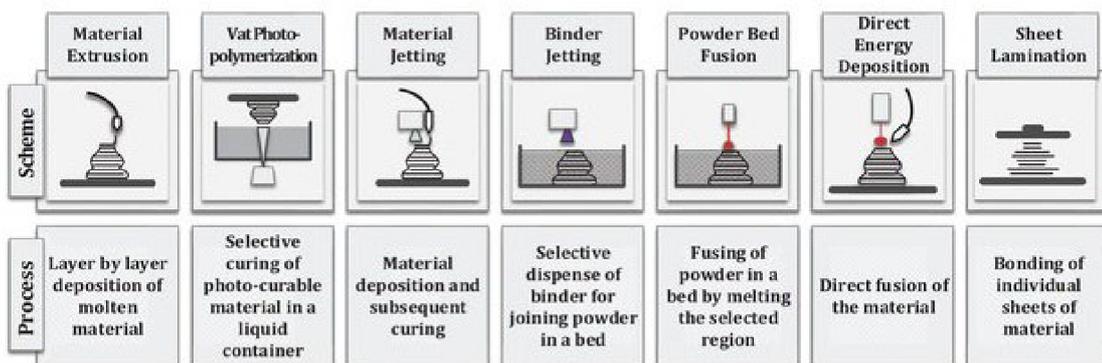


Figure 3 Overview of 3D printing categories showing how the layers are processed. Source: Perrot & Amziane (2019)

2.2.1 Fused Filament Fabrication

Currently, the most popular of the 3D printing methods is FDM or FFF. FDM and FFF both refer to the same method of 3D printing. The FDM technology was developed by S. Scott Crump in 1988 and patented in 1989 (Jiménez et al., 2019). The technology was commercialised by his company, Stratasys Inc., and they marketed their first FDM printer in 1992. Stratasys Inc. also trademarked the abbreviation “FDM”. The term FFF was created by the members of the RepRap project, a network of DIY 3D printer developers and users, to be synonymous with FDM but allow for unrestricted use by the public (Jones et al., 2011).

FFF is a material extrusion system that lays down polymer material to create a physical object. The technology is very versatile and can be used for multi-material and multicolour prints. In the FFF process, a polymer filament is fed into a computer-controlled heated print head. The feed rollers grip the filament and ensure a continuous flow of material into the print head. The material then passes through a barrel which serves as a divider between the hot and the cold parts of the print head to prevent the filament from expanding and getting stuck inside the print head. This part is usually designed as a heat sink with a cooling fan attached (Shaqour et al., 2021). The filament is then heated slightly above its melting point into a semi-molten state as it passes through the heating block and the heated nozzle. The material is finally deposited onto the build plate in successive layers along the extrusion path to form the required object. The technology also allows for the creation of support structures when creating more complex objects. Where supports are needed, the 3D printer deposits a removable material that serves as a frame whose purpose is to give the object a structure upon which to be printed (Griffey, 2014; Shahrubudin et al., 2019). The FFF process and extruder system are shown in Figure 4 below using a two-filament printing setup, with the orange filament being used to print removable support structures.

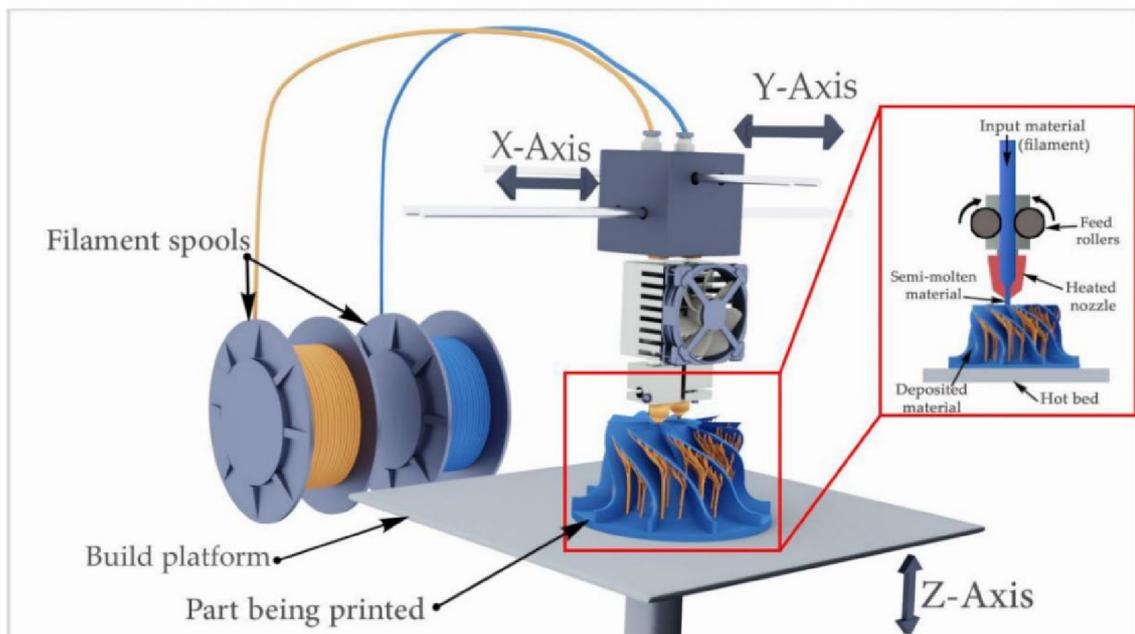


Figure 4: Fused Filament Fabrication (FFF) process. Source: Elkaseer et al. (2020)

The process of FFF printing (or any type of 3D printing) follows a series of four main steps to produce the final printed object. These steps include modelling, slicing, printing, and post-processing (shown in Figure 5 below). The modelling workflow starts with the design of the 3D model using any 3D modelling software such as AutoCAD, SolidWorks, SketchUp or Blender. The model is then exported to a 3D printing file format such as STL or 3MF which are identifiable by the “.stl” and “.3mf” file extensions respectively. The STL file format is the industry standard for 3D printing and stores the surface geometry of a 3D object as a tessellation of triangles (Krishnanand & Taufik, 2021). In the slicing process, the STL or 3MF file is imported into a slicing software such as PrusaSlicer, Ultimaker Cura or Slic3r. In this software, the file is sliced into many layers and the amount of filament needed for the print is calculated. Other parameters such as support structures, layer thickness, infill and build orientation can be configured in the slicing software. After slicing, the software generates a G-code that determines the movement and speed of the extrusion nozzle. The printing step starts by uploading the G-code file to the 3D printer and calibrating the printer. As highlighted in the 3D printing review paper by Gokhare et al. (2017) and many other researchers and professionals, the printing time varies based on the parameters set in the slicing software and the size and complexity of the model. After the printing is completed, post-processing steps can be conducted such as the removal of support structures and smoothing the object by sanding or polishing.

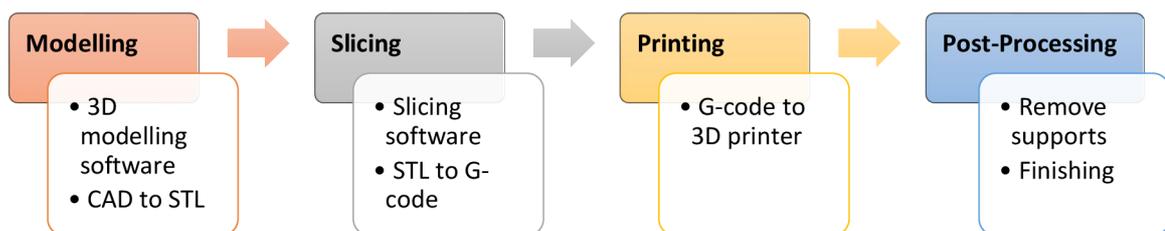


Figure 5 3D printing process.

2.2.2 Advantages and Disadvantages of FFF

FFF 3D printing is widely used for a variety of reasons. The primary advantage is that FFF technology is cost-effective. As noted by 3D printing companies such as Protototal UK (2022), FFF printers can be bought cheaply to start and this affordability has resulted in FFF printers being the most likely option to be found in small businesses, schools and homes. Additionally, replacement parts for FFF printers can be found easily and many companies can service or repair these printers. Another advantage is that FFF offers a flexibility of materials. According to All3DP (2023) and Protototal UK (2022), a wide variety of filaments and thermoplastic materials can be utilised depending on the cost and desired quality. Scalability is another benefit of using FFF technology as these printers can be scaled in size to allow for the creation of larger models. The results of the RepRap project (Jones et al., 2011) highlighted scalability through a self-replicating prototyping machine that could print a significant amount of its parts, therefore allowing a user to create a new 3D printer(s) as needed. Also, according to All3DP (2023), another major advantage is that FFF printing is relatively easy compared to other 3D printing methods. By using a filament such as PLA, a user can learn to 3D print a simple model in a few minutes as the steps are logical and easy to follow. Also, with FFF printing there are fewer steps needed in the finishing process. There is limited cleaning needed for the printed object compared to some 3D printing methods that require compressed air blasting, alcohol baths or curing.

FFF has some disadvantages as with any of the 3D printing methods. According to Kholghi Eshkalak et al. (2020) one of the disadvantages is limited detail as a result of the nozzle size being restricted in most cases to 0.4 mm. The nozzle size limits how detailed specific parts of the model can be. A second disadvantage comes from the layer-by-layer deposition of material that results in a rough surface with lines present where the layers meet. Another disadvantage is that some low-cost FFF printers still require adjustments and tweaking, particularly the levelling of the print bed before each print to achieve high-quality outputs. It is now common that most new printers have built-in sensors that perform the bed levelling automatically, hence reducing the occurrence of this challenge.

2.3 FFF Multicolour 3D Printing Methods

Multicolour 3D printing, sometimes referred to as multi-material 3D printing, uses multiple filaments of varying colours or materials to fabricate an object. 3D printing was restricted to printing in a single colour or single material up to the mid-2000s when advancements in technology saw the launch of the first multi-material 3D printer. The Fab@Home was an open-source 3D printer launched in 2006 by students from Cornell University (Malone & Lipson, 2006). This technology was adopted by the industry and became more widespread in the following years and more consumer-grade printers were produced. In recent times, multicolour 3D printing can be achieved using various methods such as FFF, SLA and material jetting. The pinnacle of colour 3D printing can be seen with high-end industrial printers such as the Stratasys J8 series of 3D printers (shown in Figure 6). These printers can achieve full-colour prints by material jetting, with the capability of using up to 7 materials and producing up to 600,000 colour combinations. However, the high cost of this industrial printer means that FFF technology remains the cheapest method to produce multicolour prints. The main methods of achieving a multicolour print using FFF printers are reviewed below.

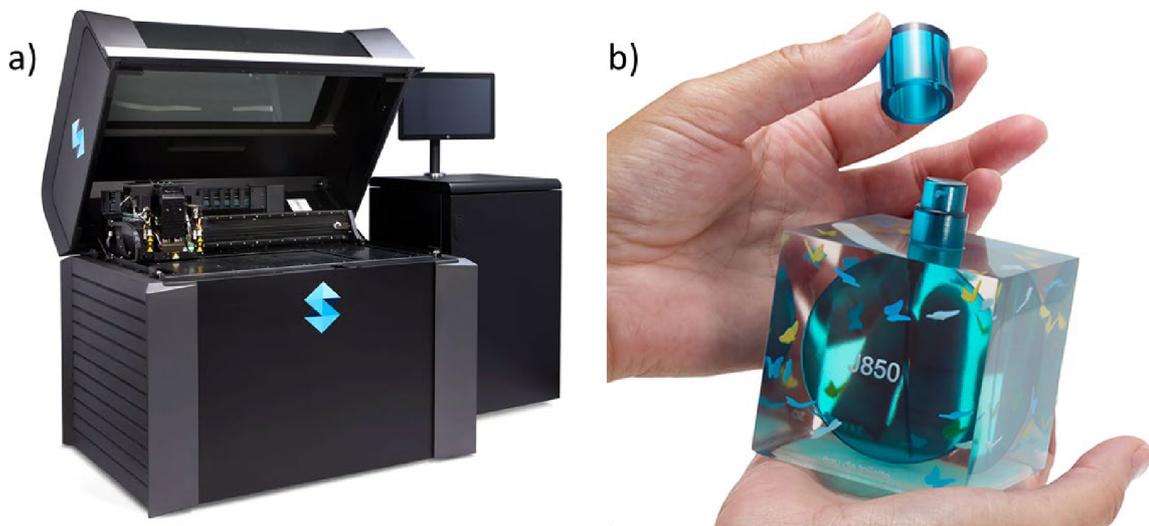


Figure 6: a) Stratasys J850 Polyjet printer. b) Perfume bottle printed using the J850 printer. Source: Stratasys (2024)

2.3.1 Pause and Swap

To achieve a multicolour print using FFF technology, several methods can be used. The easiest method is filament swapping which can be used on any FFF type printer. This process works by manually changing the filament colour at a certain layer height.

The swap is configured in the slicer application through a command (M600) in the G-code script that tells the printer to pause at the end of a layer to allow the change in filament before resuming the print (Hill, 2024). The user is required to purge the print head to clear old filament before resuming the print. Figure 7 below shows a sample object printed using black as the base colour and then orange after the pause and swap of the filament.



Figure 7: Sample object printed using the pause and swap printing method. Source: MikeL via Printables (2022)

2.3.2 Dual Extruder

In this technique of multicolour 3D printing, there are usually two extruders on the same axis with each having a different filament colour. The G-code provides the instructions to switch between extruders based on the required colour. Multiple extruder 3D printers are available from many companies such as Prusa, Bambu, Creality and Snapmaker. In the case of dual extruders like the Snapmaker J1 (shown in Figure 8), it uses an independent dual extruder (IDEX) system that allows each extruder to print independently, and this enables more complex and high-precision printing (Hullette, 2023). IDEX systems allow the two extruders to print at the same time, and this reduces cross-contamination of colours.

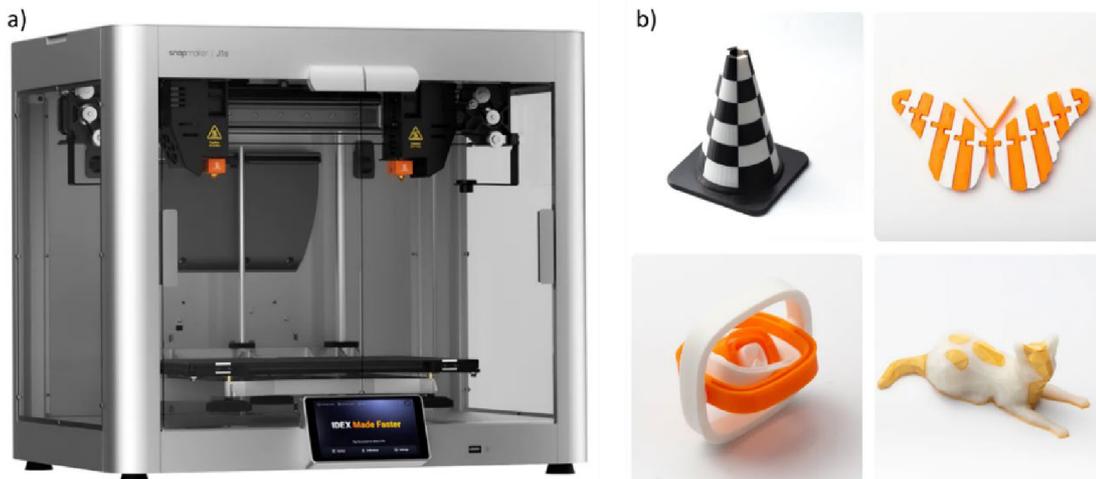


Figure 8: a) Snapmaker J1 dual extruder printer. b) Print samples from the Snapmaker printer. Source: Snapmaker (2024)

2.3.3 Single Extruder with Multi-Material Add-on

This method adds extra functionality to existing single extruder FFF printers. The multi-material add-on allows for the use of additional filaments or materials. The principle behind these add-ons is similar across devices from different manufacturers as they allow for an automatic change to a new filament as is needed by the object being printed (Hullette, 2023). This change can facilitate the use of a new filament colour and avoids the limitation of the Pause and Swap method as one layer height can have multiple colours. One of the main disadvantages of the multi-material add-on is the requirement to purge the extruder of the old filament before depositing the new filament (colour). This results in excess waste and adds time to the print. The wipe/purge tower varies in size and can sometimes be larger than the object being printed (Kelly, 2023). Examples of these add-on devices include the Prusa Multi-Material Upgrade (MMU), Bambu Automated Material System (AMS) and the Mosaic Palette. Figure 9 shows these devices and their attachment to existing FFF printers.



Figure 9: a) Prusa MMU3. b) Bambu AMS. c) Mosaic Palette 3 Pro. Source: Bambu Lab, (2024); Mosaic Manufacturing, (2024); Prusa Research, (2024a)

The Prusa MMU and Bambu AMS work similarly as they collect all the filament simultaneously and swap as needed by the single extruder to print the model. The main difference between the two is that the MMU produces a purge block with the waste material while the AMS expels its waste as small threads of the old and new filament (Kelly, 2023). The Mosaic Palette works differently from the other two as it splices the filaments instead of swapping them. The Palette cuts the filament and splices it together by heating it and then feeds a single, continuous length of filament to the printer (Hullette, 2023). To maintain a high-quality print, the extruder purges filament between colour transitions and this waste material is placed in a wipe/purge tower. However, Mosaic has introduced a few strategies to reduce waste material. These include reducing the transition length, using the waste material as infill in the model and printing multiple models at the same time (Mosaic Manufacturing, 2023). Similar settings are available for the Bambu and Prusa devices. It should be noted that when a wipe/purge tower is

present, this reduces the printable area as the tower needs a dedicated amount of space on the print bed. The size of the wipe tower can be significantly larger than the model itself, hence limiting the potential projects that can be undertaken with these devices.

2.3.4 Tool Changer

Multimaterial 3D printing methods are very suitable for producing multicolour prints. Another example of this occurs with 3D printers with a tool changer. The tool changer allows for the use of independent hot ends/extruders that can utilise filaments of the same or a different material. The hot ends can be swapped during the print and in most cases, tool changers are placed in large-format printers that offer more build volume (Kelly, 2023). Novel tool changers have been explored by researchers such as Conrad et al. (2021) and Laureto and Pearce (2017) as they have placed multiple hot ends next to each other to prototype parts. Tool changers are seen as a more advanced or complex technology and are not as widely available today. Prusa Research offers this technology in the Prusa XL 3D printer, with the ability to use up to 5 hot ends (shown in Figure 10). With 5 hot ends, it is possible to use up to 5 colours to produce multicolour prints. The Prusa XL also has a large build volume of 360×360×360 mm which further enhances its printing capabilities.

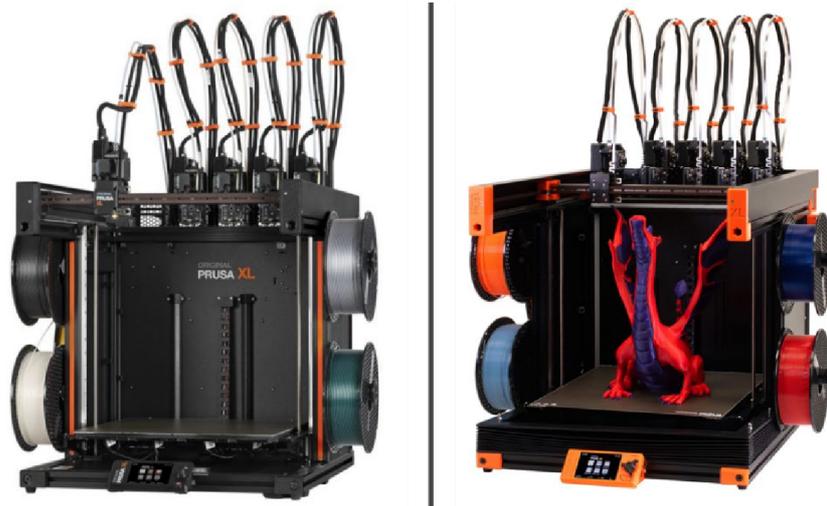


Figure 10: Prusa XL 3D printer with 5 hot ends/extruders and a tool changer. Source: Prusa Research (2024b)

2.4 Geospatial 3D Printing

Geospatial data is most often conveyed two-dimensionally via printed maps or digital maps on a screen. Representing data three-dimensionally has its set of challenges and the first thought when doing so is to create an interactive digital interface, for example, a web application showing 3D buildings in a city or the terrain viewer in Google Earth. However, reading and properly analysing these maps correctly, whether 2D or digital 3D, oftentimes require a specialised skillset. Research by Heidkamp & Slomba (2017) revealed that creating tactile/physical 3D maps—or, as they put it, "geospatial sculptures"—make geospatial data more approachable, offers sensory experiences, materialises the underlying information, and encourages audience engagement. Examples of tactile maps are present in many European cities such as Zagreb, Ljubljana, Zurich, Salzburg, and Olomouc as bronze city models (shown in Figure 11) that can be used by both visually impaired and sighted people.



Figure 11 Bronze city models in (L-R) Zagreb, Ljubljana, Zurich, Salzburg, and Olomouc. Source: Merdjanova, (2018); Polák, (2013); TSG Tourismus Salzburg GmbH, (2024); Zagrebist, (2015); Zürich Tourismus, (2024)

Research examining the use of physical 3D models created using rapid prototyping technologies has been explored by researchers such as Wolf-Dieter Rase (2002, 2012). In his 2002 research, models were prepared of cities, landscapes with relief and conceptual surfaces, which were then 3D printed in multicolour using a Z Corporation powder and binder jet 3D printer. Figure 12 below shows a smooth surface and 3D choropleth map which were some of the printed results from Rase's research. The Z Corp. 3D printers were quite expensive, with a suggested retail price of \$49,900 in the United States. However, these were the only devices available on the market that could produce multicolour parts. This made the Z Corporation printers ideal for cartographic products as colour is an essential graphic variable in geovisualisation.

It is important to note that there are significant variations in terms of time, expense, and environmental effects when comparing digital and physical 3D models in geospatial applications and other areas such as architecture. According to the 3D rendering company RealSpace 3D (2023), physical models are constrained by their rigidity and resource-intensiveness, even if they provide concrete and powerful presentation forms. Despite being less haptic, digital 3D models are incredibly flexible and effective. Whether a physical or a digital 3D model is needed depends on the audience and the goal of the geovisualisation.

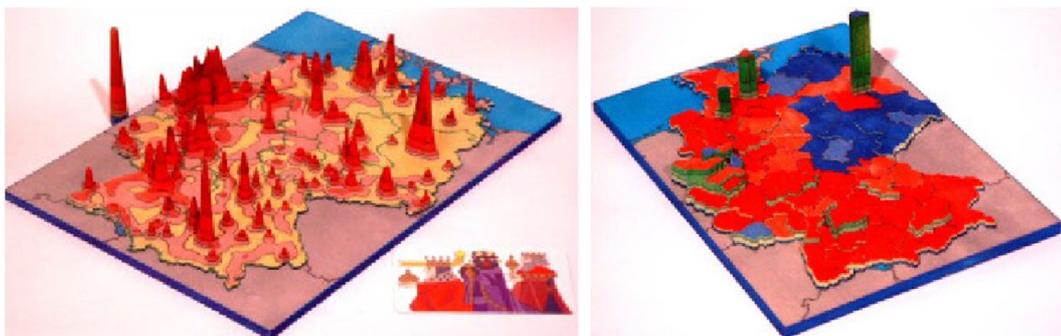


Figure 12 A smooth surface population density model and 3D choropleth map of Germany printed with a Z Corporation 3D printer. Source: Rase (2002)

Visualisation of **topographic models** is one of the popular applications of 3D printing. Elevation data is widely available at both a global and local scale from sources such as Copernicus, NASA, and local governments. Research has shown that elevation is more easily understood when using 3D models, compared to conventional 2D contour maps as the cognitive burden on the user is reduced (Hasiuk & Harding, 2016). By being able to use your hands to interact with a **3D terrain model**, an additional layer of interactivity is added, and this helps make sense of the geospatial data. 3D terrain models are durable and can be utilised in the classroom as a teaching aid to bolster paper maps. Hasiuk and Harding (2016) documented a prototype of a web tool called TouchTerrain that could be used for creating digital 3D models ready for printing. TouchTerrain was further developed as an open-source web application, making it easier to create 3D-printable terrain models, which benefits scientists, students, and other stakeholders (Hasiuk et al., 2017). Several other researchers such as Horowitz and Schultz (2014), Cockrell and Petcovic (2022) and Santamaría-Peña et al. (2023) have looked at the application and benefits of 3D-printed terrain models in geoscience education and research. The key takeaway from these studies is that 3D-printed terrain models possess great potential as a teaching and learning resource that can be customised for various applications in earth science classrooms. Additionally, the models enable the development of an accessible physical object library for individuals with visual impairments. Topographic models are one area where 3D-printed models will continue to be used to enhance the learning experience of students.

3D printing has been applied in the creation of **tactile maps** for visually impaired individuals. Creating high-quality tactile maps is still a demanding task as it first requires a sighted individual to design and print the maps. 3D printing technology is not widely accessible in all cities and regions of the world, and this limits the prospective benefits that the technology could bring to the visually impaired. However, as 3D printing becomes more widespread, this technology has the potential to greatly aid the visually impaired in learning new concepts. Research has shown that 3D-printed models enable the use of more easily understood icons, allow for relative heights to be better understood, improve both space and text memorisation, aid in spatial orientation and understanding spatial relationships (Giraud et al., 2017; Gual et al., 2014; Holloway et al., 2018; Rener, 2017; Taylor et al., 2016; Voženílek & Vondráková, 2014).

Advancements in multimaterial printing have seen the combination of 3D-printed models and mobile devices to add extra functionality to models. The tactile maps serve as an interactive overlay, using conductive filament to provide the underlying touchscreen device with input (Barvir et al., 2023; Barvř et al., 2019; Taylor et al., 2016). The resulting combination allows the user to dynamically interact with the map and gain additional information from vibrations and audio descriptions. 3D-printed tactile maps can improve the learning potential of the visually impaired (Auricchio et al., 2017; Rener, 2017) and those without visual impairment (Cockrell & Petcovic, 2022; Horowitz & Schultz, 2014).

Other geovisualisations that have been produced using 3D printing include the documenting of cultural sites and historical monuments (Hevko et al., 2020; Themistocleous et al., 2015; Zwirowicz-Rutkowska et al., 2023), reconstruction of historical landscapes (Pacina et al., 2022), and design in architecture and urban planning (Ghawana & Zlatanova, 2013; Kim et al., 2021). The convergence of 3D printing and geospatial data is not without its set of challenges. Some of these include the large variety of geospatial data formats that need to be translated into a 3D-printable format such as STL, loss of resolution due to physical limitations of printers and considerations about

projection from 2D to 3D (Ghawana & Zlatanova, 2013). The use of affordable FFF printers for geovisualisation also has some limitations including the materials, the number of colours and the size of the print volume (Allahverdi et al., 2018). Even though the goal of this current study is to investigate the improved use of multiple colours, the cost of adding more colours to a model using printer add-ons can become significant. Also, careful consideration must be given to the features displayed and the use of colours as the technologies used in this study are limited to four to eight colours. These are challenges inherent in using FFF printer add-ons and the ideal solution would be the use of full-colour 3D printers that uses a different method of 3D printing such as material jetting.

Even though there have been diverse applications of 3D printing to showcase geospatial data, there is still limited use of multicolour models that are more complex, meaning the colour variations occur at the same layer height. Research conducted by Brus et al. (2023) highlighted the application of the pause and swap (results shown in Figure 13 below) and multi-material add-on methods of multicolour 3D printing to produce geovisualisations. However, the methods to achieve more complex FFF multicolour models (such as device add-ons or tool changers) are not as widely used as traditional single-colour printing. One reason for this could be the additional cost of utilising these methods. FFF printers with multi-material tool changers are still not widely available and entry-level options are relatively expensive. As part of the current study, the Prusa XL with the tool changer technology is tested and evaluated to gauge its potential to create multicolour geospatial models.

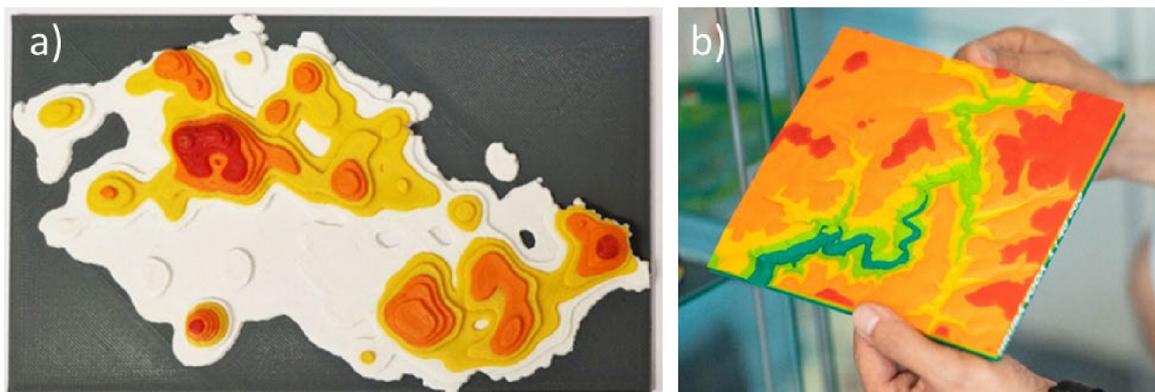


Figure 13: Multicolour 3D models created using the pause and swap method.
Source: Brus et al. (2023)

Based on previous studies by researchers such as Wabiński and Kuzma (2017), Barviř et al. (2023) and Brus et al. (2023) covering FFF 3D printing of geospatial data, there is room for the further utilisation of multicolour models. This highlights the need for additional research into how these models can be created, applied, and adopted. Multicolour FFF printing of geospatial data has the potential to further enhance tactile maps, and convey complex information therefore improving the learning, communication, and decision-making processes. More consumer-grade printing options are now available to produce multicolour geovisualisations with the main challenge to overcome being the preparation of the geospatial data and creation of 3D models that use multiple colours to its advantage.

3 METHODOLOGY

This chapter introduces the general methods used in creating and printing the multicolour 3D models to achieve the objectives of the research. The data types and sources that were utilised, the software that was used for data processing, analysis, and modelling and the printing equipment used are highlighted. In addition, the workflow of this diploma thesis is provided to highlight the data acquisition, modelling, 3D printing and results presentation.

Methods

The research was divided into two main sections, firstly, creating or acquiring the 3D models, and secondly, printing the multicolour 3D models using different equipment. In creating the 3D models, the first step was ideation and data acquisition. In most models, the data was processed using GIS software to extract the necessary components and carry out operations such as the smoothing of DEMs and simplification of complex geometries. The GIS software was also used to create the comparative map used in the user testing. The processed data was exported to 3D modelling software to create the desired model. The exported models were repaired and refined using 3D model viewer software.

The second section involved printing the model. The finished model was configured and sliced using the slicer application for the specific printer that would be used. The sliced model was uploaded to the printer using a USB drive or WLAN connection. The filament colours were prepared for the printer and the model was printed. The printing process was checked occasionally to ensure it was progressing smoothly. The completed print was post-processed to remove any unwanted parts. The waste material produced in the printing process was weighed and recorded for comparison. Each printed model was photographed for presentation in the multicolour printing booklet.

Data

The research utilised data from a range of sources to create various models that would test the multicolour printing capabilities. Table 1 below shows the data sources and types that were used in the research.

Table 1 Datasets and sources used during the research.

Dataset	Source	Type
Copernicus GLO-30 DEM	European Space Agency	Raster
CORINE Land Cover	Copernicus Land Monitoring Service	Vector and Raster
Lucerne Land Use	OpenStreetMap	Vector
Praha Metro Map	Pražská integrovaná doprava (PID)	Image
Earth layers diameter	National Geographic	Statistics
Czechia population data	ArcČR, ARCDATA PRAHA	Vector
Austria population data	Esri, Michael Bauer Research GmbH 2023, Bundesanstalt Statistik Österreich, Eurostat	Vector and statistics
New York City model	Thingiverse	STL model
New York City data	Cadmapper	SketchUp model
Luxembourg City model	geoportail.lu	STL test model

Jamaica Earthquake 2023	USGS	Vector test data
Caribbean Bathymetry	GEBCO	Raster test data

Software and Equipment

The two sections of the research required different software and equipment to create and print the multicolour models. Additional software was used to carry out user testing and to prepare the multicolour 3D printing booklet. Table 2 shows all the software used in the research and Table 3 shows the 3D printing equipment used to achieve high-quality FFF printing.

Table 2 Software used to process data and create 3D models.

	Name	Use
	ArcGIS Pro 3.2.2	Clean and process vector and raster data for the 3D models. Create the paper map for the user testing exercise.
	QGIS 3.28.4	Clean and process the vector and raster data for the 3D models.
	DEMto3D	Plugin in QGIS software used to export DEM or a raster layer to STL format for 3D printing.
	SketchUp 2018	Create 3D models by extruding polygons and editing STL files to remove erroneous features. Several extensions were added to improve the design and export functions of the software.
	3D Builder	View, modify and repair STL and 3MF files.
	Autodesk Netfabb	View, modify and repair STL and 3MF files.
	PrusaSlicer 2.7.3	Desktop application for Prusa printers for configuring 3D model files for printing by repairing, colouring, slicing, and exporting G-code.
	Canvas	Web application for the Palette 3 Pro for configuring 3D models for printing by colouring, slicing, and exporting a zipped file with the G-code.
	Bambu Studio	Desktop application for Bambu printers and Bambu AMS for configuring 3D model files for printing by repairing, colouring, slicing, and exporting G-code.

	ArcGIS Survey123	Creation of a digital questionnaire for collecting user feedback. The mobile app was also used to submit the responses from the survey participants.
	Inkscape 1.3	Edit simplified geometries in SVG format to be converted into DXF format for use in SketchUp modelling.
	Adobe InDesign 2024	Design and edit the layout and content of the multicolour 3D printing booklet.
	Adobe Illustrator 2024	Design workflow and other graphic elements.
	Adobe Photoshop 2024	Edit images captured of the models and other content to be used in the multicolour 3D printing booklet.

Table 3 Equipment used to print the 3D models.

Image	Name	Specifications
	Original Prusa i3 MK3S	<p>MSRP: €999</p> <p>Build volume: 250×210×210 mm</p> <p>Layer height: 0.07-0.25 mm</p> <p>Nozzle: 0.4 mm</p> <p>Filament diameter: 1.75 mm</p> <p>Max tool head speed: 200 mm/s</p> <p>Max nozzle temperature: 300 °C</p> <p>Max build plate temperature: 120 °C</p> <p>Shell: Open</p>
	Original Prusa XL – 5T Input Shaper 0.4 nozzle	<p>MSRP: €4.199</p> <p>Build volume: 360×360×360 mm</p> <p>Layer height: 0.07-0.3 mm</p> <p>Nozzle: 0.4 mm</p> <p>Filament diameter: 1.75 mm</p> <p>Max tool head speed: 450 mm/s</p> <p>Max nozzle temperature: 290 °C</p> <p>Max build plate temperature: 120 °C</p> <p>Tool Changer: 5 tool heads</p> <p>Shell: Open</p>

	<p>Bambu Lab P1S</p>	<p>MSRP: €762 Combo with AMS: €1.016 Build volume: 256×256×256 mm Layer height: 0.08-0.28 mm Nozzle: 0.4 mm Filament diameter: 1.75 mm Max tool head speed: 500 mm/s Max nozzle temperature: 300 °C Max build plate temperature: 100 °C Shell: Enclosed Air Filter: Activated Carbon Filter</p>
	<p>Bambu Lab AMS</p>	<p>MSRP: €359 Filament inputs: 4 Filament diameter: 1.75 mm</p>
	<p>Mosaic Manufacturing Palette 3 Pro</p>	<p>MSRP: €750 Filament inputs: 8 Filament diameter: 1.75 mm Splicing technology: 3rd generation Splice Core PRO</p>
	<p>Scale</p>	<p>Measuring scale for weighing the waste material from printing.</p>

Processing procedure

Figure 14 shows the workflow that was carried out in the execution of this study. The workflow covers the data collection, data processing, 3D modelling, 3D printing, post-processing, user testing and booklet creation steps.

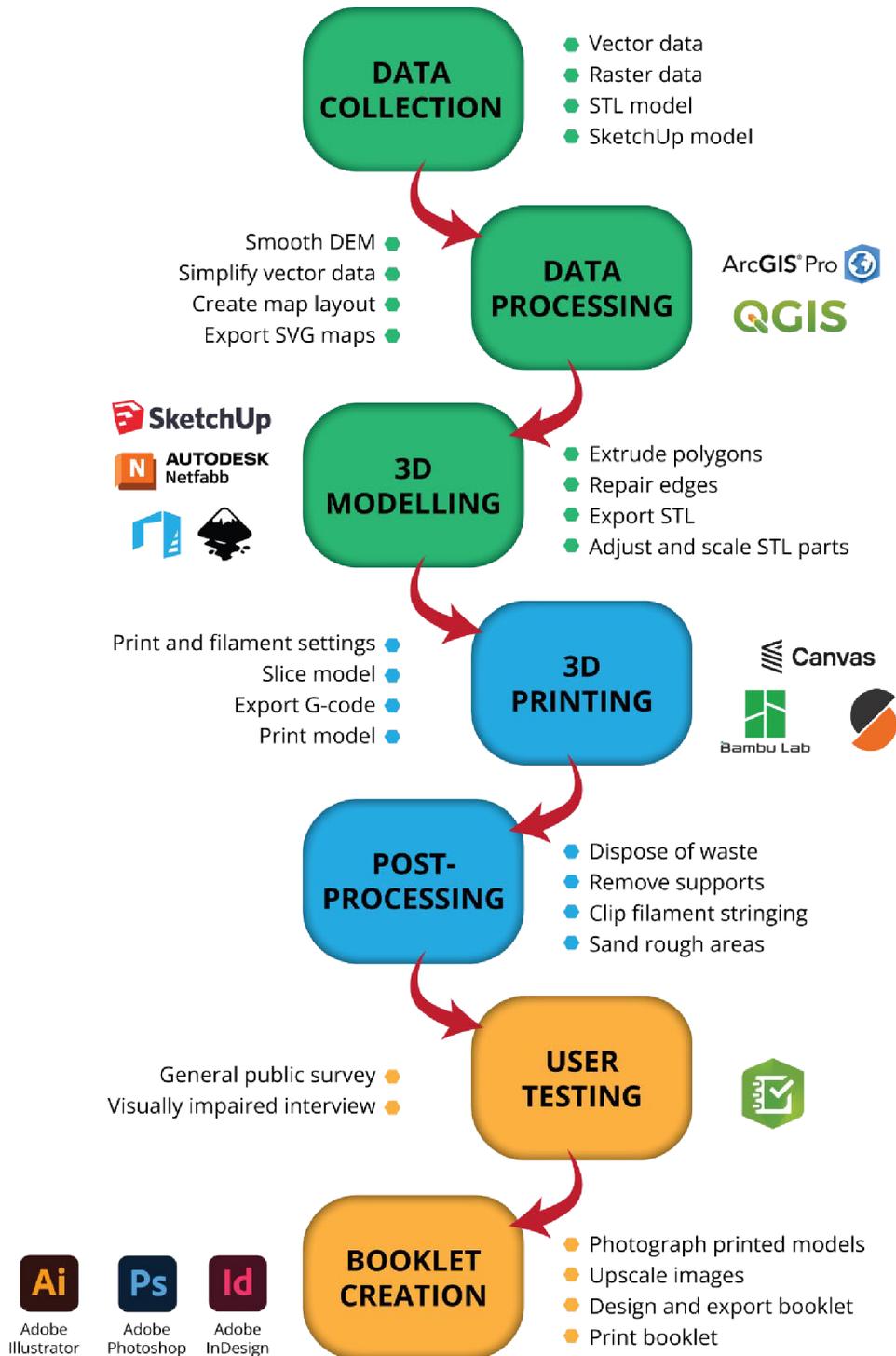


Figure 14 Research procedures and workflow.

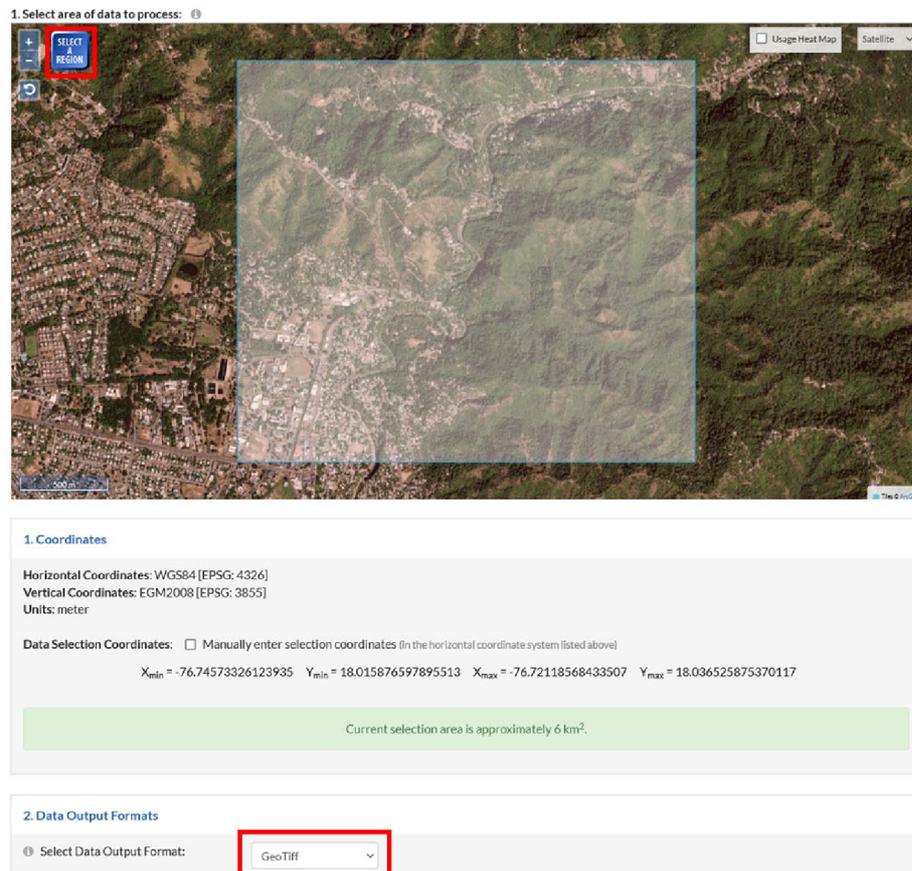
4 DESIGN OF 3D MODELS

This chapter delves into the process of creating 3D models for multicolour printing. The first steps of the workflow from Figure 14 are expounded upon including data collection and processing, modelling in SketchUp and other software and making maps that are 3D printable. The 3D model design steps are the basis of successful 3D printing.

4.1 Data Collection

Raster Data

The Copernicus programme is the European Union's Earth observation programme that offers free and open-access data to users. The Copernicus DEM is a Digital Surface Model (DSM) that was derived from the WorldDEM product and is based on radar satellite data (OpenTopography, 2021). The data was obtained between 2011 and 2015 during the TanDEM-X Mission. The Copernicus DEM is available in 30m and 90m resolutions. For this research, the Copernicus 30m DEM (COP30) was accessed through OpenTopography, with the data being provided by Sinergise via an AWS S3 bucket.



1. Select area of data to process: 

1. Coordinates

Horizontal Coordinates: WGS84 [EPSG: 4326]
Vertical Coordinates: EGM2008 [EPSG: 3855]
Units: meter

Data Selection Coordinates: Manually enter selection coordinates (in the horizontal coordinate system listed above)

$X_{min} = -76.74573326123935$ $Y_{min} = 18.015876597895513$ $X_{max} = -76.72118568433507$ $Y_{max} = 18.036525875370117$

Current selection area is approximately 6 km².

2. Data Output Formats

Select Data Output Format:

Figure 15 OpenTopography data download configuration for acquiring the DSM for Model 1.

For Model 1, the DSM for an area of Kingston, Jamaica was extracted from the COP30 download page on OpenTopography. Figure 15 above, shows the simple and user-friendly steps taken to download the data. The area of interest was selected and the data output format was set as GeoTIFF. To download the data, a job title, job description and email address are provided for tracking jobs in OpenTopography.

The General Bathymetric Chart of the Oceans (GEBCO) is a free-to-access bathymetry dataset of the world's oceans. The dataset is available as a gridded raster terrain model covering both the seafloor and land. According to the GEBCO (2024) dataset description, the elevation model was generated by assimilating regional and global grids and individual surveys collected from national and international databases. The data for one of the planned models was downloaded as a GeoTIFF from the online GEBCO data download tool shown in Figure 16.

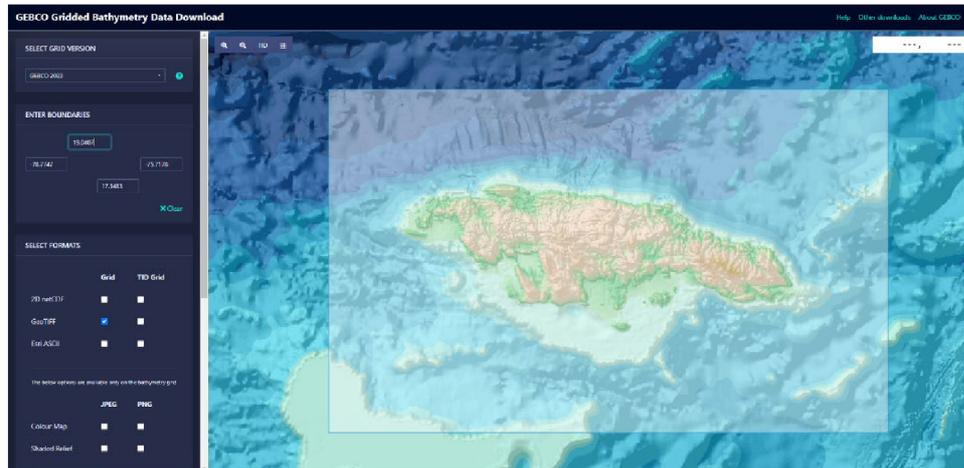


Figure 16 GEBCO data download website.

The Prague Metro data was extracted from official Metro maps that are publicly available. The Prague Metro maps and other public transit maps are made by Pražská integrovaná doprava (PID), in English, Prague Integrated Transport. Figure 17 shows the original map that was used to create a model adapted for the visually impaired. Additional maps of the individual lines were also used to create models suitable for the visually impaired.

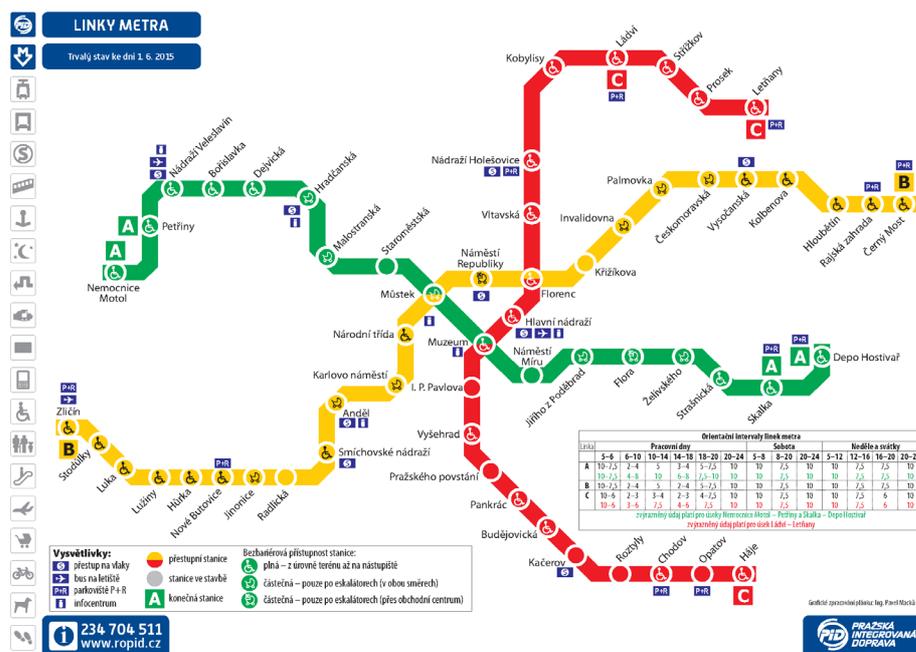


Figure 17 Prague Metro map. Source: PID (2024)

Vector Data

The vector data used in the research came from various sources. Earthquake data was acquired from the Earthquake Hazards Program of the United States Geological Survey (USGS). A magnitude 5.4 earthquake hit Jamaica on October 30, 2023, and this was the design idea for one of the models to be created. KML event data was downloaded from the Earthquake Hazards Program (2023) website and later converted to a feature class and a shapefile.

Vector data for the Czech Republic was acquired from the ArcCR® version 4.2 digital database made available by ARCDATA PRAHA. ARCDATA PRAHA is the official Esri distributor in the Czech Republic. The database contains administrative divisions from the Land Surveying Office enriched with population census data and other statistical data from the Czech Statistical Office (ARCDATA PRAHA, 2023). Additionally, vector data for Austria was acquired from the ArcGIS Living Atlas. The dataset contains the federal province boundaries along with population statistics provided by Michael Bauer Research GmbH and sourced from Statistik Austria (Esri, 2024).

The QuickOSM plugin in QGIS was used to acquire land use data from the OpenStreetMap database for Lucerne, Switzerland. Figure 18 shows the configuration of the query that was used to acquire the data as polygons within a specific bounding box. The land use data was extracted using the following tags, “admin level 8”, “residential”, “farmland”, “forest”, “meadow” and ‘water’. The most recent CORINE Land Cover (CLC) dataset was downloaded in both raster and vector format from the Copernicus Land Monitoring Service (CLMS) to acquire comparison land cover data for Lucerne. The CLC dataset was first produced in 1990 and the last update occurred in 2018 (CLMS, n.d.).

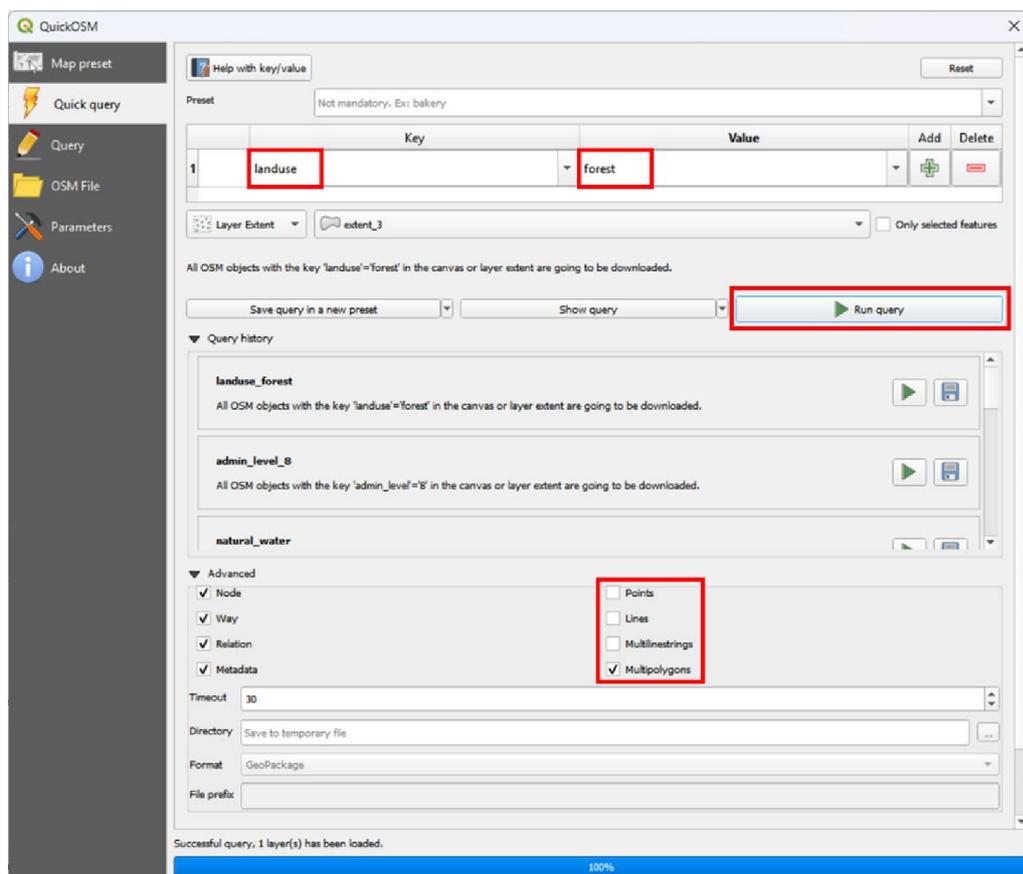


Figure 18 QuickOSM configuration to download data in QGIS.

Pre-made Models

Many cities and countries have geoportals that provide 3D data for public use. Some cities go further by providing platforms to download STL models of the city based on the available 3D data. Luxembourg offers data through its national portal, [Geoportail.lu](https://geoportail.lu). The geoportal offers a 3D printing tool for extracting and downloading terrain and building data for areas up to 500 m² as a 3D model in STL format. Figure 19 shows the layer selection options for the 3D model and the download options of a single combined model or separate files for each layer (ideal for multicolour printing).

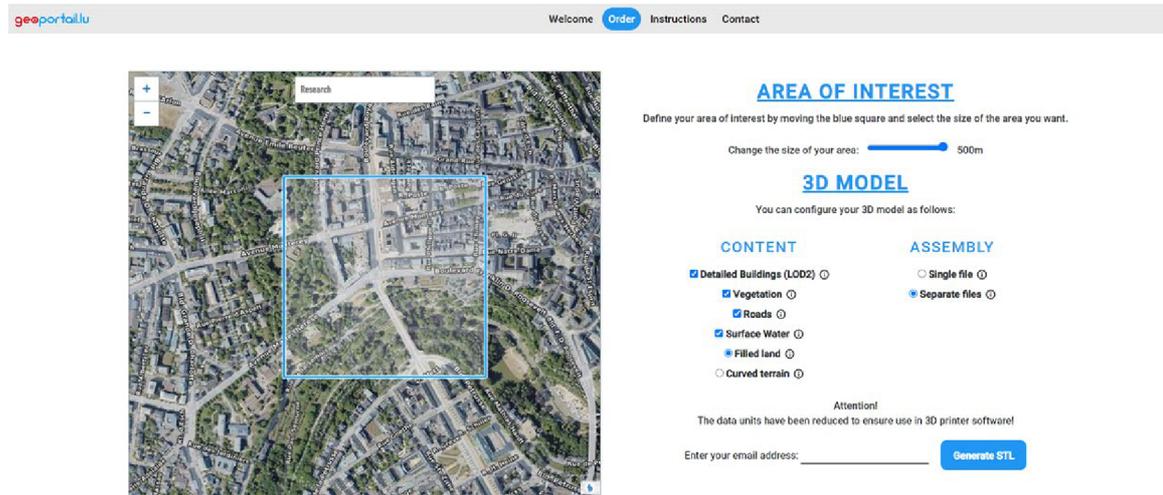


Figure 19 Luxembourg 3D model download tool. Source: Geoportail.lu (n.d.)

A second source that was used to acquire 3D city data was Cadmapper. Users are allowed to download CAD files for any location based on data transformed from public sources such as OpenStreetMap and USGS (Cadmapper, 2024). Figure 20 shows the Cadmapper website and the configuration of the map that was used for the New York City model. The map contains 3D buildings and topography information, and the user can download up to 1 km² of data for free. The user is also able to select the output file type and configure the road geometry.

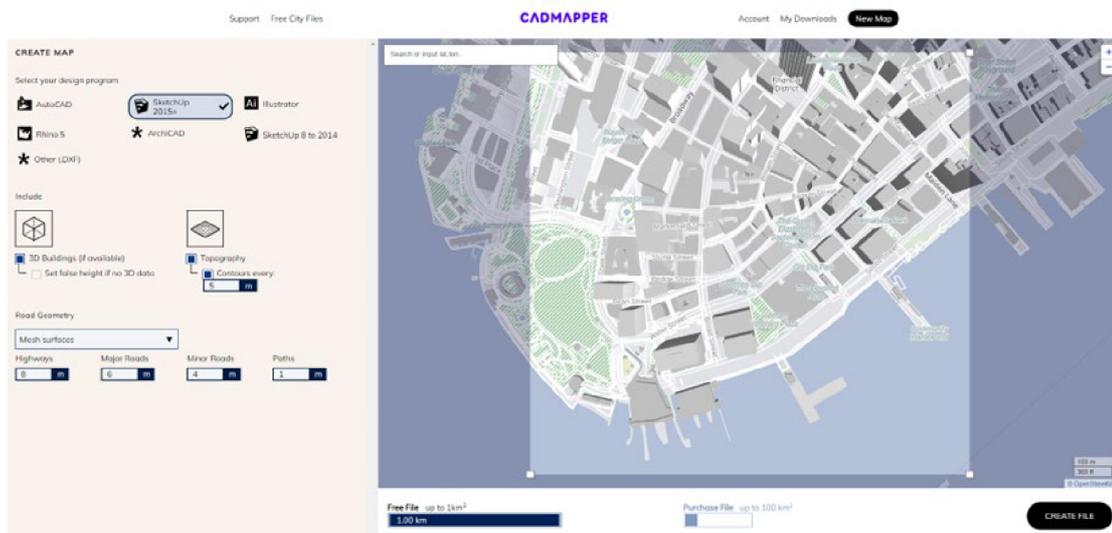


Figure 20 Cadmapper 3D model download configuration.

There are community-driven online platforms where users can share, discover, and download 3D models for 3D printing. Some of these platforms include Thingiverse (by Ultimaker) and Printables (by Prusa). A model of a large section of New York City was downloaded from Thingiverse (shown in Figure 21) to be used in addition to the 1 km² of data downloaded from Cadmapper. The Manhattan Project by Jib22 contained 52 files including 51 STL files and a SketchUp model of the project (Thingiverse.com, 2020).

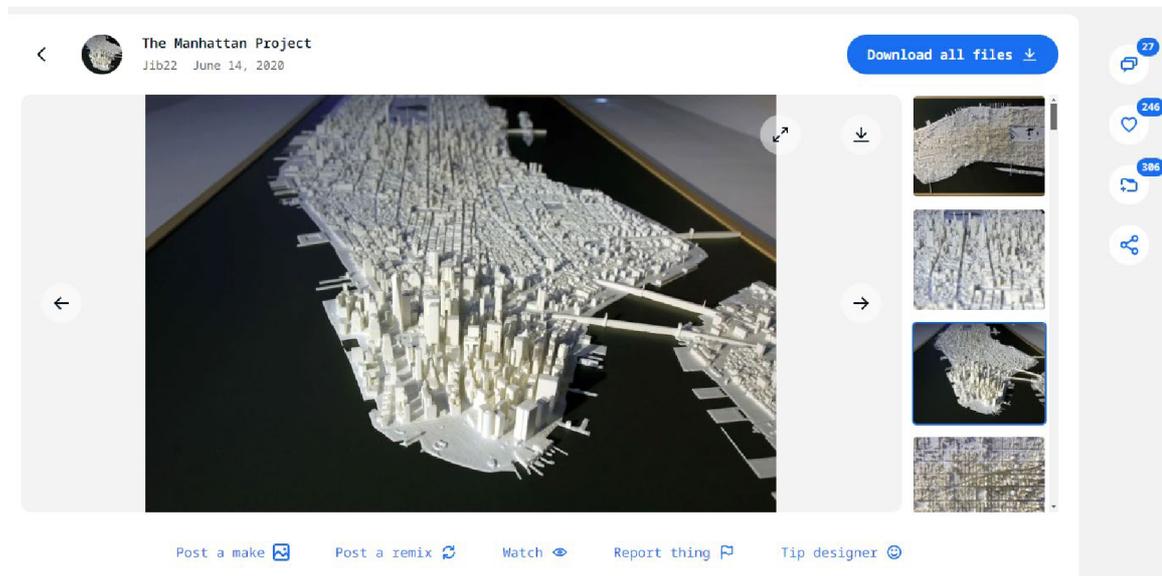


Figure 21 The Manhattan Project page on the Thingiverse website.

4.2 Data Processing and Model Creation

4.2.1 Modelling using GIS Software

Several steps and file conversions are needed to take a complete map produced with ArcGIS Pro or QGIS and convert it into a 3D-printable map. ArcGIS Pro supports 3D scenes within the application and exports to ArcGIS Online for web display, however, there are no export options to common 3D formats such as OBJ, COLLADA or STL. QGIS supports plugins that enhance the 3D capabilities. One of which (DEMto3D) is capable of exporting STL files ready for 3D printing. The GIS software was essential for data processing and cleaning and the outputs were made 3D printable using additional modelling software highlighted in the following sections.

Model 1: Kingston Terrain

The Pause and Swap method was the first to be used in creating a multicolour model in this study. To create Model 1, the downloaded COP30 DEM for a section of Kingston, Jamaica was opened in QGIS. A polygon was created for the desired extent of the model. The QGIS plugin, DEMto3D was used to create an STL file from the DEM. Within the plugin, the DEM was set as the target layer to print and the area of interest polygon was set as the print extent. The model size was configured to have a spacing of 0.2 mm, a scale of 1:25,000 and a vertical exaggeration of 1.5. The settings for the height and base height can be varied to achieve the desired overall model height. These settings can be seen in Figure 22a below. After *Export to STL* was selected the file browser opened to select the destination of the STL file. The exported STL for Model 1 was checked in the software 3D Builder and can be seen in Figure 22b below.

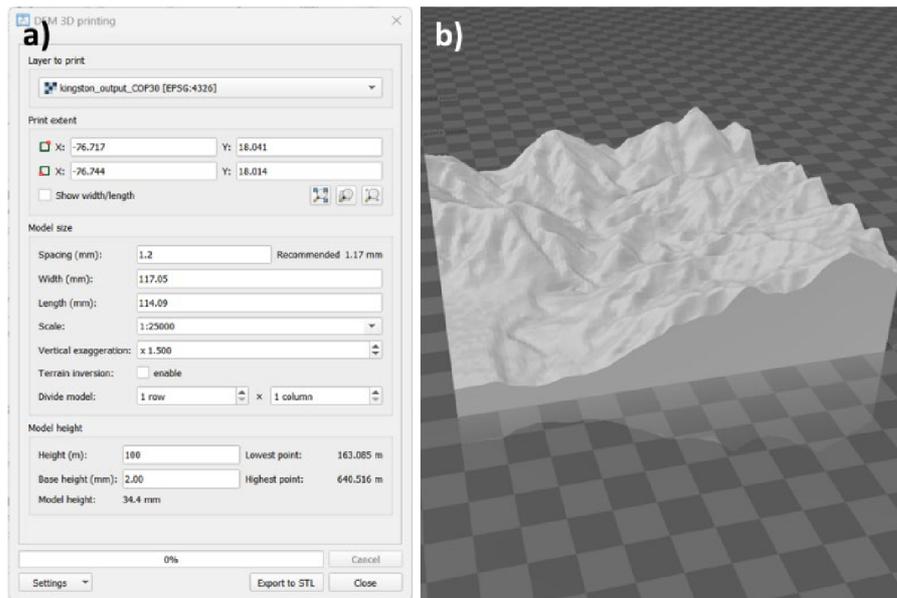


Figure 22 DEMto3D configuration and resulting STL for Model 1.

Model 5: Austria Population Density 2023

ArcGIS Pro was used to process the Austrian data to create Model 5. Two methods were tested to create the model with the results being very similar. Method one was raster-based while method two was vector-based. The methods are described below:

Method one (raster) included the following steps:

- A new field was added to the attribute table for the respective population density class.
- The provinces were converted from vector to raster using the Polygon to Raster geoprocessing tool (see Figure 23b). The pixel value was set as the newly generated field with the population density class. A cell size of 30 m was found to be a good balance between resolution and file size of the final STL model.
- The Reclassify geoprocessing tool (see Figure 23c) was used to reclassify the pixel value from the population density class to an elevation value. These values were set to intervals of 1000. No data pixels were set to zero.
- The resulting raster was opened in QGIS and then used as the target layer in the DEMto3D plugin.
- The STL file was exported.
- 3D Builder was used to scale the model to clip the base of the model to remove the section with zero values (no data), leaving the correct shape of Austria. The resulting model can be seen in Figure 24a.

Method two (vector) included the following steps:

- Simplifying the geometry of the province boundaries using the Simplify Polygon geoprocessing tool (see Figure 23a). The simplification was done to reduce the number of small corners in the data, hence improving the 3D printing result.
- Calculating the population density by normalising the total population in 2023 by the area of the provinces.
- Classifying the density into 4 classes based on the availability of a set of filaments to create a yellow-red colour scheme.
- The classified data was placed on a map and exported as an SVG file.

- The SVG file was converted to DXF format using Inkscape.
- The DXF file was imported into Sketchup for 3D modelling.
- The DXF file was scaled up in size to improve the performance of SketchUp as working with small mm-sized objects reduced the performance of the software.
- The province polygons were manually extruded based on the population density classification.
- The completed model was exported as an STL file.
- The STL file was checked for errors using 3D Builder to ensure it is manifold/watertight (has no holes).
- The resulting model can be seen in Figure 24b.

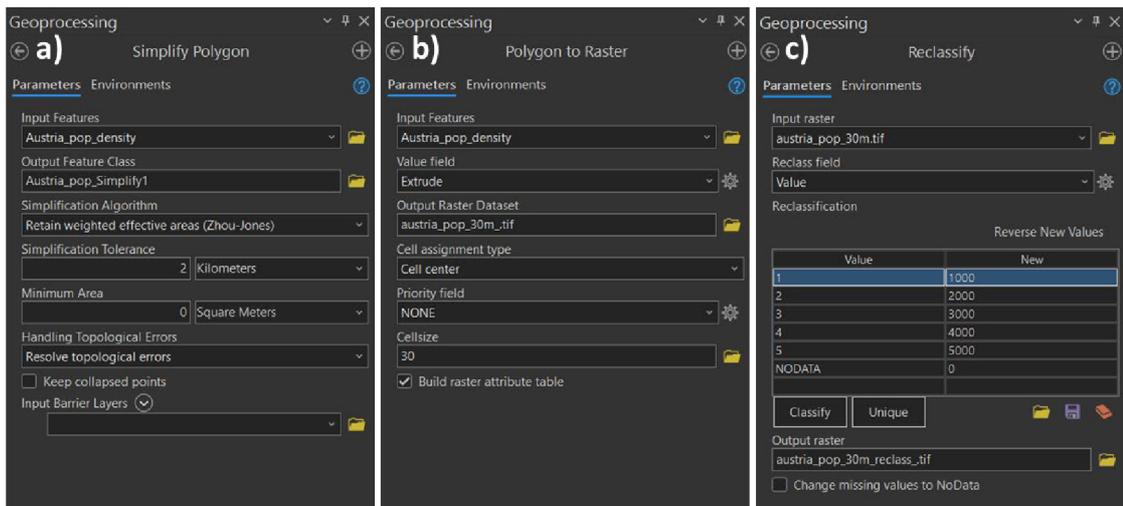


Figure 23 a) Simplify Polygon tool settings. b) Polygon to Raster tool settings. c) Reclassify tool settings.

The vector-based model from method two had smooth polygons and was selected for printing as the model from method one had sharp edges from the raster pixels. The pixel size of the converted polygons could be reduced to get a smoother model. However, this reduction in pixel size was tested and the file tripled in size. This increase in the raster file size also resulted in a significant increase in the export time for the STL file from the DEMto3D plugin.

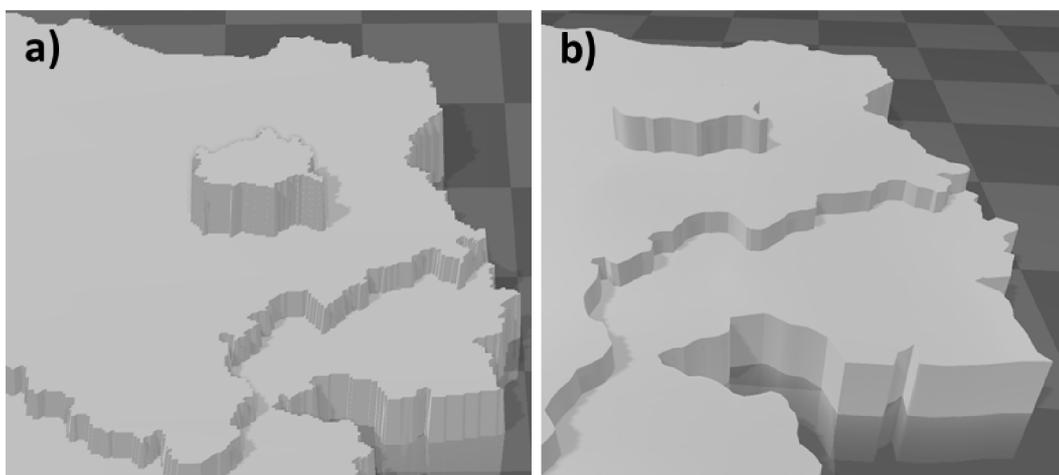


Figure 24 a) Model 5 STL from the raster-based method. b) Model 5 STL created from the vector-based method.

4.2.2 Modelling using SketchUp

SketchUp was the primary application used to create and edit the 3D models produced in this research. A series of steps and extensions were used depending on the requirements of the model.

Model 2A: New York City

The processing steps included:

- Importing the downloaded SketchUp project from Cadmapper into SketchUp.
- The Eneroth Terrain Volume extension was used to generate a solid object under the terrain.
- The model was exploded to edit the different layers
- Buildings at the edge of the model that had been cut in the export were removed.
- The roads were extruded simultaneously using the JointPushPull extension (trial version).
- The CleanUp³ and Solid Inspector² extensions were used to inspect and repair components.
- Each layer of the project was exported as an STL file.

Model 3A-D: Praha Metro Map

The processing steps included:

- The Praha Metro map was imported as a texture to the model base that was created.
- The metro lines were drawn as polygons and the stops as circles.
- Multiple shapes were extruded using the JointPushPull extension.
- Missing faces were fixed with the Eneroth Face Creator extension.
- The Czech braille font was installed and used to place the station names as extruded 3D objects (in this case cylinders for the dots). Settings used, **braille height** = 7.5 mm and **extrusion height** = 0.8 mm.
- The cylinders were edited using the RoundCorner extension (trial version) to give them a domed top. The rounding of the top was done to achieve a smoother texture for the braille dots and improve its readability.
- The main settings for the RoundCorner tool were the **number of segments** = 10 and **Offset** = 0.7 mm.
- The CleanUp³ and Solid Inspector² extensions were used to inspect and repair components.
- The base of the model, the lines, stations, and braille labels were exported as individual STL files for Lines A, B, and C and the overall Metro Map.
- The combined model was checked and repaired in 3D Builder (shown in Figure 25).

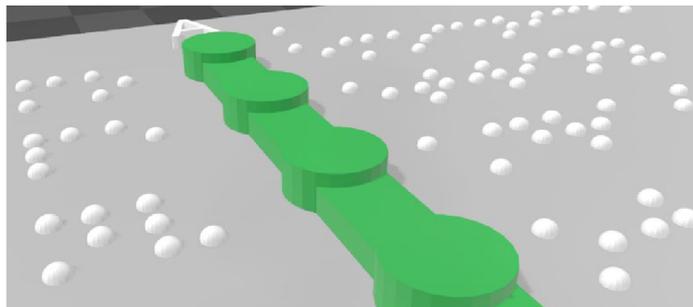


Figure 25: Braille dots designed with rounded tops.

Model 4A-C: Earth Structure

Images and statistics from National Geographic were used to create a model showing the layers of the Earth. The end goal was to create a single model with a different colour for each layer and a cut-out section. The steps followed included:

- The radius of the layers was scaled down from km to mm scale.
- A circle was created for each layer.
- The circles were extruded into spheres.
- Each sphere was exported as an individual STL file from SketchUp.
- Using 3D Builder, the spheres were progressively subtracted from each other to create hollow spheres for each layer.
- The model was split into quadrants using the Split tool to create the cut-out.
- After removing the quadrant, the remaining sections were merged.
- A hexagon base was created in 3D Builder to hold the model.
- Each layer of the whole model and the cut-out section was saved as individual STL files to make the colouring process easier when printing.

4.2.3 Paper Maps to 3D-Printable Maps

There are limited resources that outline in detail how to go from a paper map to an equivalent 3D-printed map with ease. The series of steps previously mentioned in the data processing method two that was used for Model 5 was effective in converting complete maps saved as SVG to 3D models using modelling software such as SketchUp. These steps were further utilised to create models 6, 7A and 7B.

Model 6: Population Structure Pardubický kraj

The processing steps included:

- Using ArcGIS Pro, the paper map was completed and exported with all the necessary symbology and layout elements to be used in User Testing.
- The geometry of the Pardubický kraj administrative areas was simplified using the Simplify Polygon tool.
- The simplified map with chart symbols and legend was exported in SVG format.
- The SVG map was converted to DXF using Inkscape.
- The DXF file was imported into SketchUp.
- To improve system performance, the model was scaled up in size.
- The administrative areas and chart symbols were extruded to the required heights.
- The relative scale of the legend was maintained and the symbols extruded to match the map field.
- The administrative areas, chart symbols and legend were exported as separate STL files.
- The combined files were checked in 3D Builder.

Model 7A-B: Lucerne Land Cover

This model was more challenging to create as the goal was to create a model that shows land cover classes and the terrain of the city. After testing several tools, the following steps were found to be successful in achieving the desired model.

- Using ArcGIS Pro, the COP30 DEM was smoothed using the Focal Statistics geoprocessing tool to improve the quality of the geovisualisation. The settings were

configured to the following, **Neighbourhood** = Circle, **Radius** = 3, **Units type** = Cell and **Statistics type** = Mean.

- The smoothed DEM was imported into QGIS and an STL model was exported using the DEMto3D plugin.
- The outputted terrain STL was simplified in 3D Builder to reduce its size by reducing the number of triangles.
- The OSM vector data was simplified using the Simplify Polygon geoprocessing tool to reduce the sharp edges.
- The land use classes were generalised by removing smaller parts and merging adjoining sections of similar uses.
- The OSM data was exported in SVG format using the map extent matching the DEM.
- The CLC data had a resolution of 100 m, hence very generalised and no need for simplification. The map extent was exported to SVG format.
- Both SVG files were converted to DXF using Inkscape.
- The OSM DXF file was imported into SketchUp
- The polygons were extruded to a fixed height and each class was exported as an individual STL file.
- The same import, extrusion and export operations were carried out on the CLC DXF file.
- The DEM and the individual OSM extruded layers were imported into Autodesk Netfabb.
- Using the Boolean functions in Netfabb the forest, water and urban layers were subtracted from the DEM to get the area covered by agriculture on the DEM. Layer subtraction is possible in 3D Builder, but Netfabb had significantly faster processing times for the operations. Figure 26 below shows the Boolean tool setup.
- The new water area model was exported as an STL file.
- Alternating layers were subtracted from the DEM to get the forest, urban and agriculture STL models of each.
- Each STL was opened in SketchUp to remove a few unwanted faces that had no volume but were generated during the subtraction process.
- The steps in Netfabb were repeated for the CLC layers.
- The legend and labels for Model 7A and 7B were created in SketchUp.
- The complete models were checked and positioned correctly using 3D Builder. The CLC model can be seen in Figure 27.

4.2.4 Test Models

The pre-made model of Luxembourg was used as an early resource to test the capabilities of the Canvas software, especially the painting tools and project settings. This model was not printed as it contained some errors including, clipped buildings that were not manifold and broken road segments. These errors would have resulted in the model not printing correctly. The second test model was intended to show earthquake intensity on bathymetry and topography for a 2023 earthquake in Jamaica. However, it proved very challenging to export this combination of data into a final 3D-printable form. Nevertheless, the steps carried out for this model provided insight into translating paper maps to 3D-printable maps.

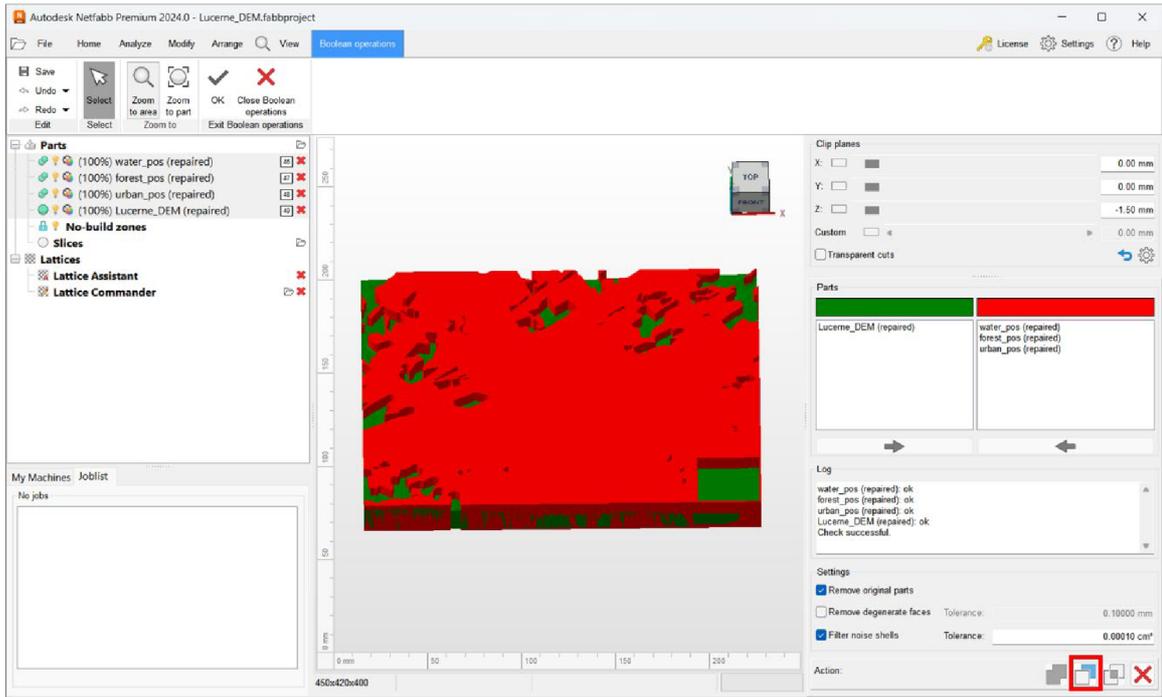


Figure 26 Subtraction Boolean function in Autodesk Netfabb.

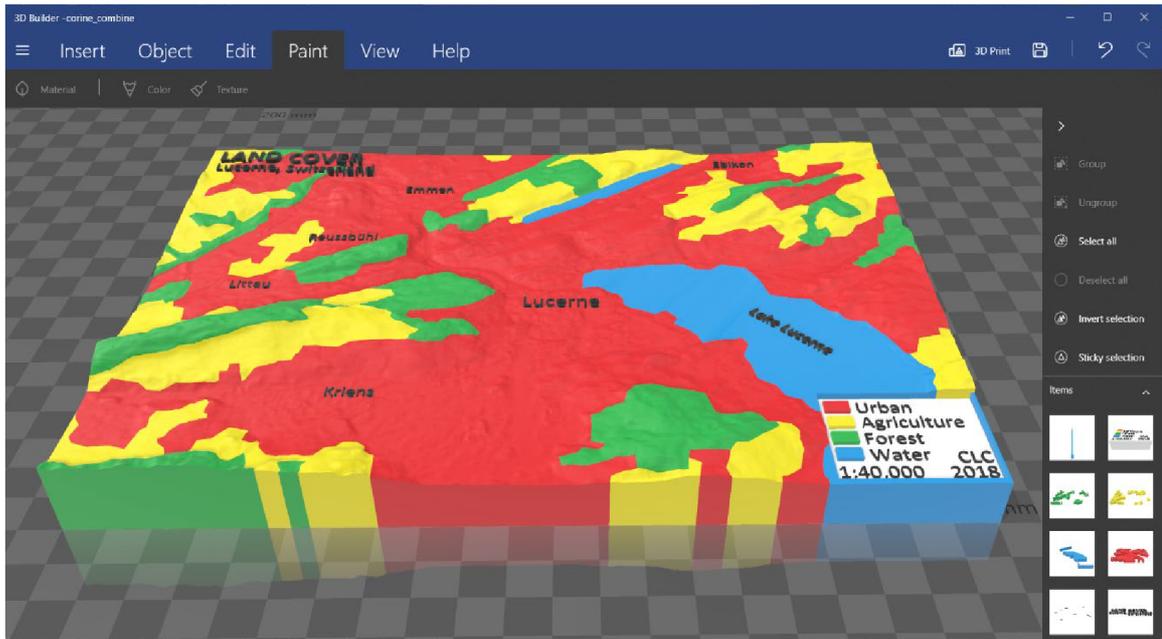


Figure 27 Final CLC model in 3D Builder with the layers coloured with the intended filament colours.

5 MULTICOLOUR 3D PRINTING

This chapter goes through the process of printing the acquired and designed 3D models. The 3D printers used to print the models have different capabilities as described in Table 3 and each printer uses a dedicated slicing application. The topics covered in this chapter include the configuration of the model and the printer, printing processes and post-processing steps taken after the printing is complete.

5.1 Model and Printer Configuration

After designing the model, the next step is slicing the model for printing. Each printer manufacturer's slicing application has different tools, but the main functionalities are the same across all the applications. The slicing application allows you to configure the model and the printer settings. The slicing applications used to prepare the models for printing were PrusaSlicer, Canvas and Bambu Studio. PrusaSlicer was used to configure models 1, 2A, 3A-D, 4B, 5, 6 and 7A-B. Canvas was used to configure models 2B and 4A and Bambu Studio was used to configure model 4C. All the printers and models were configured to use Polylactic Acid (PLA) filament with a diameter of 1.75 mm. PLA is the most common type of filament used in FFF 3D printing as it is inexpensive and versatile (Andronov et al., 2023; Statista, 2020).

PrusaSlicer

For Model 1, the STL terrain model was loaded into the slicer and the printer was selected as Original Prusa i3 MK3S & MK3S+. The slicer has three modes, Simple, Advanced and Expert. Expert mode was used for all the models in this research to unlock all the printer and filament settings. The 0.2 mm QUALITY preset, meaning a layer height of 0.2 mm was selected for a balance between speed and detail and the infill was maintained as the default 15%. For this model, the multicolour final output was achieved by using the Pause and Swap method. The model was positioned correctly on the print bed and then sliced. After slicing it is possible to configure a filament change using the **M600** command in the G-code. Two filament changes were inserted to create a model with three (3) colours as shown in Figure 28. The model was sliced again and then the final G-code was exported.

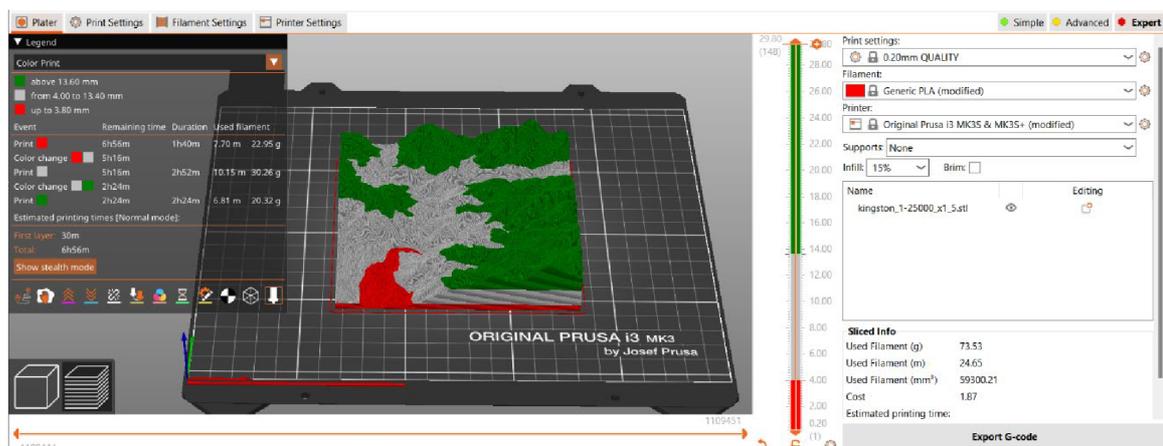


Figure 28: Model 1 sliced and coloured in PrusaSlicer.

For Model 2A the printer was selected as Original Prusa XL – 5T Input Shaper 0.4 nozzle and the individual STL files were imported. The 0.2 mm SPEED print setting was selected, and each of the five filaments was changed to the Generic PLA preset.

The STL files were added to the build plate by dragging and dropping them into the application window. An option was selected to add the objects as a single object with multiple parts. The infill for the model was set to 15% and scaled to 20% of its original size. The model and the wipe tower were positioned correctly on the build plate. Under the Printer Settings tab, the colour of each extruder was changed to match the final filament colours to be used. In the contents list, for each layer, the specific extruder (one to five) was selected to print that layer. All the buildings were exported on a single layer, but this provided the opportunity to test the manual painting capabilities by painting some buildings in white.

The painting tool is accessed through the *Multimaterial painting* button on the left tab. The tool is shown in Figure 29 below, with the first option allowing you to assign an extruder to the left mouse click (first colour) and the right mouse click (second colour). After selecting the colours, it is possible to select the specific tool type to be used, with the options being Brush, Smart fill and Bucket fill. The Brush tool type allows you to paint faces based on the selected brush shape and the brush size. The Sphere brush shape paints all faces inside the sphere regardless of orientation. The Circle brush shape only paints faces in the current camera direction and the Triangles brush shape paints individual triangle faces. The Smart fill tool paints a region up to a sharp edge and the Bucket fill tool paints neighbouring faces with the same colour. Hovering over each button gives a short description of the tool's function. Given the shape of the buildings, a combination of the Smart and Bucket fill was used to paint the buildings. After painting, the model was sliced and exported to a USB drive.

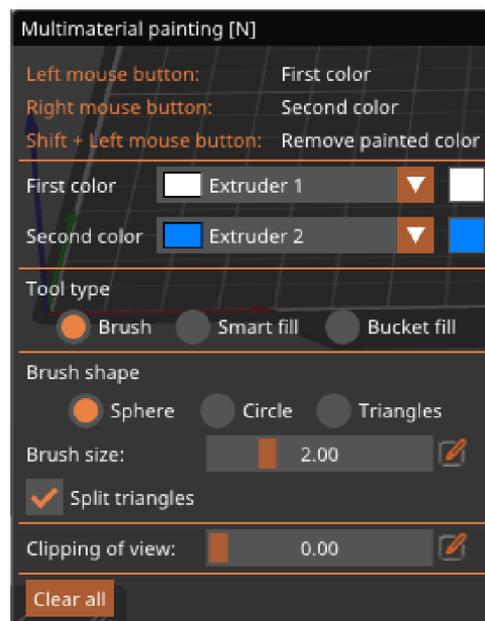


Figure 29 Painting tool options in PrusaSlicer.

The configuration of Models 3A-D started similarly to the previous models with the individual layers being assigned an extruder with a specific colour. For this model maximum detail was required, hence the Print settings preset was set to 0.1mm FAST DETAIL, meaning a layer height of 0.1 mm. In PrusaSlicer you can apply specific settings to individual layers. For Model 3A and 3B, ironing was enabled for the top surfaces of the metro lines to give them a smooth finish. For Model 3B, ironing was also enabled for the top surface of the base. The layers containing the braille text were configured to slow down the printing speed to improve the quality of dots seeing as they were designed with

rounded tops. Under the Extrusion Width settings, **External perimeters** and **Perimeters** were reduced to **0.4 mm** from 0.45 mm. Under the Speed settings, the print speed of **Small perimeters** was reduced from 150 mm/s to **5 mm/s**. Each model in the series was sliced and the G-code was exported.

Model 4B was downscaled to 30% of its designed size to reduce the print time across all the printers tested. The layer height was set as 0.2 mm as all three printers were able to print with this setting. The layers were coloured by selecting the extruder with the desired colour. Supports were enabled for the main section of the model to allow because of the spherical base shape. The sliced model was exported to a USB drive for transfer to the printer.

Seeing as Model 5 was more “map-like” and the desire was to maintain as much detail as possible, the Print setting was set to the preset 0.1mm FAST DETAIL. The provinces were coloured manually using the Brush tool (specifically the Triangles brush shape) and Smart Fill tool. Each extruded part was coloured using the left and right mouse buttons. This model had many faces that needed to be coloured because of the complex shape of the province boundaries.

For Model 6, the original intention was to create a model with five colours, however, after testing different designs of the map legend, it was discovered that a sixth colour could be added. The text and numbers in the legend all started at a specific height and this provided the opportunity to perform a **M600 filament change** on one of the extruders. The layer height for the model was set to 0.1 mm for maximum detail seeing as the model had small text and numbers. For the legend layer, under the Extrusion Width settings, **External perimeters** and **Perimeters** were reduced to **0.4 mm**. Under the Speed settings, the print speed of **Small perimeters** was reduced from 150 mm/s to **10 mm/s**. The chart symbols were manually coloured using the Smart Fill and Bucket fill tools, while the colour for the other layers was assigned by the specific extruder colour. The model was then sliced to implement the filament change on Extruder 2 from white to black at a height of 2.6 mm as shown in Figure 30 below.

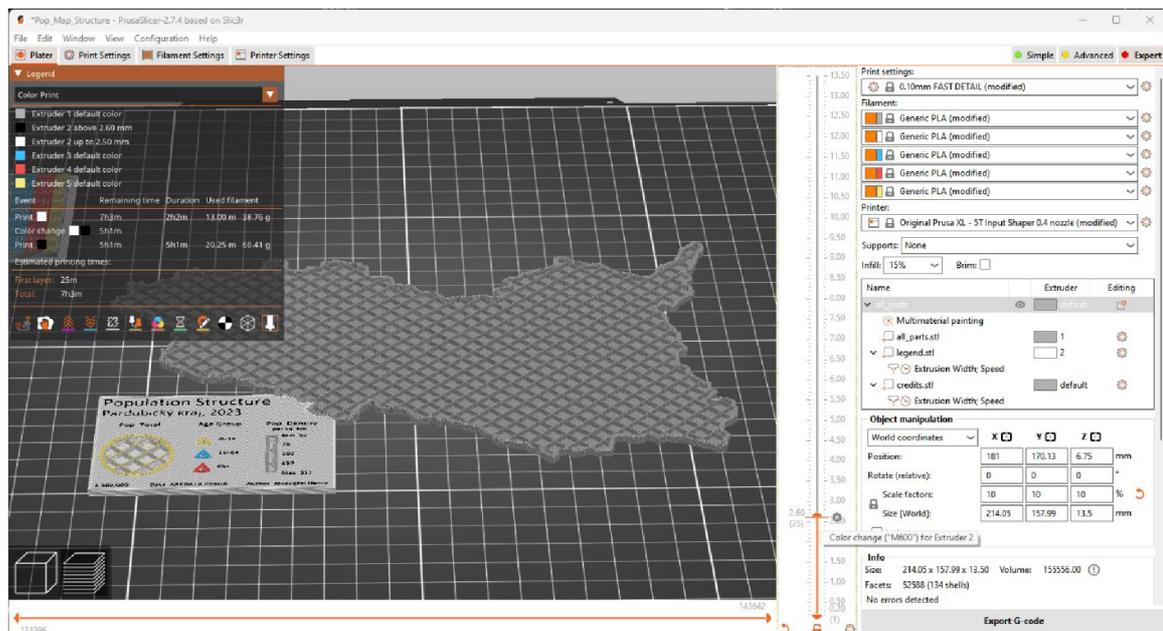


Figure 30 Filament change configured in PrusaSlicer for one extruder on the Prusa XL.

For Models 7A and 7B, the layer height was set to 0.1 mm to maintain as much detail as possible in the map. Seeing as these models had many small areas that would require colour changes, the infill of all the layers was set to a single extruder. This was achieved by adding an **Extruders setting** on each layer for the **Infill extruder**; which was set to extruder 3 for both models. A filament change was also configured at a height of 1.8 mm for extruder 5 to go from white to black as shown in Figure 31 below. This change was done to print the text in the legend, map labels and the map title in a more contrasting colour. For the legend, map labels and map title layers, the settings for **External perimeters** and **Perimeters** were reduced to **0.4 mm** and the print speed of **Small perimeters** was reduced from **5 mm/s**. For the legend, the swatch of each layer was manually painted using the Smart fill tool and a modification box was added around the swatches to enable ironing on the top of the surfaces. Each model was sliced again, and the G-code was exported.

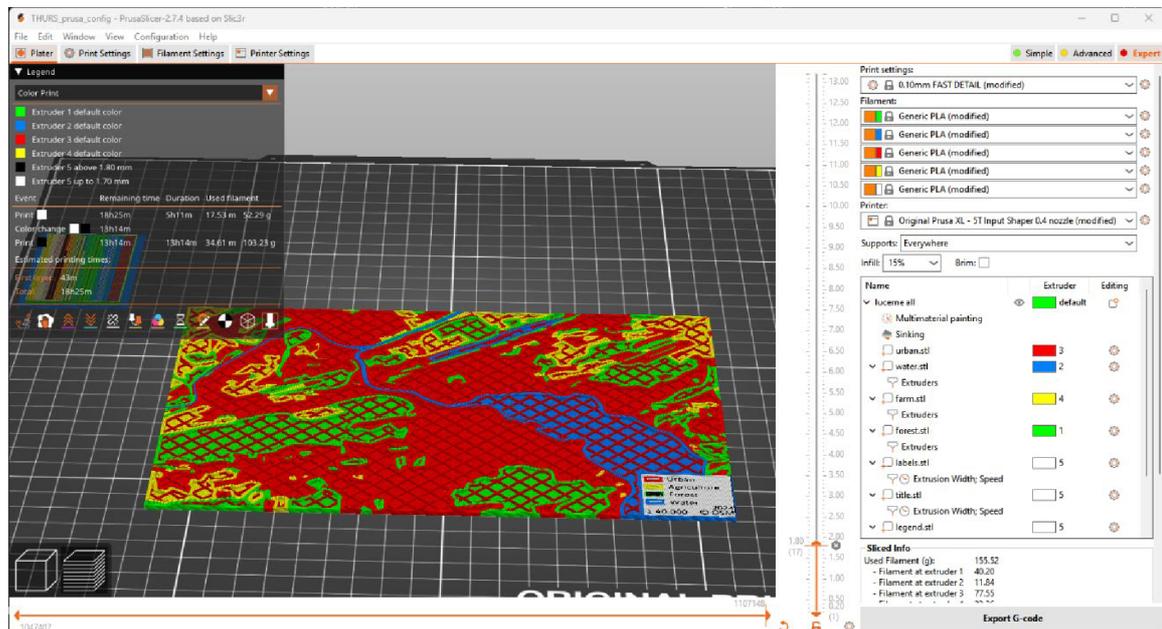


Figure 31 Model 7A sliced preview with filament change for text and labels.

Canvas

The first step taken before working with a model was selecting the printer preset as Prusa MK3S from the list of options. A new project was created on the My Projects and then the Palette 3 Pro was selected as the device to be used. At this stage, the desired colours were selected for each of the inputs into the Palette 3. The STL file for Model 2B was added to the build plate and positioned accordingly to leave sufficient space for the wipe tower. Model 2B was manually coloured to test the painting tools in Canvas. In the Paint tool, as shown in Figure 32, four brush tools are available and a filament colour selector. The Facet tool paints individual triangle faces, the Sphere tool allows you to select a sphere size and paint freely, the Fill tool paints an entire connected section, and the Stamp tool allows you to upload an image, simplify the image colours using the available filaments and then paste the image on the model.

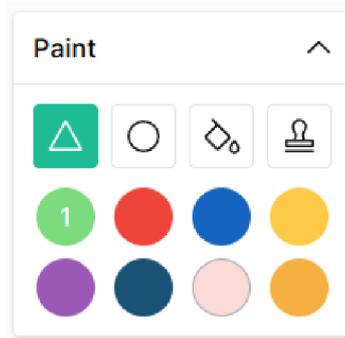


Figure 32 Painting tool options in the Canvas application.

For Model 4A, the five STL files were added to the build plate as a multi-material model. Using the drag-and-drop functionality, each layer was coloured by dragging the desired colour onto each layer. In the project settings, it is possible to make changes to the printer settings such as the layer height, infill, and perimeters. For this model, supports were enabled similarly to the configuration in PrusaSlicer for Model 4B. Lastly, the coloured model was sliced (visible in Figure 33) and downloaded in a “.mcfx” file which is a zip file with the G-code and other metadata.

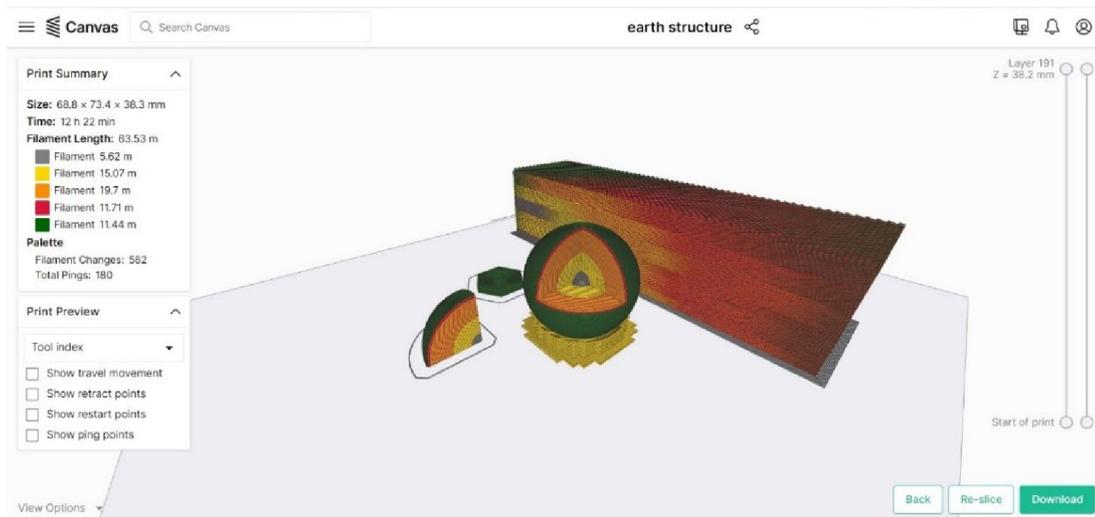


Figure 33 Sliced preview of Model 4A in Canvas.

Bambu Studio

For Model 4C, the first step in the printing process was configuring Bambu Studio. Under the Prepare tab, the printer preset was selected as Bambu Lab P1S 0.4 nozzle and the plate type was set as Textured PEI Plate. The next step was to add the AMS under the filament settings to allow for the configuration of the colours to be used. After adding the AMS, each filament was set to generic PLA from the preset options and the five colours were selected to match Models 4A and 4B. The system preset was maintained as 0.12 mm High Quality @Bambu X1C. The STL files were added to the build plate and duplicated to have 1 model at 30% print scale and two duplicates at 50% print scale. Preliminary slicing showed that the 30% scale model (matching Model 4A) would not print the Earth’s crust layer correctly, hence a 50% scale model was added that would print the layers correctly (shown in Figure 35). As with Model 4A and 4B, supports were enabled to allow for the printing of the spherical shape.

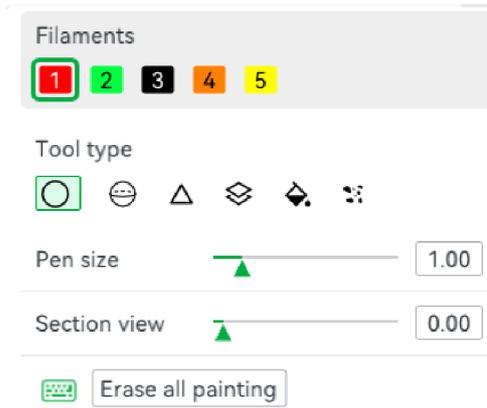


Figure 34 Painting tool options in Bambu Studio.

In Bambu Studio, the colouring options are found under the *Color Painting* button in the tools panel. As shown in Figure 34 above, the tool types available for colouring the model are *Circle*, *Sphere*, *Triangle*, *Height Range*, *Fill* and *Gap Fill*. Similarly to PrusaSlicer, there is a cross-sectioning tool that allows you to split the model to manually paint a specific section without affecting others. The Circle, Sphere and Triangle tools work similarly to those in PrusaSlicer and Canvas. Unique to Bambu Studio is the Height Range tool that colours all faces between a specified height range. The Fill tool colours a group of connected faces up until there is a face with a different colour. The Gap Fill tool works to refine the results of all the other tools by automatically detecting small gaps and filling them with the colour of a neighbouring group of faces. These tools were tested to successfully colour Model 4C. However, for the final model, seeing as the individual layers were present it was possible to select a single filament colour for each layer, hence simplifying the colouring process. After colouring the model, it was sliced and the result can be seen in Figure 35 below.

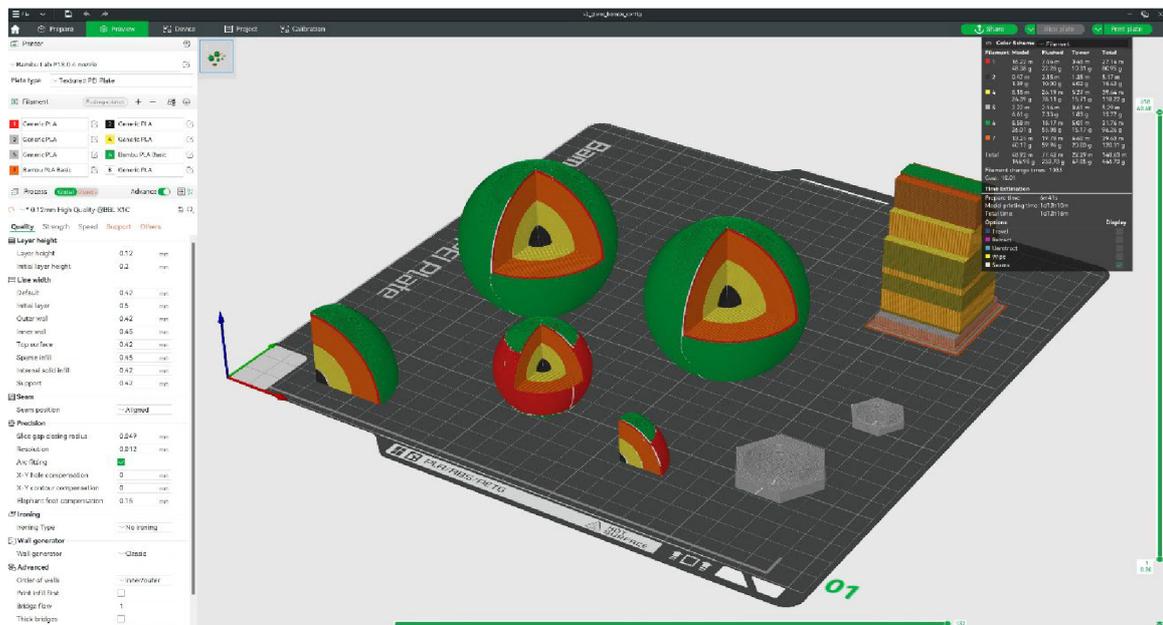


Figure 35 Sliced preview of Model 4C in Bambu Studio.

Waste Reduction

One of the most notable drawbacks of multicolour 3D printing is the production of waste filament in the colour-changing process. As mentioned in previous sections, each printer produces waste in different quantities and formats as shown in Figure 36 below. Prusa XL is very efficient in the colour-changing process as it uses different tools, while the other devices are splicing the filaments together to continue printing. 70% of the models in this research were printed using the Prusa XL to reduce material waste and print time (ultimately reducing electricity consumption). Some of the steps taken to improve waste management and efficiency in the production of the models included:

- For the Palette 3 Pro, the *Use infill for transition* setting was enabled to allow the device to use some of the transitioning filament as infill instead of placing it in the wipe tower. Similar settings, *Flush into objects' infill* and *Flush into objects' support* are available in Bambu Studio and were enabled for Model 4C.
- For the Palette 3 Pro, it was possible to use a variable transition length when switching between filament colours. In testing this method for Model 4A, the minimum transition length was set to 95 mm and the maximum was maintained at 105 mm. Lower minimum values were tested but the software experienced an error and would not slice the model with these lower minimum lengths. From this outcome, finding the optimal minimum and maximum lengths is an iterative process and can vary between models and filament colours.
- For the Prusa XL, it was possible to set the infill to a single extruder and this helped to slightly reduce the print time and the size of the wipe tower. For example, in Models 7A and 7B, the infill was set to the extruder with the red filament colour and this had no impact on the overall appearance of the finished model.
- For the Bambu AMS, multiple models (duplicates) were printed at the same time to reduce the overall amount of filament waste. The number of colour transitions remains the same for single or multiple models.
- In the AMS controls in Bambu Studio, in the flushing volumes setting, the multiplier was reduced from 1.0 to 0.6. This change caused the filament usage to decrease from 600 g to 415 g, which was a 31% reduction.

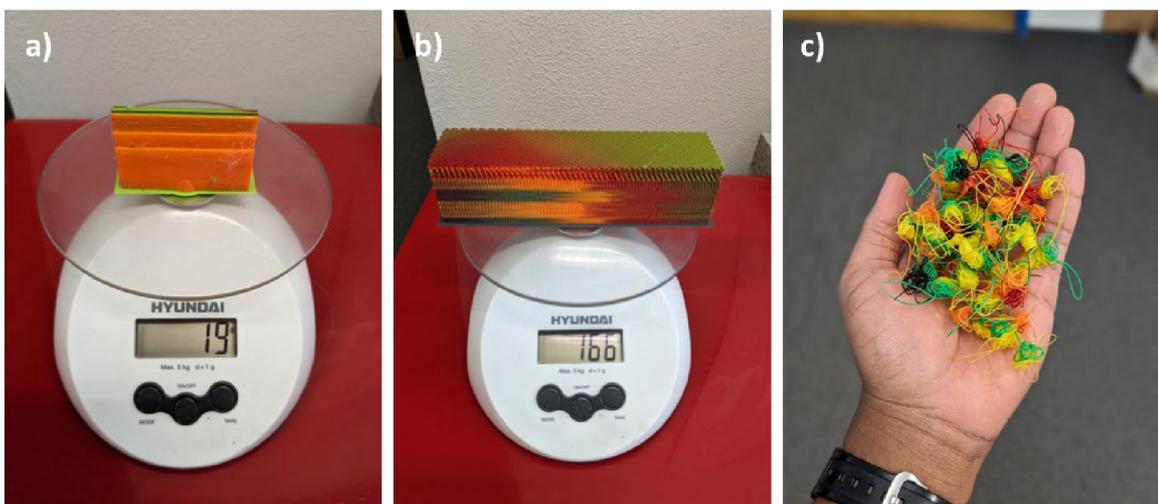


Figure 36 Comparison of waste material produced by a) Prusa XL wipe tower b) Palette 3 Pro wipe tower and c) Bambu AMS waste strips.

5.2 Printing the Models

Prusa i3 MK3S

The printer was powered on using the switch at the rear of the device. The print bed was removed from the printer and checked to be clear of any debris and a thin coat of adhesive spray was applied. The print bed snaps into place on the heat bed as it is magnetic. The first filament colour was mounted on the filament holder and the filament was inserted into the top of the extruder. Next, the SD card with the G-code for the model was inserted into the SD card slot on the printer. Using the LCD panel and the scroll knob, the model was chosen and the option to start the print was selected. After this, the printer began to heat the print bed to 60° C and the nozzle to 215° C. The printer then performed the auto bed levelling and X-Y geometry calibration functions to ensure the print bed and extruder were ready for printing. The nozzle began to extrude the filament to form the first layer and continued upwards.

The printing was checked occasionally to ensure everything was progressing smoothly. At the point of the filament change, the printer paused and pushed the filament out of the extruder. The user had to complete the filament unloading and loading the new filament. After loading the filament, the scroll knob was used to purge the old filament from the extruder until the correct colour was being extruded. The printer continued printing after selecting that the filament change was completed correctly. A second filament change was executed after a few hours to produce Model 1 with three colours. The printing was completed overnight and at the end of the print, the printer automatically disabled the heating based on a safety timer. The finished model was carefully removed from the print bed and the surface was cleared of any remaining debris.

Prusa i3 MK3S and Palette 3 Pro

The Palette 3 Pro was powered on, and the device was connected to the printer via USB. A layer of adhesive spray was applied to the print bed and the calibration of the Palette 3 was checked as it was not in use for an extended period. The device guided the user through the calibration check which included steps such as checking for firmware updates and checking the outgoing tube length (80 cm) connected to the printer. The filaments were placed into the filament holder for feeding into the device. Using a USB drive, the .mcfx file with the model was inserted into the device. Using the touchscreen, the model was selected for printing. Palette 3 then started the printing process by requesting each filament be loaded into the respective port numbered one to eight. The final setup of the Palette 3 can be seen in Figure 37a. After all the filaments were loaded, the printer then began preheating, and Palette 3 started to splice the filament together (shown in Figure 37b) to create the colour order needed to print the model. The spliced filament was pushed through the outgoing tubing and the device displayed a pop-up advising how to feed the spliced filament into the extruder. The tubing was then connected to the extruder and the print started. The extruder moved between the model and the wipe tower to purge between the colour changes as shown in Figure 37c below. The model was checked intermittently and in the case of Models 2B and 4A, they were left to print overnight due to the long print time. At the end of the print, the model and the wipe tower were removed from the print bed. The printer and Palette 3 were powered off after removing the model.

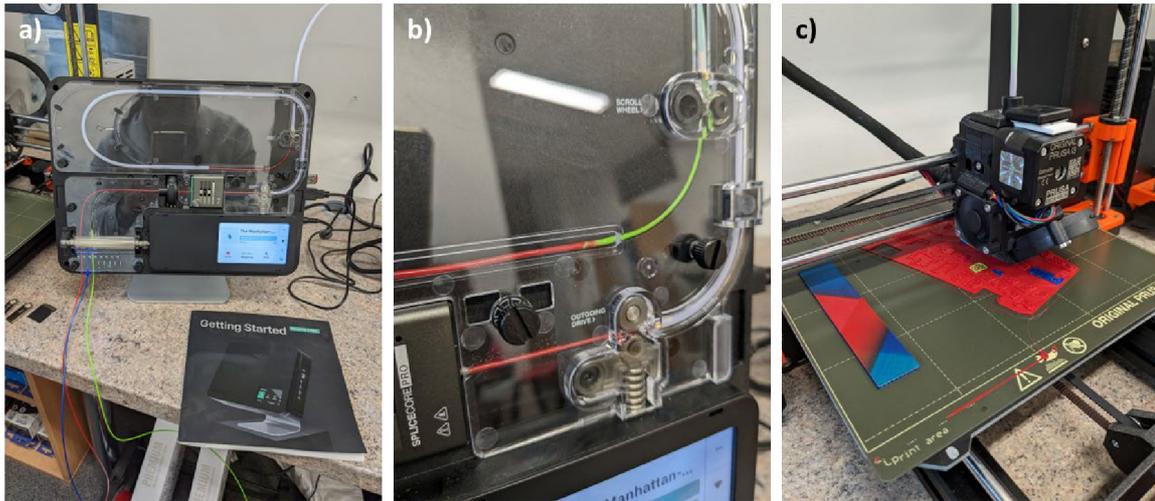


Figure 37 a) Setup of the Palette 3 Pro for Model 2B. b) Spliced filament being fed to the outgoing tube. c) Spliced filament being used to print the model and the wipe tower.

Prusa XL

The print bed was removed from the printer and checked for any unwanted debris and a layer of adhesive spray was applied. The primed bed was then placed on the magnetic heat bed with guiding pins at the back for correct alignment. Using the screen and scroll knob, the filament settings were accessed to load the five filaments into the printer. *Load filament* was selected and then *Tool 1* was selected from the list. The tool changer then moved Tool 1 from the parked position to over the print bed and started to preheat the extruder. The spool of filament was placed on the filament holder on the side of the printer and the filament was fed into the labelled tubing for Tool 1 until it reached the filament sensor in the extruder, as shown in Figure 38a. After being prompted by the screen to continue, the filament type was selected as PLA 215/60 and the filament was pulled into the extruder. *Purge more* was selected to ensure the filament colour being extruded was correct. This filament-loading process was repeated for the other four tools.

After loading the filaments, the USB drive containing the G-code was inserted into the printer. The software automatically detects the most recently added G-code file when the USB is inserted and loads this model on the screen. If another file is desired, the scroll knob can be used to browse and select a different model. With the model selected, the *Print* button was selected by pressing down on the scroll knob. An overview screen presents information about the print time and filament colours that were configured in PrusaSlicer. These colours can be checked with the filaments loaded into the printer before proceeding. With the settings confirmed, the printing process started. The printer started to heat the print bed and the nozzle. This was followed by the automatic bed levelling and checking each of the five tools for free movement from the parked position. Each tool was then used to extrude a small amount of filament at the edge of the print bed, outside the print area. After all these calibration steps were completed, the print started. The progress of the printer was checked intermittently for any errors. Before and after using each tool, a small amount of filament is extruded into the wipe tower to maintain colour integrity. This results in a relatively small wipe tower at the end of the printing in comparison to the overall model size, as shown in Figure 38b and c below.

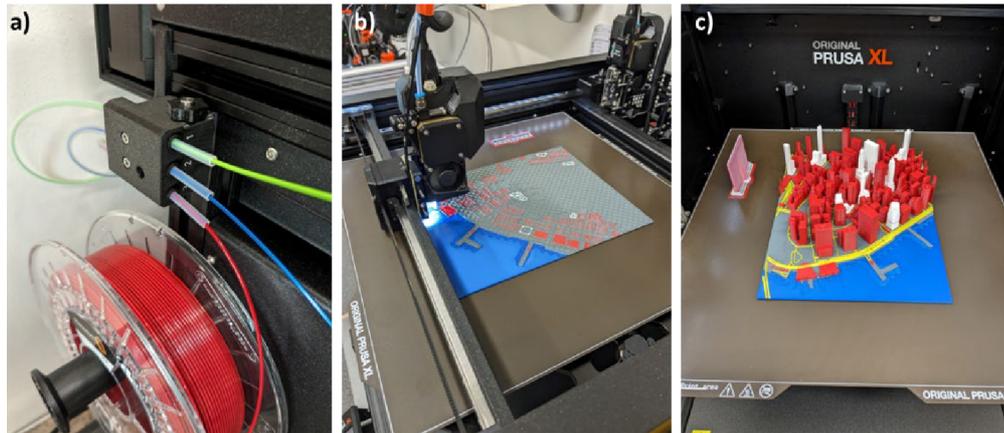


Figure 38 a) Filament loaded into Tools 1, 2 and 3 on the Prusa XL. b) Model 2A printing on the Prusa XL. c) Completed 5-colour model with the small wipe tower to the left.

Bambu P1S and Bambu AMS

The 3MF file for Model 4C was sent to the printer via a WLAN connection to start printing. Also, it is possible to upload files to the printer using a MicroSD card. Two AMS devices were connected to the printer, allowing up to eight colours to be printed. The first attempt at printing was plagued by several pauses by the printer. The root cause of this challenge was filament-related and is noted in the section 5.2.3 Printing Challenges below. This caused the first attempt to continue for approximately three days. The model printed partially, but a second attempt was made to print the main structure of the model. The pausing issue persisted, and the final model was printed over three days.

5.2.1 Safety Measures

When working with 3D printers it is important to follow general safety measures to prevent exposure to potential health and safety hazards. One of the first steps undertaken before the production of the models in this research was gaining a better understanding of the risks associated with FFF printers and the necessary safety practices and procedures. According to information from the National Institute for Occupational Safety and Health in the United States (2023) and All3DP (2022), some of the potential hazards of FFF printing include, but are not limited to:

- Fire hazard from electrical faults or heating-related failure
- Mechanical hazards (cutting yourself when removing supports or by sharp edges and getting your finger pinched or burned by the nozzle)
- Inhalation of unsafe airborne particulates [volatile organic compounds (VOCs)]
- Electrical shock from the high voltage of the printer

To reduce these potential risks, the following measures were taken when printing:

1. **Before Printing**
 - a. Review the specific printer's instructions and operations manual.
 - b. Inspect the printer to ensure it is clean and in good working condition.
2. **During Printing**
 - a. Avoid touching the hot print bed and extruder while in operation.
 - b. Limit the time spent observing the printer while it is in operation.
3. **After Printing**
 - a. Cool down and turn off the printer.
 - b. Clean up the print bed and surroundings of any waste material.
 - c. Wash hands after handling the filament and printed objects.

5.2.2 Post-processing Steps

FFF printing results in models having layer lines, seam lines and support marks that need post-processing to improve the overall appearance of the model. The steps that were taken for the models produced in this research included:

- Carefully removing supports.
- Disposal of the wipe/purge tower.
- Using a filament cutter and tweezers to remove unwanted pieces of extruded filament. Research through online 3D printing forums showed that a heat gun could be used to remove the thin “stringing” that happened during printing. However, this method was not tested.
- Using sandpaper to smooth areas where the layers were rough or extra smoothness was necessary. Some of the braille dots were smoothed using sandpaper.

5.2.3 Printing Challenges

Throughout the printing process, some challenges were encountered and have been outlined below. Most of these challenges were resolved, but some impacted the final products.

- Palette 3 Pro ran into an issue loading filament from the device into the printer. Sometimes the filament was not inserted correctly into the printer through the tubing and unloading the filament from the printer caused the Bowden tubing to become detached. The solution was to reinsert the tubing and carefully load the filament at the start of the print.
- The Palette 3 Pro Velcro attached piece for holding the tubing to the printer detached on two occasions. The piece was then secured using glue and tape.
- Palette 3 Pro experienced two filament jams caused by using old and brittle filament.
- Both the Prusa XL and Palette 3 Pro experienced slicing errors with streaks of misplaced colours in Models 2A and 2B. An update released for PrusaSlicer subsequently fixed these slicing issues.
- Palette 3 Pro experienced significant colour bleed on Model 4A.
- On the Prusa XL, a loose screw on one tool resulted in a problem with the tool not parking properly. This caused repeated printer collision errors. The temporary solution was to properly park the tool manually. The print continued after the proper parking was done and the printer completed a homing process to recalibrate the print head with the bed. The screws were tightened, and all subsequent printing proceeded without error.
- On Model 7B using the Prusa XL, the black filament was defective/old and caused a block in the extruder. This resulted in the labels and map title not being printed. The blockage was purged after the model was printed.
- While printing Model 4C on the Bambu P1S, the printer paused printing several times because of the filament spool shifting in the AMS. The shifting was a result of using non-Bambu filament spools in the AMS. The shifting of the filament spool caused the filament to get tangled with other spools in the AMS. The extended print time resulted in the supports fusing to the model near the base as the build plate was heated and cooled several times. This fusing made the supports very hard to remove.

6 USER TESTING

This chapter gives an overview of the user testing exercises that were carried out to determine the quality of the multicolour models through user feedback. Initially, only one exercise was planned with the public using Model 6. However, the opportunity arose to conduct a second user testing exercise with users with visual impairments. This was ideal as Models 3A-D were designed specifically for this user group.

General Public

A user testing exercise was devised to be carried out with Model 6: Population Structure Pardubický kraj. The participants in this exercise were mainly students studying in different areas such as Geoinformatics, Biology and Mathematics and had varying levels of knowledge of using and reading maps. A questionnaire was developed to ask questions about map content and interpretation, general feedback about the quality of the model, and questions comparing the model to the equivalent paper map. The questionnaire was transformed into a digital form using ArcGIS Survey123. The full questionnaire is available in Attachment 1 for reference.

The survey was carried out using mobile devices with the Survey123 application between March 18 and April 2, 2024. The researcher conducted the user testing with individuals who could speak English at a level good enough to understand the explanation of the exercise. One of the participants of the test can be seen in Figure 39 interacting with the model before answering the questions. The survey was made available in English and Czech using a translation function in Survey123. Some of the participants preferred to complete the questionnaire in the Czech language for ease of understanding.



Figure 39 A participant from the user testing exercise interacting with the model before completing the questionnaire.

The questionnaire was structured in four sections. After the introduction, part one asked map interpretation questions based on the content shown in the map field and the legend. There was no time limit on answering the questions and all the questions in this section were mandatory. Section two asked general feedback questions about the users' knowledge of maps, opinions about the layout, the use of colours and the legend. All the questions in this section were mandatory. The format of the survey for sections one and two can be seen in Figure 40 below. Part three of the questionnaire had the user interact

with the 3D-printed map and the equivalent paper map (shown in Figure 41). After this, the user was asked which of the two media they preferred. The user could also provide additional feedback in this section. The last section asked the user for optional demographic information.

Map Interpretation

Please answer the following questions about the contents of the map.

Can you identify which administrative area has the lowest population density?*

Polička Králupy Litomyšl

Svitavy

Can you identify which 2 administrative areas have the highest population densities?*

Pardubice Vysoké Mýto Česká Třebová

Chrudim

Which age group is the largest in Žamberk?*

0-14 15-64 65 and over

General

Please examine the 3D-printed map and answer the following questions.

How familiar are you with using and reading maps?*

E.g. printed maps or web maps such as Google Maps, etc.

Extremely familiar Very familiar Moderately familiar Slightly familiar Not familiar

How much do you agree or disagree with the following statements about the map layout?

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The pie charts on the map are legible and well placed.*	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The population density of municipalities is easy to read.*	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The size of the map is good for understanding the information shown.*	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Figure 40 Format of the questionnaire in Survey123.

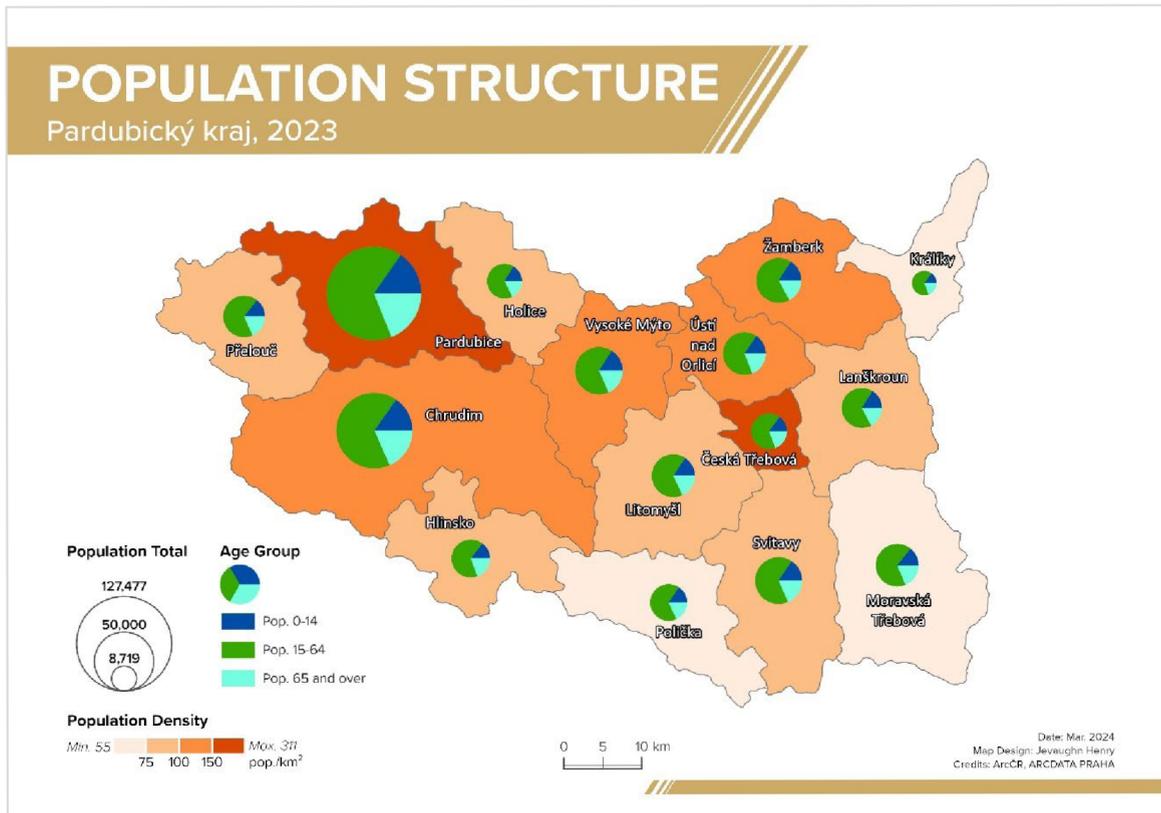


Figure 41 Paper map used for comparison in the user testing exercise.

Users with Visual Impairment

Models 3A and 3B from the Praha Metro model set and Model 7A from the land cover set were tested by students in Prague. These students had varying levels of visual impairment, from complete blindness to having some remnants of sight. Participants in the test can be seen in Figure 42 and Figure 43 below. The students tested the 3D models and other mapping products created by researchers in the KGI department. RNDr. Alena VONDRÁKOVÁ, Ph.D., LL.M. was the contact person and collected and shared the feedback from the students.



Figure 42 Visually impaired user interacting with Model 3B.



Figure 43 Visually impaired user interacting with Model 3A.

7 BOOKLET CREATION

The goal of creating a booklet for this research was to showcase the results and findings in a simple and user-friendly format. The intended audience for the booklet is the current and future users of the KGI 3D Lab and other researchers interested in creating 3D-printed geovisualisations. The two main components of preparing the booklet were design and printing. The design process was iterative and involved many revisions to capture all the results in a visually pleasing way while providing important descriptive text giving an overview of the research.

Design

Adobe InDesign was the main software used to collate the information and design the booklet. Adobe Illustrator was also used to create graphic elements for the booklet and the accompanying thesis poster and website. To make the booklet easier to hold and more inviting, A5 (210 × 148 mm) page size in landscape format was selected. A key component of the design was the utilisation of high-quality images to capture the best view of the 3D-printed models and users interacting with the models. The booklet also contains tips and resources for creating 3D-printable geovisualisations. The booklet was designed in the CMYK colour space as the product was intended to be printed.

Parent pages were created to standardise the layout of the booklet as shown in Figure 44. The main elements on the parent pages included the page title, page number and image frames. The colour palette for the design was comprised of four main colours, yellow (C=0, M=10, Y=80, K=0), blue (C=80, M=30, Y=30, K=0), green (C=40, M=0, Y=100, K=0) and red (C=20, M=100, Y=100, K=25). Before importing the images into the design, they were upscaled to 300 DPI. The upscaling was done using Adobe Photoshop Image Processor to batch process all the images. The upscaling action was created and saved and then applied using the Image Processor and the resulting upscaled images were saved in the designated folder location. Other graphics were added as SVG to maintain quality when exporting the final booklet.

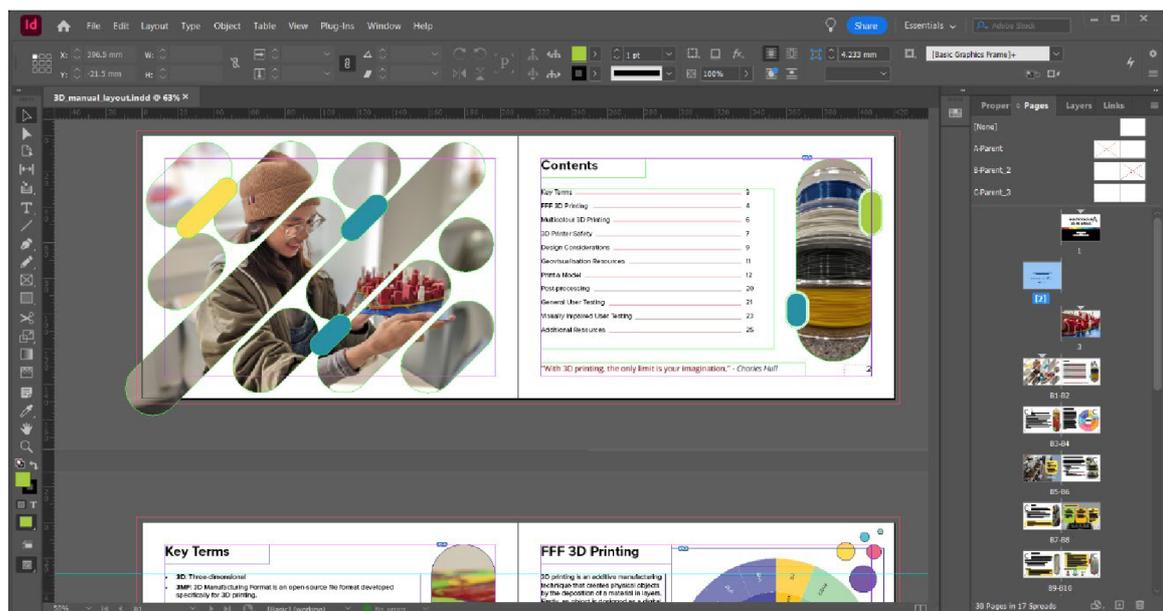


Figure 44 Booklet layout in Adobe InDesign.

Printing

The booklet was exported as two PDF files, one for print production and another for web viewing. The web PDF was exported as an interactive PDF to maintain hyperlinks and bookmarks. The print production version was exported using the PDF/X-1a:2001 standard at a resolution of 300 DPI. As shown in Figure 45, crop marks and a 3 mm bleed were enabled to ensure precise printing and cutting of pages by the publishing house. The colour profile was set to Coated FOGRA39 (ISO 12647-2:2004). The booklet was printed on Xerox Colotech 280 g paper and assembled with Wire-O binding.

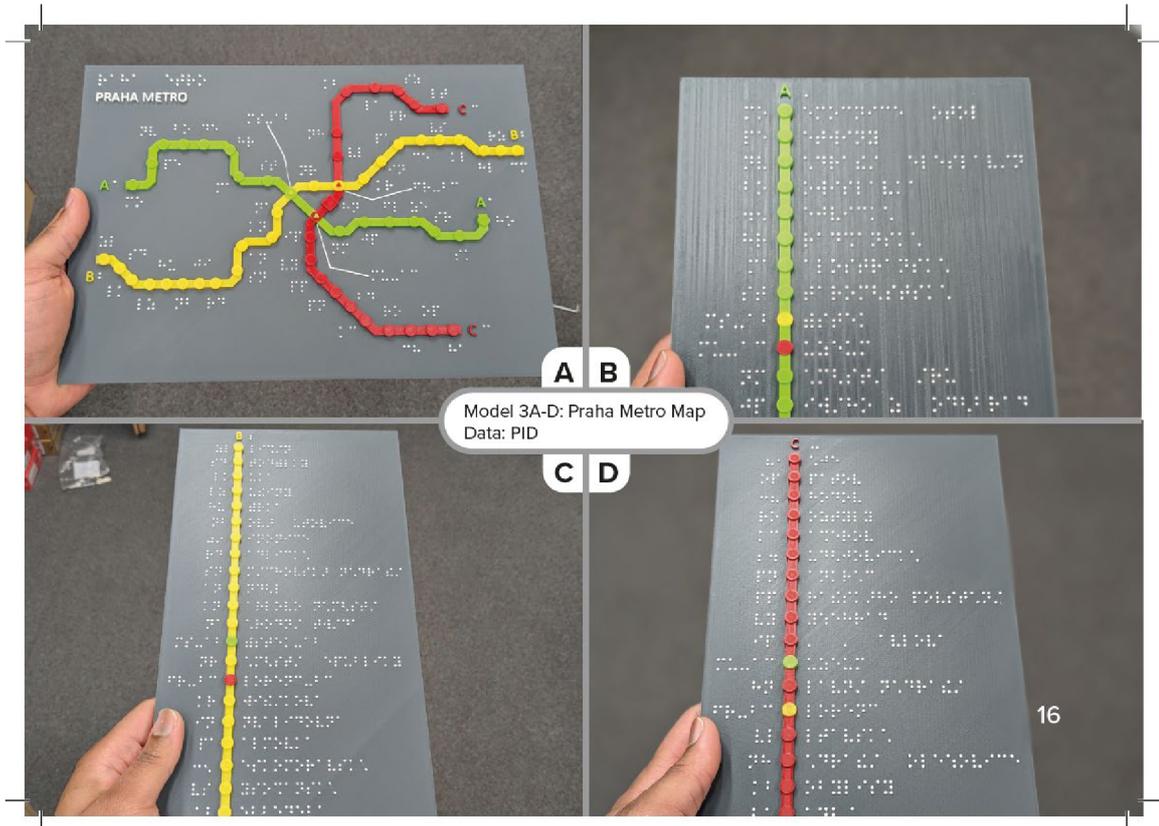


Figure 45 An example page featuring crop marks and bleed from the print PDF.

8 RESULTS

In this chapter, the models designed and printed are presented. The quantity of waste produced from each print and a comparison between printers is also showcased. The results of the user testing survey are described in detail and the feedback from the visually impaired users is also presented. However, given the time constraints of this research, most of the improvements needed for the models have been noted for future research.

8.1 Multicolour Models

In achieving the primary objective of this research, a series of 3D-printed multicolour geovisualisations were produced with the printers available in the 3D Lab. Table 4 gives an overview of the 14 models that were printed using PLA filament and the 2 test models that were not printed but were used to develop the methods described in Chapter 4 Design of 3D Models. Figure 46 gives a preview of all the printed models, with the full details of each model being available in Attachment 2. The physical models are also available as Free Attachments 5-17.

Table 4 List of the completed and test models.

#	Name	Scale	# of colours	Dimensions [mm] (L×W×H)	Printer
1	Kingston Mountains	1:25,000	3	117×114×30	Prusa i3 MK3S
-	Jamaica Earthquake		5		
-	City of Luxembourg		4		
2A	New York City	--	5	181×225×59	Prusa XL
2B	New York City	1:6,500	3	131×157×84	Prusa i3 MK3S & Palette 3 Pro
3A	Praha Metro Map	N/A	5	301×213×7	Prusa XL
3B	Praha Metro Line A	N/A	5	168×242×6	Prusa XL
3C	Praha Metro Line B	N/A	5	162×329×6	Prusa XL
3D	Praha Metro Line C	N/A	5	162×281×6	Prusa XL
4A	Earth Structure	1:333,000,000	5	69×73×38	Prusa i3 MK3S & Palette 3 Pro
4B	Earth Structure	1:333,000,000	5	81×68×38	Prusa XL
4C	Earth Structure	1:200,000,000	5	203×162×64	Bambu P1S & AMS
5	Austria Population Density 2023	1:5,000,000	4	170×87×9	Prusa XL
6	Population Structure Pardubický kraj	1:500,000	6	257×190×13.5	Prusa XL
7A	Lucerne Land Cover OSM	1:40,000	6	211×149×13	Prusa XL
7B	Lucerne Land Cover CLC	1:40,000	6	211×149×13	Prusa XL

Completed Test Model

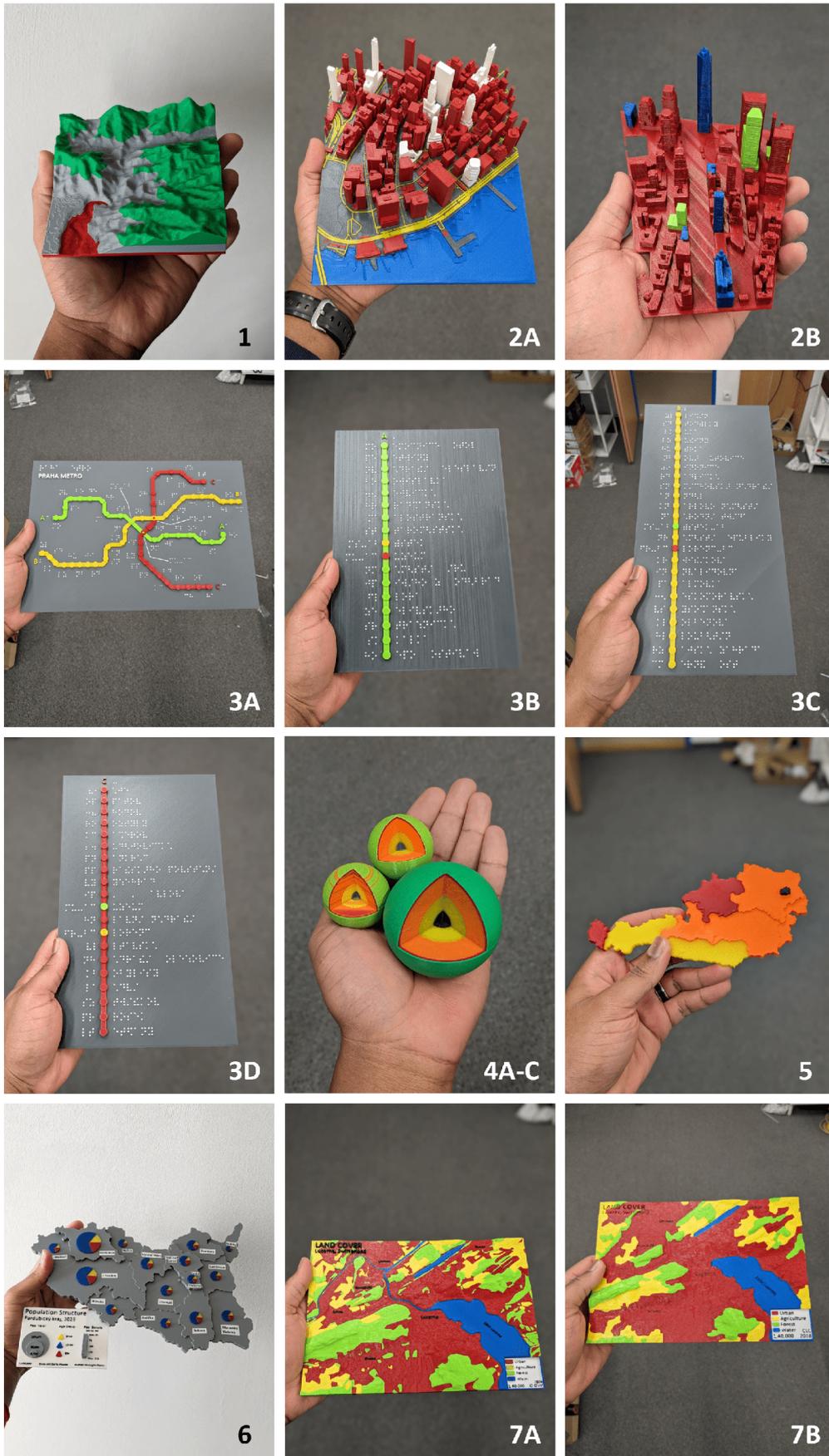


Figure 46 Preview of all the printed models.

8.2 Multicolour 3D Printing Booklet

The booklet provides an easy-to-read overview of multicolour FFF 3D printing and shares valuable insights from this research. The A5 form factor of the booklet makes it a quick handheld resource for addition to the KGI 3D Lab. The physical booklet is available as Free Attachment 3 and a view can be seen in Figure 47. A digital flipbook version was published on Issuu and is available [HERE](#).



Figure 47 Printed Multicolour 3D Printing booklet.

8.3 Waste Management

Based on the methods applied in Chapter 5.1 Model and Printer Configuration, the wipe tower from each print was photographed and weighed before disposal. Table 5 shows the amount of waste produced by each model, with the least waste by percentage highlighted in green and the most wasteful highlighted in orange. Model 1 used the Pause and Swap method and produced no waste, making it the most environmentally friendly. For Model 4C, three copies were printed in the same session with a minimal increase in waste and print time.

Table 5 Waste produced, and total filament used for printing each model.

#	Printer	Print Time	Waste (g)	Total filament (g)	Percentage of waste
2A	Prusa XL	14h 08m	10	254	4%
2B	Palette 3 Pro	18h 01m	153	209	73%
3A	Prusa XL	10h 22m	5	165	3%
3B	Prusa XL	9h 34m	3	109	3%
3C	Prusa XL	7h 26m	3	141	2%
3D	Prusa XL	6h 20m	3	122	3%
4A	Palette 3 Pro	12h 22m	166	183	91%
4B	Prusa XL	2h 42m	19	40	48%
4C	Bambu AMS	34h 16m	300	447	67%
5	Prusa XL	2h 48m	4	32	13%
6	Prusa XL	8h 36m	12	129	9%
7A	Prusa XL	18h 21m	12	145	8%
7B	Prusa XL	13h 24m	12	128	9%

8.4 Results of User Testing

Survey Results

The public user testing exercise had a total of 20 participants. The demographics of the participants can be seen in Figure 48. The participants were mainly university students between the ages of 18 and 34. 50% of the participants were very familiar with reading and using maps as shown in Figure 49. This familiarity aided in the quick understanding of the exercise and sparked insightful conversations about the attractiveness of the 3D-printed map compared to previously used maps.

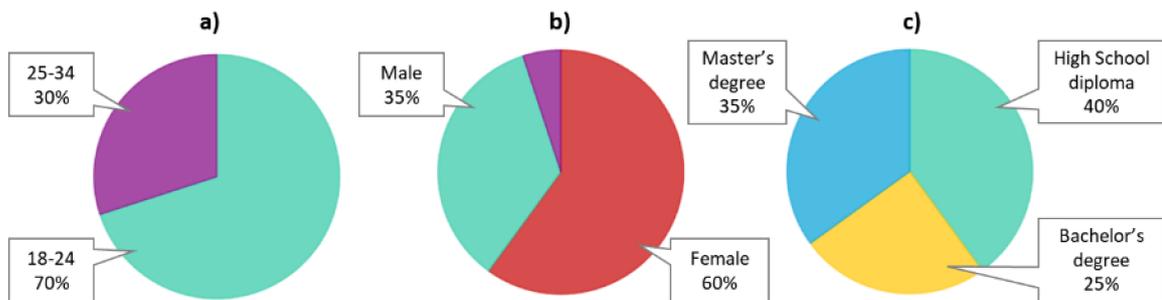


Figure 48 Demographics of the participants by a) age group, b) sex and c) educational level.

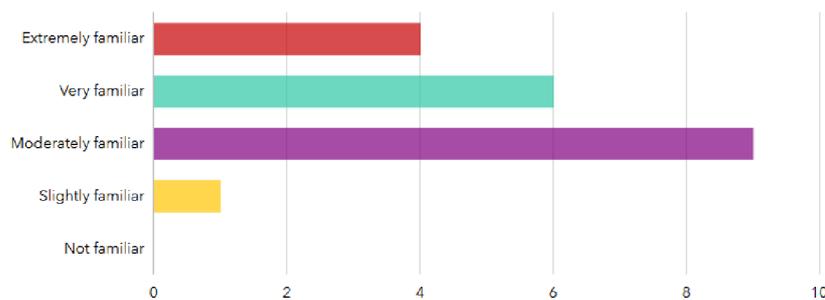


Figure 49 Participants' familiarity with using and reading maps.

90% of the participants answered all the map interpretation questions correctly. A few participants confused the size of the chart symbols (representing the total population size) with the population density which was represented by the height of the extrusion for each administrative area. The spread of responses in Figure 50 shows that the differences in the extrusions could have been made more significant for easier understanding. Notwithstanding, **75%** of the participants indicated the population density was easy to read. More conclusively, **90%** of the participants agreed that the use of multiple colours aided in better understanding the 3D-printed map and made it more appealing.

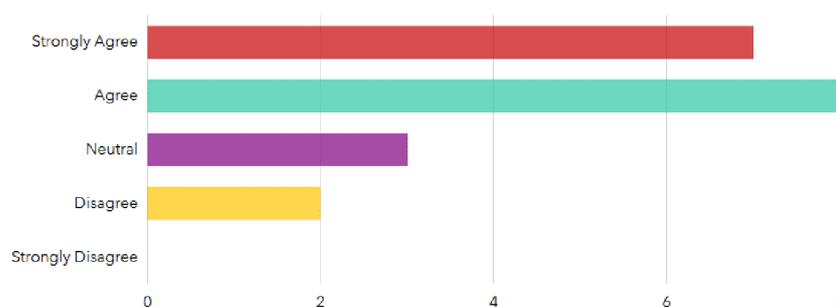


Figure 50 Participants' feedback on the understandability of the extrusions showing the population density.

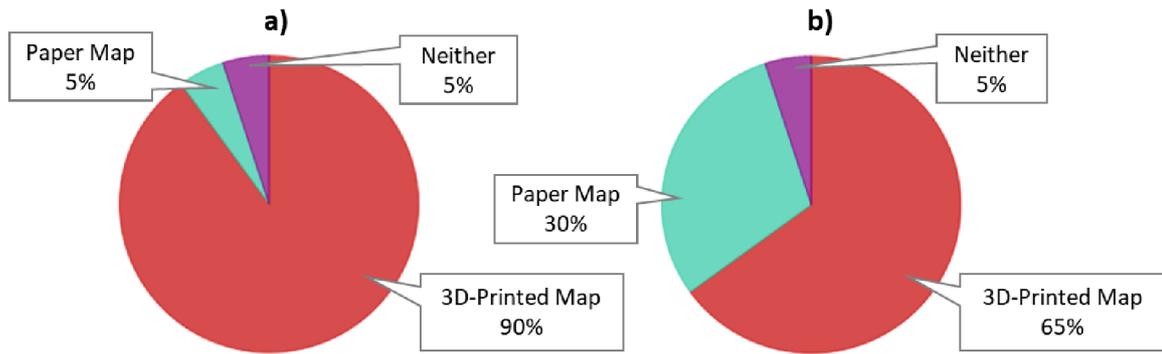


Figure 51 Map comparison based on a) attractiveness and b) understandability.

For the map legend, **15%** of the participants found that the text descriptions were not well-sized and readable and **20%** indicated that the number descriptions were not well-sized and readable. This feedback was used to make improvements to Models 7A and 7B. Finally, compared to the paper map showing the same information, **90%** of the participants found the 3D-printed map more attractive (see Figure 51a). However, only **65%** found the 3D-printed map to be more understandable than the paper map (see Figure 51b). The verbal feedback from participants highlighted that this type of multicolour 3D model was new to them, and they enjoyed interacting with the map and saw great potential for its application in teaching exercises.

Feedback from users with visual impairment

The feedback from this user testing exercise was noted for future work to create a refined set of products that could be shared with the school or similar teaching institutions. The main feedback received from the students is highlighted below:

- The models were found to be very helpful, especially the model of Metro Line A.
- The braille on the metro maps was very readable even though the surface of the dots was a bit unusual for the participants.
- In the braille, some words were missing their first letter (e.g. instead of Metro Praha there is “etro raha”). The reason for this was a mistake in attempting to use capital letters as these are not present in the braille font.
- Some labels were more challenging to link with the appropriate station because of spacing in the complete metro map in Model 3A.
- Transfer stations could have been made more significant or distinguishable.
- The land cover model (7A) could be adapted for the visually impaired with changes to the use of colour for features and elevation.

9 DISCUSSION

This research's overarching goal of exploring and evaluating the possibilities of multicolour 3D-printed geovisualisations using KGI 3D lab resources led to the discovery of many technicalities and considerations during the modelling and printing phases. The equipment tested provided a good overview of products available in the commercial 3D printing market to the public and other researchers. Therefore, the insights from this study can be applied in research institutions and by hobbyists using the same or similar equipment worldwide.

The most notable observation throughout the research was that there remains a challenge in converting geospatial data into 3D-printable formats. QGIS offers a plugin that aids in this process but is limited to DEMs or raster data. ArcGIS Pro offers good 3D visualisation options in local and global scenes; however, these cannot be exported to 3D file formats that can be further prepared for 3D printing. The solution/workaround involved multiple file format conversions to get the necessary data into 3D modelling software. These conversions increase the time and complexity of the 3D modelling process. The additional loss of some of the original data further reduces the likelihood of adoption of these methods by many users. As an area for future work, potentially outside of academic research, is the need for more options within the GIS applications to export 3D models.

The 14 models fully tested the capabilities of each printer for multicolour FFF printing. These models utilised different colours both horizontally and vertically and pushed the limits of the equipment. The resulting physical models covered case studies such as terrain models, city models, geology, transit maps, tactile maps, and thematic maps. The geovisualisations produced indicate that multicolour FFF printing can be applied to a range of subject matters. The user testing also corroborated the range of applications for multicolour 3D-printed geovisualisations. Users reiterated the potential application of the outputs in the classroom for knowledge transference and maintaining students' interest. If used in conjunction with paper maps, which continue to be advantageous in terms of cost, time, and understandability, 3D-printed geovisualisations can be a great learning resource in schools, conferences, exhibitions, museums, and other settings.

Of the printers, the Prusa XL produced the best outputs with the lowest environmental impact (waste and print time). The technology of the Prusa XL is unrivalled in the 3D printer market and the cost premium is very high. This reduces its accessibility to users who would benefit significantly from multicolour printing. The multimaterial add-ons to single extruder printers therefore provide a reasonable compromise in terms of cost and accessibility. The offerings from Bambu Labs provide good value for money and excellent quality, with the disadvantages being significantly increased material waste and print time. However, for creating geovisualisations, which is not a time-sensitive matter in most cases, the multimaterial add-on method is the most viable for academic research and teaching institutions.

The three FFF multicolour printing methods tested proved effective in producing high-quality outputs. The challenges experienced during printing did affect some of the results, but this provided a learning opportunity for navigating the world of 3D printing. The versatility of PLA filament also proved ideal for producing these models at a relatively low cost. An improvement to the current research that can be conducted is the use of a different filament type to print braille dots to enhance the texture and readability. The waste reduction strategies had varying levels of success. The purge to infill settings offered minimal waste savings, and this may only produce significant results if the infill

is set to a value over 50% on larger models. Future research can delve more deeply into waste reduction strategies as this area warrants more studies. Regarding geovisualisations and multicolour 3D printing, future research can look at creating more detailed thematic maps and combining them in an “atlas” of 3D-printed maps with open-access digital files for reproduction.

10 CONCLUSION

This research delved into multicolour 3D printing, specifically focusing on fused filament fabrication 3D printers available in the KGI 3D Lab to create attractive geovisualisations. Through a systematic exploration, examination, and evaluation, the research aimed to test the potential of this technology with a series of defined objectives. The first of which was the preparation of a variety of models, each varying in complexity. This foundational step was crucial in understanding the boundaries and possibilities inherent in the technology.

In bringing the models to life, the research sought to develop and optimise printing parameters and processes to attain high-quality multicolour prints. This iterative process involved fine-tuning the models and settings to achieve the desired level of detail, colour accuracy, and structural integrity. The resulting physical models are a testament to the quality of the outputs. Select models were tested with the public and users with visual impairment, with most of the feedback being positive in regards to the use of colour, understandability, and attractiveness of the models. The feedback from both user groups provided insight into improving the models and concept ideas for future work.

A comprehensive multicolour 3D printing booklet was created as a tangible outcome of this research, providing a valuable resource for the department and beyond. By documenting the printing results and lessons learned, this booklet facilitates internal knowledge transfer and promotes the dissemination of best practices to a wider audience. Additionally, endeavours were made to reduce the environmental impact of multicolour 3D printing by evaluating and reducing waste material production. The savings in material and energy used, however minimal will lessen the impact of 3D printing on the environment. Among the tested equipment, the Prusa XL stood out for its efficiency, albeit with cost considerations. The balance between price and functionality with multi-material add-ons for single extruder printers was explored, and even though there is increased waste and print time this option offers excellent value and is more likely to be adopted by a wider audience.

As multicolour 3D printing continues to become more accessible, the significance of this research extends to its potential applications. Through impactful multicolour geovisualisations, the models produced hold promise in diverse fields such as education, urban planning, and accessibility for the visually impaired community. These visualisations can simplify complex concepts, facilitate spatial understanding, and enhance communication in various domains. Furthermore, by sharing the findings and methodologies, this research can empower other researchers and enthusiasts to leverage multicolour 3D printing for their projects.

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ATTACHMENTS

LIST OF ATTACHMENTS

Bound attachments

Attachment 1	User Testing Survey
Attachment 2	Data Sheet for the Models Printed

Free attachments

Attachment 3	Multicolour 3D Printing Booklet
Attachment 4	Model 1: Kingston Mountains
Attachment 5	Model 2A: New York City
Attachment 6	Model 2B: New York City
Attachment 7	Model 3A: Praha Metro Map
Attachment 8	Model 3B: Praha Metro Line A
Attachment 9	Model 3C: Praha Metro Line B
Attachment 10	Model 3D: Praha Metro Line C
Attachment 11	Model 4A: Earth Structure
Attachment 12	Model 4B: Earth Structure
Attachment 13	Model 4C: Earth Structure
Attachment 14	Model 5: Austria Population Density 2023
Attachment 15	Model 6: Population Structure Pardubický kraj
Attachment 16	Model 7A: Lucerne Land Cover OSM
Attachment 17	Model 7B: Lucerne Land Cover CLC
Attachment 18	Poster (A2 Format)
Attachment 19	Thesis Website

Structure of Digital Data

Output_Models:

- M1_kingston_mountains.3mf
- M2A_new_york_city.3mf
- M2B_the_manhattan_project.stl
- M3A_metro_map.3mf
- M3B_metro_LineA.3mf
- M3B_metro_LineB.3mf
- M3B_metro_LineC.3mf
- M4AB_earth_structure.3mf
- M4C_earth_bambu_studio.3mf
- M5_austria_population.3mf
- M6_pardubicky_kraj.3mf
- M7A_lucerne_land_cover_OSM.3mf
- M7B_lucerne_land_cover_CLC.3mf

Booklet

- multicolour_3d_printing_300dpi.pdf

Attachment 1

3D-Printed Map Evaluation

Survey123 Link: <https://arcg.is/1KWbyC>

I am a graduate student at the Palacký University Olomouc specialising in Geovisualization and Geocommunication. As part of my Master thesis, I am conducting a short usability test for cartographic products that I created. The information that you provide will be treated as confidential and will only be used for research purposes.

Thank you in advance!

** Required question*

Map Interpretation

Please answer the following questions about the contents of the map

1. Can you identify which administrative area has the lowest population density?*

 - a. Králíky
 - b. Litomyšl
 - c. Polička
 - d. Svitavy

2. Can you identify which 2 administrative areas have the highest population densities?*

 - a. Česká Třebová
 - b. Vysoké Mýto
 - c. Pardubice
 - d. Chrudim

3. Which age group is the largest in Žamberk?*

 - a. 0-14
 - b. 15-64
 - c. 65 and over

4. Which administrative area has the smallest total population?*

 - a. Polička
 - b. Holice
 - c. Hlinsko
 - d. Králíky

5. Which administrative area has the largest total population?*

 - a. Česká Třebová
 - b. Vysoké Mýto
 - c. Chrudim
 - d. Pardubice

6. Which of the four administrative areas from the same class (Chrudim, Vysoké Mýto, Žamberk, Ústí nad Orlicí) has the highest population density?* (Use both the Paper and 3D-Printed Map to answer this question.)

 - a. Vysoké Mýto
 - b. Chrudim
 - c. Ústí nad Orlicí
 - d. Žamberk

General Feedback

Please examine the 3D-printed map and answer the following questions.

7. How familiar are you with using and reading maps?* (E.g. printed maps or web maps such as Google Maps, etc.)
 - a. Extremely familiar
 - b. Very familiar
 - c. Moderately familiar
 - d. Slightly familiar
 - e. Not familiar

8. How much do you agree or disagree with the following statements about the map layout?

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The pie charts on the map are legible and well-placed.*					
The population density of administrative areas is easy to read.*					
The size of the map is good for understanding the information shown.*					

9. How much do you agree or disagree with the following statements about the use of colour?

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The presence of multiple colours helped in better understanding the map.*					
The colours used were easily distinguishable.*					
The multiple colours of the model made it more appealing.*					

10. How much do you agree or disagree with the following statements about the map legend?

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The legend contains the symbols needed to understand the map.*					
Text descriptions are well-sized and readable*					
Number descriptions are well-sized and readable*					

Map Comparison

Please look at the paper map and the 3D-printed map showing the same information and answer the following questions.

11. Which of the two maps do you find more attractive?*

 - a. Paper Map
 - b. 3D-Printed Map
 - c. Neither

12. Which of the two maps was easier to understand?*

 - a. Paper Map
 - b. 3D-Printed Map
 - c. Neither

13. Do you have any additional feedback?

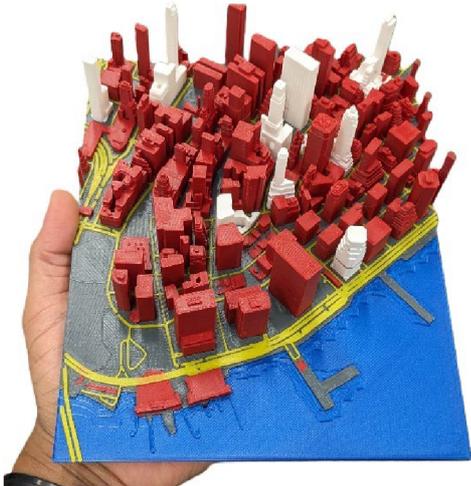
Demographics

14. What age group are you in?
 - a. Under 18
 - b. 18-24
 - c. 25-34
 - d. 35-44
 - e. 45-54
 - f. 55+
15. What is your sex?
 - a. Male
 - b. Female
 - c. Prefer not to say
16. What is your educational level?
 - a. No formal education
 - b. High School diploma
 - c. Vocational training
 - d. Bachelor's degree
 - e. Master's degree
 - f. Ph.D.

Attachment 2

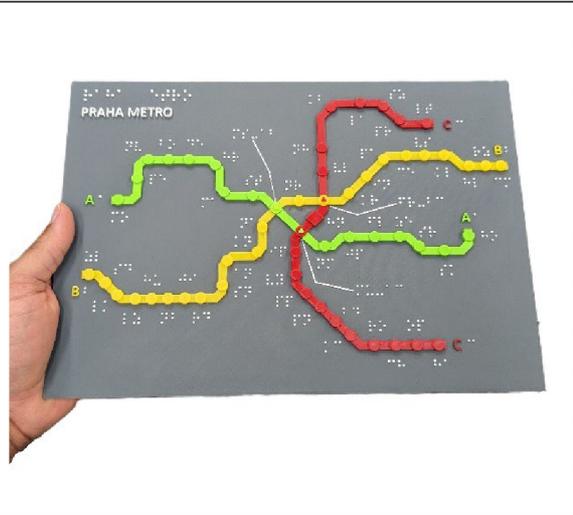
Data Sheet for the Models Printed

Model: 1	
Name: Kingston Mountains	
Data Source: Copernicus 30m DEM	
Scale: 1:25,000	
Dimensions (mm): 117×114×30	
Z Factor: 1.5	
Print Size: 100%	
Number of Colours: 3	
Printer: Prusa i3 MK3S	
Print Time: 6h 54m	
File: M1_kingston_mountains.3mf	

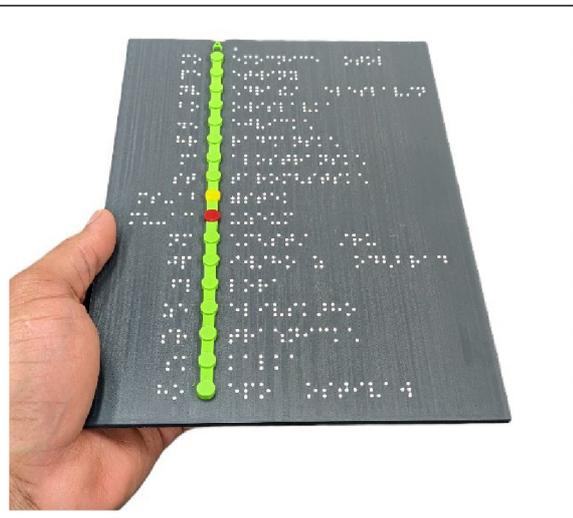
Model: 2A	
Name: New York City	
Data Source: Cadmapper	
Scale: --	
Dimensions (mm): 181×225×59	
Z Factor: 1	
Print Size: 15%	
Number of Colours: 5	
Printer: Prusa XL	
Print Time: 14h 08m	
File: M2A_new_york_city.3mf	

Model: 2B	
Name: New York City	
Data Source: The Manhattan Project by Jib22 on Thingiverse	
Scale: 1:6,500	
Dimensions (mm): 131×157×84	
Z Factor: 1	
Print Size: 100%	
Number of Colours: 3	
Printer: Prusa i3 MK3S & Palette 3 Pro	
Print Time: 18h 01m	
File: M2B_the_manhattan_project.stl	

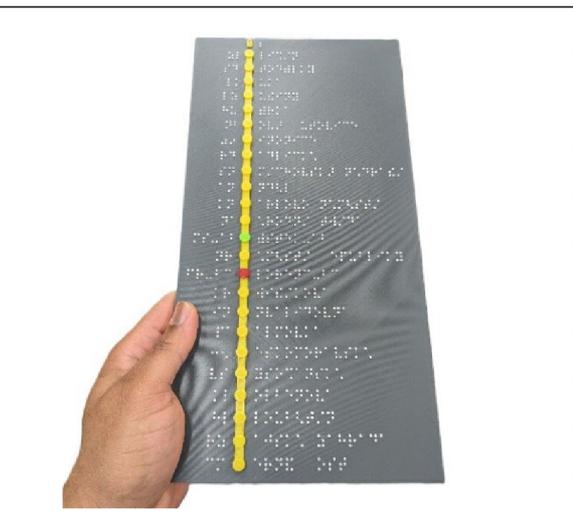
Model: 3A
Name: Praha Metro Map
Data Source: PID
Scale: --
Dimensions (mm): 301×213×7
Z Factor: 1
Print Size: 100%
Number of Colours: 5
Printer: Prusa XL
Print Time: 10h 22m
File: M3A_metro_map.3mf



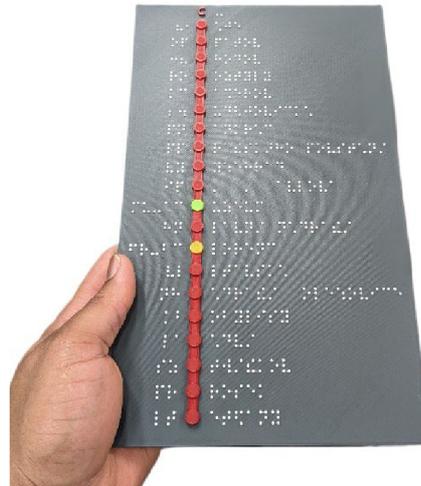
Model: 3B
Name: Praha Metro Line A
Data Source: PID
Scale: --
Dimensions (mm): 168×242×6
Z Factor: 1
Print Size: 100%
Number of Colours: 5
Printer: Prusa XL
Print Time: 9h 34m
File: M3B_metro_LineA.3mf



Model: 3C
Name: Praha Metro Line B
Data Source: PID
Scale: --
Dimensions (mm): 162×329×6
Z Factor: 1
Print Size: 100%
Number of Colours: 5
Printer: Prusa XL
Print Time: 7h 26m
File: M3C_metro_LineB.3mf



Model: 3D
Name: Praha Metro Line C
Data Source: PID
Scale: --
Dimensions (mm): 162×281×6
Z Factor: 1
Print Size: 100%
Number of Colours: 5
Printer: Prusa XL
Print Time: 6h 20m
File: M3D_metro_LineC.3mf



Model: 4A
Name: Earth Structure
Data Source: National Geographic
Scale: 1:333,000,000
Dimensions (mm): 69×73×38
Z Factor: 1
Print Size: 30%
Number of Colours: 5
Printer: Prusa i3 MK3S & Palette 3 Pro
Print Time: 12h 22m
File: M4AB_earth_structure.3mf



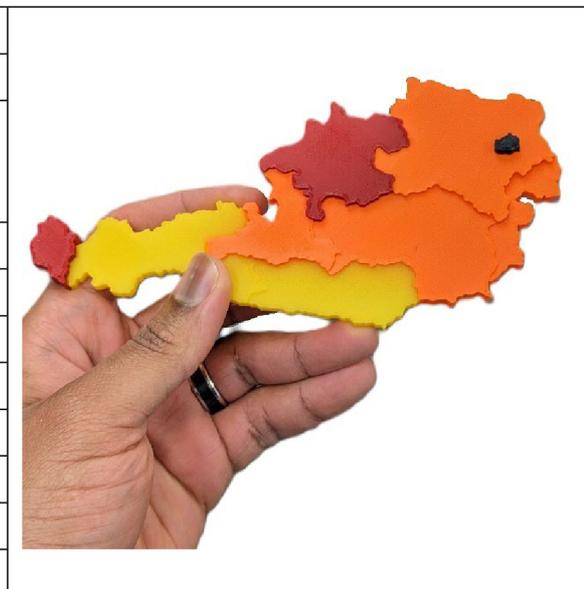
Model: 4B
Name: Earth Structure
Data Source: National Geographic
Scale: 1:333,000,000
Dimensions (mm): 81×68×38
Z Factor: 1
Print Size: 30%
Number of Colours: 5
Printer: Prusa XL
Print Time: 2h 42m
File: M4AB_earth_structure.3mf



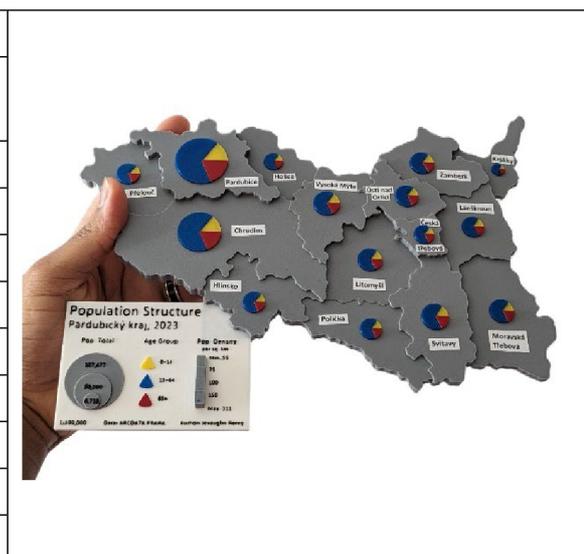
Model: 4C
Name: Earth Structure
Data Source: National Geographic
Scale: 1:200,000,000
Dimensions (mm): 203×162×64
Z Factor: 1
Print Size: 50%
Number of Colours: 5
Printer: Bambu P1S & AMS
Print Time: 34h 16m
File: M4C_earth_bambu_studio.3mf



Model: 5
Name: Austria Population Density 2023
Data Source: Esri, Michael Bauer Research GmbH 2022, Bundesanstalt Statistik Österreich 2023, Eurostat
Scale: 1:5,000,000
Dimensions (mm): 170×87×9
Z Factor: 1
Print Size: 10%
Number of Colours: 4
Printer: Prusa XL
Print Time: 2h 48m
File: M5_austria_population.3mf



Model: 6
Name: Population Structure Pardubický kraj
Data Source: ArcČR, ARCDATA PRAHA
Scale: 1:500,000
Dimensions (mm): 257×190×13.5
Z Factor: 1
Print Size: 12%
Number of Colours: 6
Printer: Prusa XL
Print Time: 8h 36m
File: M6_pardubicky_kraj.3mf



Model: 7A	
Name: Lucerne Land Cover OSM	
Data Source: OpenStreetMap, Copernicus 30m DEM	
Scale: 1:40,000	
Dimensions (mm): 211×149×13	
Z Factor: 1.25	
Print Size: 100%	
Number of Colours: 6	
Printer: Prusa XL	
Print Time: 18h 21m	
File: M7A_lucerne_land_cover_OSM.3mf	

Model: 7B	
Name: Lucerne Land Cover CLC	
Data Source: Corine Land Cover, Copernicus 30m DEM	
Scale: 1:40,000	
Dimensions (mm): 211×149×13	
Z Factor: 1.25	
Print Size: 100%	
Number of Colours: 6	
Printer: Prusa XL	
Print Time: 13h 24m	
File: M7B_lucerne_land_cover_CLC.3mf	